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नवीकरणीय ऊर्जा मंत्रालय
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NEW AND
RENEWABLE ENERGY
सत्यमेव जयते

Energy Storage Systems for RE Dominated Indian Grid:

A Detailed Technical Review & Analysis



giz Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

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Grid Integration Lab
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Executive Summary

India’s Energy Storage Transition

India’s power system is approaching a phase in which energy storage is becoming increasingly important for Renewable Energy (RE) integration, generation adequacy, operational flexibility, grid stability and system resilience. Rapid growth in variable RE, particularly solar PV and wind, is resulting in significant midday net-load reductions, steeper evening ramps, periods of RE curtailment and emerging grid-strength concerns. These challenges are becoming more prominent as large RE resources are increasingly located in RE-rich regions away from conventional generation centres and major load centres, creating additional requirements flexibility (both short-term and long-term), transmission availability, congestion management and system-strength support.

The scale of this transition is already evident from changes in India's daily electricity demand profile. During May, the average afternoon-to-evening increase in net load, between 1:00 PM and 8:00 PM nearly doubled from approximately 35.7 GW in 2023 to 73.7 GW in 2026. This indicates a substantial increase in the additional generation required to meet electricity demand as solar generation reduces towards evening. Furthermore, during April and May 2026, electricity shortages at non-solar-hour peak demand were recorded on 36 out of 61 days, compared with only six days at solar-hour peak demand, with the maximum non-solar-hour shortfall reaching approximately 5.4 GW. These trends indicate that India's energy storage requirements are increasingly driven by the temporal variability of renewable generation and electricity demand, rather than aggregate installed generation capacity alone. Energy storage deployment planning therefore needs to consider the required grid services, response time, discharge duration, location, control capability, availability and verifiable operational performance.

Energy Storage Deployment Framework

In response to the growing requirements for operational flexibility, generation adequacy and grid stability, India is transitioning from pilot-scale energy storage installations towards large commercial-scale deployment. Operational Battery Energy Storage System (BESS) capacity reached approximately 3.03 GW/9.08 GWh by August 2026, while the overall BESS project portfolio, including operational, under-construction, awarded and tender-stage projects, stood at approximately 56.9 GW/176.7 GWh. The scale of future deployment is expected to increase substantially, with planning estimates indicating energy storage requirements of approximately 411 GWh by 2031–32, and 888 GWh by 2035–36.

Alongside the expansion of BESS, PSP continues to remain the principal mature option for bulk and long-duration energy storage in India. With approximately 7.43 GW of installed capacity, PSP is expected to undergo substantial expansion, with the CEA roadmap projecting approximately 100.8 GW of capacity in the longer term. The anticipated growth of both BESS and PSP highlights the need for coordinated project development, transmission planning, supply-chain establishment, financing and regulatory support.

Translating these planned capacities into operational projects will require coordinated policy support, regulatory certainty and market mechanisms that facilitate investment and long-term project viability. Government initiatives, including the National Framework for Promoting Energy Storage Systems, Energy Storage Obligations, Viability Gap Funding (VGF), transmission-charge incentives and support for domestic Advanced Chemistry Cell manufacturing, are strengthening the enabling environment for storage deployment in India. Competitive procurement has contributed to a substantial reduction in quoted standalone BESS tariffs, improving the commercial prospects of grid-scale storage. However, meaningful tariff comparisons require normalisation across storage duration, cycling requirements, charging-energy responsibility, availability obligations, VGF support and contractual structures. Consequently, the economic viability of storage projects needs to be assessed based on comparable procurement conditions, lifecycle costs and expected operational performance rather than headline tariffs alone.

Energy Storage Technology Assessment

The technical and economic viability of energy storage deployment also depends on selecting technologies appropriate for the intended power-system services. No single energy storage technology can satisfy all requirements

of the Indian power system. Technology selection should therefore consider response time, rated power, usable energy capacity, discharge duration, cycling requirements, round-trip efficiency, degradation, operational lifetime, safety, siting constraints and lifecycle cost. BESS provides rapid and precise active and reactive power control and are particularly suitable for frequency response, voltage regulation, RE smoothing, management of rapid changes in net load, peak shaving, congestion management and short- to medium-duration energy shifting. PSP complements BESS by providing large-capacity and long-duration energy shifting, bulk balancing and support for Round-the-Clock (RTC) RE power supply. Other long-duration energy storage technologies may become relevant where extended discharge periods, system resilience or multi-day energy balancing are required. The complementary characteristics of these technologies determine their suitability for different applications across the power system.

Applications of Energy Storage System for India

The technical characteristics of different energy storage technologies translate into distinct applications across utility-scale, distribution and Behind-the-Meter (BTM) systems. At the utility scale, energy storage is increasingly being deployed or procured in India for energy arbitrage, energy shifting, peak-demand management, RE firming, assured peak-hour supply and improved utilisation of RE evacuation infrastructure. In addition to these, energy storage can also provide grid-support services, including synthetic inertia, fast frequency response, reactive power and voltage support, congestion management, and short-term and long-term operating reserves. These applications are particularly relevant for India, where large solar and wind resources are concentrated in RE-rich states and connected to major load centres through long-distance transmission networks. The increasing adoption of energy storage is reflected in SECI's procurement initiatives, beginning with India's first-of-its-kind competitive tender for 500 MW/1,000 MWh of standalone BESS in April 2022, comprising two projects of 250 MW/500 MWh each, designed to provide DISCOMs and other buying entities with energy storage capacity for on-demand energy shifting. SECI subsequently issued a larger 1,000 MW/2,000 MWh standalone BESS tender in June 2024, while procurement of solar-wind hybrid, RTC and Firm and Dispatchable Renewable Energy (FDRE) projects further demonstrates the increasing role of storage in meeting scheduled and peak-period electricity demand.

Beyond energy shifting and demand management, the increasing penetration of converter based RE generation is creating additional requirements for dynamic grid support. BESS equipped with suitable Power Conversion Systems (PCS) can provide synthetic inertial response, fast active-power response, dynamic reactive-power support, frequency regulation and grid-forming functionality, thereby contributing to power-system stability. These capabilities of BESS are particularly relevant for RE-rich regions of India where reduced system strength, and limited availability of nearby synchronous generation may become important operational considerations.

Reflecting these emerging requirements, grid-forming capability is progressing from an advanced technical option towards a formal requirement for large BESS projects in India. The Central Electricity Authority (CEA) advisory dated 10 July 2026 calls for the implementation of 100% grid-forming inverters in upcoming BESS projects with installed capacity of 50 MW and above, subject to the specified applicability conditions and exemptions. In parallel, the CEA Technical Standards for Construction of Electrical Plants and Electric Lines (Amendment) Regulations, 2026 require BESS of 50 MW and above to have automatic generation control, grid-forming control capability and black-start capability, with the regulations coming into force from 1 April 2027. These developments represent an important shift in Indian BESS design requirements, as PCS selection and plant-level controls must increasingly account for grid stability and system-support functions in addition to conventional charging and discharging operations.

Complementing utility-scale BESS, PSP plays an important role in providing bulk energy shifting, peak-demand management, RE firming and long-duration flexibility in India. PSP can utilise surplus electricity during periods of high RE generation for pumping and subsequently generate electricity during peak-demand or low-RE periods, supporting RTC and FDRE supply. In addition to energy shifting, conventional synchronous-machine-based PSP can contribute to frequency regulation, rotational inertia, voltage support, operating reserves and, where appropriately equipped, black-start capability. Recent developments, including the 1,680 MW Pinnapuram PSP project in Andhra Pradesh and the 1,000 MW Tehri PSP project in Uttarakhand, demonstrate India's increasing emphasis on large-scale storage infrastructure. The expansion of PSP, particularly through off-stream and closed-loop configurations, is expected to complement BESS in addressing flexibility requirements over different operational timescales, subject to site-specific technical, environmental and economic considerations.

While these developments are expanding the role of utility-scale energy storage, distribution-connected BESS is also progressing from pilot applications towards substation-level deployment in India. A 20 MW/40 MWh BESS has been commissioned at BRPL's 33/11 kV Kilokari Grid in Delhi. Building on this experience, a 12.5 MW/25 MWh BESS is being developed at the 33/11 kV Shivalik Grid Station, with proposed grid-forming control functionality to support voltage and frequency establishment and improve grid resilience. A further 43 MW/86 MWh of distributed BESS has been planned across Delhi's 66/11 kV G5 Matiala, G7 Dwarka and Goyla Khurd grid substations. The Delhi Electricity Regulatory Commission identifies potential applications including capacity-upgrade deferral, peak-demand reduction, management of rapid changes in load, resource adequacy, grid support and backup supply to critical loads through islanding operation. These three areas have experienced approximately 9% compound annual growth in peak demand over three years, and the proposed systems are expected to serve approximately 1.4 lakh consumers. These projects demonstrate the potential for locating BESS according to distribution-network requirements rather than solely for system-wide energy arbitrage. More broadly, distribution-connected storage can reduce feeder and transformer loading, mitigate voltage rise and reverse power flow, improve rooftop-PV hosting capacity, provide local active and reactive power support and defer selected network augmentation.

At the consumer level, BTM storage is becoming increasingly relevant with the expansion of rooftop solar PV, commercial and industrial loads, EV charging and time-varying electricity demand. India had approximately 32.5 GW of grid-connected rooftop solar capacity as of August 2026, increasing the potential role of storage in improving solar self-consumption, shifting excess daytime generation towards evening demand, reducing consumer peak demand and providing backup supply. Coordinated operation of distributed storage can also reduce local feeder and transformer stress in areas with high rooftop-PV penetration. For commercial and industrial consumers, BTM storage can support demand management, improve utilisation of captive or rooftop RE generation and enhance supply resilience. However, its economic viability will depend on consumer-specific tariff structures, time-of-day price differentials, demand charges, cycling requirements, battery degradation and the potential for combining multiple value streams.

Beyond commercially established lithium-ion technologies, emerging battery chemistries such as sodium-ion, flow batteries and metal-air systems are gaining attention for longer-duration storage and diversification of critical-material supply chains in India. In November 2025, NTPC commissioned a 600kW/3MWh Vanadium Redox Flow Battery (VRFB) system at its NETRA facility in Greater Noida, representing India's first MWh-scale flow-battery demonstration for long-duration energy storage and RE integration. Building on this development, NTPC Renewable Energy Limited invited bids in February 2026 for a 16.7 MW/100 MWh VRFB project at the Khavda Solar Park in Gujarat, targeting approximately six hours of storage integrated with solar generation, with potential applications in RE firming and energy shifting. Similarly, in September 2026, NTPC invited Expressions of Interest for grid-connected sodium-ion BESS pilot installations at its thermal power stations and office buildings to assess technology performance, safety, degradation, reliability and commercial viability under Indian operating conditions. These initiatives demonstrate increasing interest in alternative battery chemistries, while emerging iron-air and other metal-air technologies remain at an earlier stage of technological development for potential multi-day storage applications. Their wider adoption will depend on demonstrated technical performance, lifecycle economics, safety, domestic manufacturing readiness and validation under Indian climatic and grid-operating conditions.

Overall, energy storage across utility-scale, distribution and BTM systems should be considered a multifunctional power-system resource whose configuration, location and control strategy are determined by the intended services and operational requirements. Realising these applications at scale will also depend on the development of appropriate regulatory and market frameworks, particularly at the state level, to support energy storage procurement, grid integration and participation in electricity markets.

State-Level Energy Storage Policy and Regulatory Frameworks

In addition to national-level initiatives introduced by the Ministry of Power and the Ministry of New and Renewable Energy (MNRE), state governments and electricity regulatory commissions are introducing complementary policies and regulatory frameworks to support energy storage deployment. Maharashtra’s Renewable Energy & Energy Storage Policy 2025-26 to 2035-36 targets ESS capacity equivalent to at least 10% of electricity demand by FY 2035-36, corresponding to approximately 100 GWh/day or 20 GW assuming a 5-hour duration, along with 25 GW of new RE

projects with co-located storage. The policy also specifies storage power capacity equivalent to at least 50% of the RE capacity for new solar PV, wind and solar-wind hybrid projects procured by distribution licensees, with a minimum storage duration of 2 hours for projects commissioned by FY 2029-30 and 4 hours from FY 2030-31. Rajasthan has established a dedicated BESS regulatory framework and mandates ESS equivalent to at least 5% of RE capacity, with a minimum 2-hour duration, for new RE projects above 5 MW connected to the State Transmission Utility (STU) network, supported by transmission and wheeling-charge incentives. Gujarat, Kerala and Delhi have introduced progressively increasing Energy Storage Obligations, reaching 3.5%, 4.0% and 4.0%, respectively, by FY 2029-30, generally requiring at least 85% of the energy stored annually to be sourced from RE generation. Kerala has additionally specified performance requirements for grid-scale BESS, while Gujarat and Maharashtra are progressing towards dedicated BESS regulations. These developments reflect a transition from project-specific approvals towards quantified storage obligations, RE-linked deployment requirements and dedicated regulatory frameworks. However, greater harmonisation across states is required in connectivity, scheduling, network charges, aggregation, multi-use applications and revenue stacking. Such harmonisation will become increasingly important as energy storage applications expand towards distributed flexibility and cross-sector integration.

Emerging Storage Applications and Sector Coupling

Beyond conventional grid applications, energy storage in India is increasingly being explored for integration with electric mobility, distributed energy resources and other energy sectors. To harness the potential of electric vehicles as mobile energy storage resources, Vehicle-to-Grid (V2G) technology is progressing towards field demonstration. This is particularly relevant for distribution networks with increasing rooftop solar PV penetration, where excess daytime generation can lead to voltage rise, reverse power flow and local network constraints. In 2025, KSEBL and IIT Bombay initiated a V2G pilot in Kerala to evaluate bidirectional charging for peak-load management, frequency regulation and grid resilience, with potential applications in addressing these distribution-network challenges. Kerala has also introduced provisions for V2G and Virtual Power Plants (VPPs) within its regulatory framework, including an initial peak-hour export tariff of ₹10/kWh for V2G and provisions for EV participation in frequency regulation, voltage support and peak shaving.

In parallel with these distributed flexibility applications, hybrid RE and storage configurations are gaining importance as India moves towards firm and dispatchable renewable power supply. In 2026, SECI issued procurement for 1,500 MW of assured peak supply over four hours, corresponding to 6,000 MWh of contracted energy delivery, along with a separate 1,000 MW RTC FDRE procurement. These developments highlight the increasing role of energy storage in enabling variable RE generation to meet defined supply schedules and peak-period demand requirements.

Beyond electricity-sector applications, hydrogen provides an emerging pathway for sector coupling and long-duration energy storage. India's National Green Hydrogen Mission targets at least 5 million metric tonnes per annum of green hydrogen production by 2030, supported by approximately 125 GW of additional RE capacity. Large-scale electrolysers can potentially operate as flexible electrical loads to support RE integration, while hydrogen storage and Power-to-Hydrogen-to-Power systems may provide longer-duration energy shifting and system flexibility where technically and economically justified.

The integration and operation of these emerging applications will increasingly depend on advanced monitoring, communication and control technologies. Digital twins, AI/ML-based monitoring and control, VPPs and aggregation platforms can support predictive maintenance, operational optimisation and coordinated management of distributed BESS, EVs and flexible loads. Their wider adoption in India will require field validation under representative grid conditions, interoperable communication and control architectures, appropriate market mechanisms, cybersecurity provisions and clearly defined technical performance requirements.

Technical Performance, Safety and Operational Requirements

As energy storage applications expand towards advanced grid-support services and digitally coordinated operation, greater emphasis is required on power-system modelling, control validation and clearly defined technical performance requirements. BESS applications involving fast active-power response, dynamic voltage support, fault ride-through and grid-forming operation require validated dynamic models, coordinated converter controls and appropriate testing and verification procedures. Procurement specifications should therefore define measurable

performance requirements at the point of interconnection, supported by appropriate commissioning tests and operational compliance assessments.

In addition to grid-performance requirements, India's diverse climatic and environmental conditions need to be explicitly considered in ESS design and operation. High ambient temperatures in major RE-rich regions can accelerate battery degradation, increase auxiliary power consumption and impose additional thermal-management and maintenance requirements. Appropriate cooling, ventilation, thermal monitoring, fault detection, fire protection, electrical isolation and emergency-response provisions are therefore essential for reliable and safe operation. Safety assessments should cover cell, module, rack, container and plant levels, including Battery Management System (BMS) functionality, thermal-runaway prevention and propagation mitigation, and end-of-life management. Addressing these requirements will necessitate robust technical standards, validated equipment, qualified operation and maintenance practices, and adequate domestic testing and certification capabilities.

Deployment Challenges and Domestic Capability Development

Despite rapid growth in procurement, large-scale ESS deployment in India continues to face technical, commercial and supply-chain challenges. Key issues include high upfront capital requirements, uncertainty in long-term revenue stacking, battery degradation and augmentation requirements, technology and warranty risks, evolving ancillary-service markets, and differences in regulatory treatment across states. For BESS, performance under Indian operating conditions is particularly important, as high ambient temperatures can increase auxiliary consumption, accelerate degradation and impose additional thermal-management requirements. The transition towards advanced grid support services such as dynamic voltage support, fault ride-through, black start and grid-forming operation also places greater requirements on PCS capability, plant-level controls, validated dynamic models and performance testing. As project sizes increase, safety, fire protection, emergency response, end-of-life management and availability of technically skilled O&M capability will become increasingly critical.

In parallel, India is seeking to strengthen its domestic energy storage value chain, although localisation remains uneven across critical materials, battery cells, packs, Battery Management Systems (BMS), Power Conversion Systems (PCS), system integration and recycling. The Government of India's Production Linked Incentive (PLI) scheme for Advanced Chemistry Cell (ACC) manufacturing, with an outlay of ₹18,100 crore and a target of 50 GWh of domestic manufacturing capacity, represents an important initiative towards reducing import dependence. However, manufacturing capacity alone will not ensure technological self-reliance. Indigenous capabilities are also required in ESS engineering, high-power PCS and grid-forming controls, performance testing, certification, degradation assessment and safety validation. The Battery Waste Management Rules, 2022, through Extended Producer Responsibility provisions, also provide a regulatory basis for battery recycling, refurbishment and circular material management. Strengthening domestic R&D, accredited testing infrastructure, field demonstrations and industry-academia collaboration will therefore be essential for developing technically validated, reliable and cost-effective ESS solutions suited to Indian climatic conditions and grid requirements. These priorities will be critical for supporting sustainable deployment at scale and reducing long-term technology and supply-chain dependence.

Key Findings for Indian Stakeholders

The technical review identifies the following key findings and priorities for energy storage planning, deployment and integration into the Indian power system:

- System-oriented storage planning: Increasing evening net-load variations, non-solar-hour shortages and emerging grid-strength concerns require ESS planning based on specific grid services, duration, location and performance rather than MW/MWh capacity targets alone.
- Rapid deployment with implementation challenges: India's operational BESS capacity reached 3.03 GW/9.08 GWh by August 2026, against a total project portfolio of 56.9 GW/176.7 GWh. Converting this pipeline into operational capacity requires reliable technology, project bankability and effective execution.
- Complementary storage technologies: BESS and PSP should be developed as complementary resources, with technology selection based on response characteristics, storage duration, cycling requirements, siting constraints and lifecycle economics.

- Multi-stacking of grid-support applications: ESS should be recognised beyond energy arbitrage for RE firming, peak-demand management, frequency and voltage regulation, congestion relief, network deferral and improved transmission utilisation across utility-scale, distribution and BTM systems.
- Advanced grid-support capabilities: CEA's emerging requirements for grid-forming capability in applicable BESS projects of 50 MW and above highlight the importance of advanced PCS controls, validated dynamic models, testing and performance verification.
- Emerging applications and sector coupling: V2G, VPPs, hybrid and long-duration storage, hydrogen-based flexibility and digital technologies offer additional opportunities but require demonstration and validation under Indian grid conditions.
- Technical performance and safety: Reliable deployment requires validated converter controls, appropriate thermal management, fire protection, lifecycle assessment and compliance with technical and safety standards suited to Indian climatic and operating conditions.
- Domestic capability development: The ₹18,100 crore ACC PLI scheme targeting 50 GWh of manufacturing capacity provides an important foundation. Further development of domestic PCS, controls, system integration, testing, recycling and R&D capabilities remains essential.

Overall, energy storage should not be treated as a stand-alone deployment target for India. It should be considered as a portfolio resource whose technical and economic value depends on the service delivered, location of connection, duration, control strategy and ability to demonstrate sustained performance throughout the project lifecycle. Coordinated planning, technology-appropriate procurement, rigorous modelling and testing, stronger domestic capability, clear regulatory and market frameworks, and continued R&D will be essential for energy storage to support a reliable, flexible and increasingly RE dominated Indian power system.

Chapter 1.

India’s Energy-Storage Transition



1.1. Introduction

India's power system is undergoing a significant transition driven by rapidly increasing integration of renewable energy resources. Country is witnessing rapid growth in solar and wind generation as it progresses towards its target of 500 GW of installed non-fossil fuel-based power generation capacity by 2030[1]. On the other hand, rising industrial activity, urbanisation, electrification and cooling requirements are contributing to higher electricity consumption and peak demand. Recently, India recorded a peak electricity demand of approximately 270.8 GW in May 2026[2]. These developments are changing the requirements for power-system planning, operation and reliability.

The increasing penetration of variable renewable energy (VRE) is introducing new operational challenges to the Indian power system. Variability and uncertainty in solar and wind generation, steep net-load ramps, renewable energy curtailment and transmission congestion are increasing the need for system flexibility. The growing share of inverter-based generation also introduces challenges related to frequency stability, voltage regulation and system strength, particularly in weak-grid areas. At the same time, increasing peak demand and sustained electricity requirements during non-solar hours place additional pressure on existing dispatchable generation resources. The average evening solar-adjusted net-load rise between 13:00 and 20:00 increased from approximately 36 GW in May 2023 to 74 GW in May 2026[2]. These challenges require greater operational flexibility while maintaining secure and reliable power-system operation.

Energy Storage Systems (ESS) are emerging as a promising solution to address these evolving power system requirements. ESS can shift surplus RE generation to periods of higher demand, manage net-load ramps, reduce renewable curtailment and support peak-demand management. Appropriately designed systems can also provide frequency regulation, voltage support and other grid services. BESS and PSP, alongside conventional flexibility resources and demand-side measures, can support reliable renewable energy integration. Their effective deployment requires service-specific planning based on power rating, storage duration, response characteristics, location and overall system requirements.

In this entire report, all the data specified is as of August 2026 unless mentioned otherwise.

1.2. Power System in 2026: The Statistical Baseline

1.2.1 Installed capacity

India's total installed generating capacity stood at 554.54 GW as of August 2026, of which non-fossil sources accounted for 304.33 GW, or 54.88% of total installed generation capacity.[3] India, therefore, exceeded its updated Nationally Determined Contribution (NDC) target of 50% non-fossil installed capacity by 2030. Table 1 summarises the source-wise composition and Figure 1 presents a visual illustration of the current scenario. Out of total non-fossil capacity, 295.55 GW was RE, including 52.06 GW of large hydro (of which 7.43 GW was pumped storage), while nuclear power accounted for 8.78 GW.[4]

Table 1: All-India installed generating capacity by source (CEA, as on 31 August 2026)

Source	Capacity (GW)	Share (%)	Planning relevance for storage
Coal	224.408	40.47	Major source of dispatchable generation

[1] Ministry of Power, Government of India, "Non-Fossil Fuel Share In Total Installed Power Capacity," Press Information Bureau (PIB), Feb. 5, 2026.

[2] Sanjeev Sanyal and Satvik Dev, The Duck and The Camel: Tracing the Net Load on the Indian Power Grid, EAC Working Paper Series EAC-PM/WP/53/2026 (Economic Advisory Council to the Prime Minister, Government of India, 2026).

[3] Central Electricity Authority (CEA), All India Installed Capacity (in MW) of Power Stations as on 31.08.2026, Installed Capacity Report (Central Electricity Authority, Ministry of Power, Government of India, 2026).

[4] Ministry of New and Renewable Energy (MNRE), Physical Achievements – Programme/Scheme-Wise Cumulative Physical Progress as on 31.08.2026.

Source	Capacity (GW)	Share (%)	Planning relevance for storage
			• Technical-minimum and ramp-rate constraints affect operational flexibility
Lignite	3.37	1.15	Limited flexibility; typically, base-loaded
Gas (incl. liquid)	19.144	3.45	Fast-ramping but fuel-constrained; low utilisation
Diesel	0.288	0.05	Limited contribution to bulk-system flexibility
Total fossil	**250.21**	**45.12**	
Large hydro (incl. PSP)	52.065	9.39	Supports ramping and energy shifting, synchronous inertia provision, black start support capability
Wind	58.52	10.55	Monsoon-peaking complements evening and night demand in some Western Region and Southern Region states
Solar	168.04	30.30	Increases midday generation and evening net-load ramp as solar output declines
Biomass and waste-to-energy	11.748	2.12	Small but dispatchable generation
Small hydro	5.182	0.93	Generally, run-of-river, with limited energy shifting capability
Nuclear	8.780	1.58	Base-load, synchronous inertia
Total non-fossil	**304.334**	**54.88**	
All-India total	**554.544**	**100**	

Data Compiled from Multiple Sources

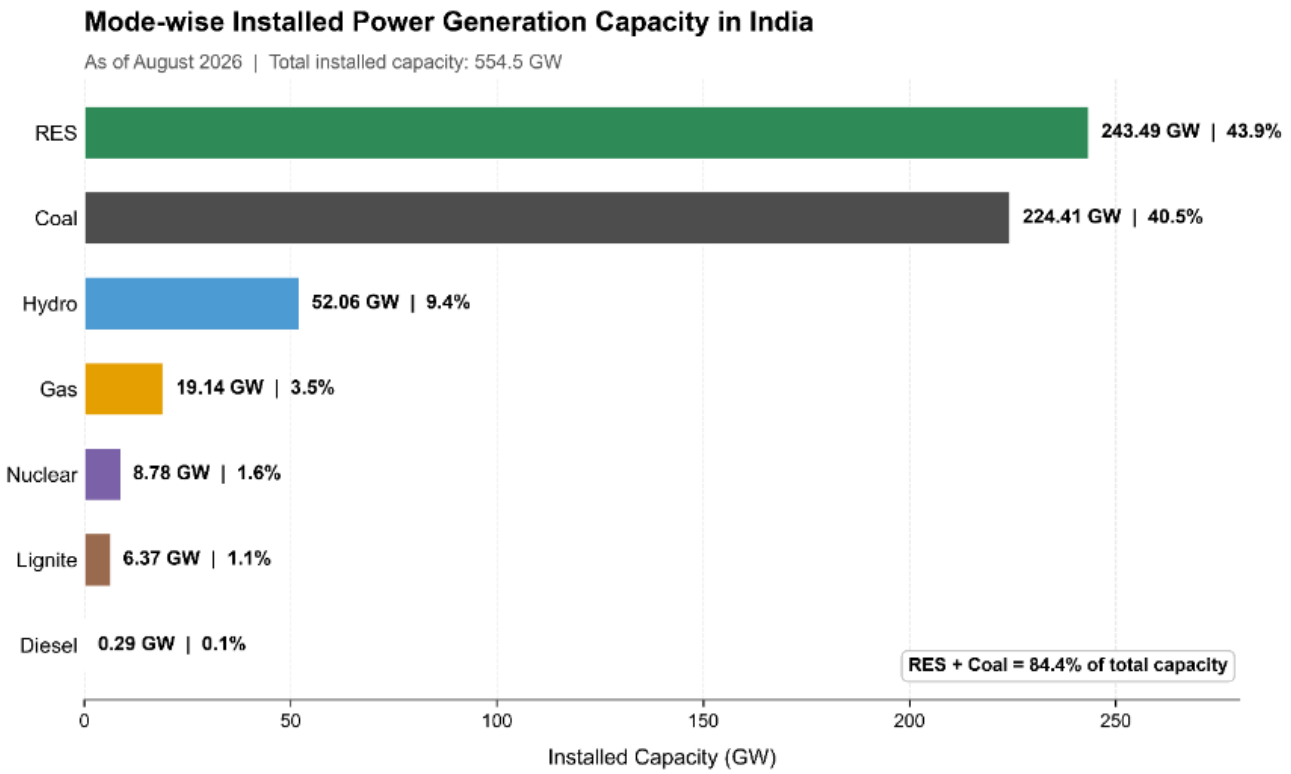


Figure 1: Mode-wise installed capacity in India, as on 31 Aug 2026 (GW and % share)

(Source: This figure has been plotted using data sources from CEA installed-capacity data as on 31 August 2026)

The growth in installed generation capacity of wind and solar has been exceptionally rapid, as illustrated in Figure 2, which shows the country's growth trajectory since 2011. In FY 2025-26, solar and wind recorded their highest annual capacity additions of 44.61 GW and 6.05 GW, respectively. A further 20.87 GW of renewable capacity (17.78 GW solar, 2.43 GW wind, 0.65 GW large hydro) was added in the first eight months of FY 2026-27.[5]

The installed capacity is also geographically concentrated in the RE-rich states of the country: Gujarat (53.63 GW), Rajasthan (50.72 GW), Maharashtra (33.28 GW), Tamil Nadu (30.05 GW), and Karnataka (27.87 GW), together hosting about two-thirds of India's renewable capacity, as presented in Figure 3. The geographical concentration of RE generation, combined with unevenly distributed demand and network constraints, increases transmission requirements and the need for locational flexibility.

[5] Central Electricity Authority, "Monthly installed capacity reports," Ministry of Power, Government of India, New Delhi, India, 2026.

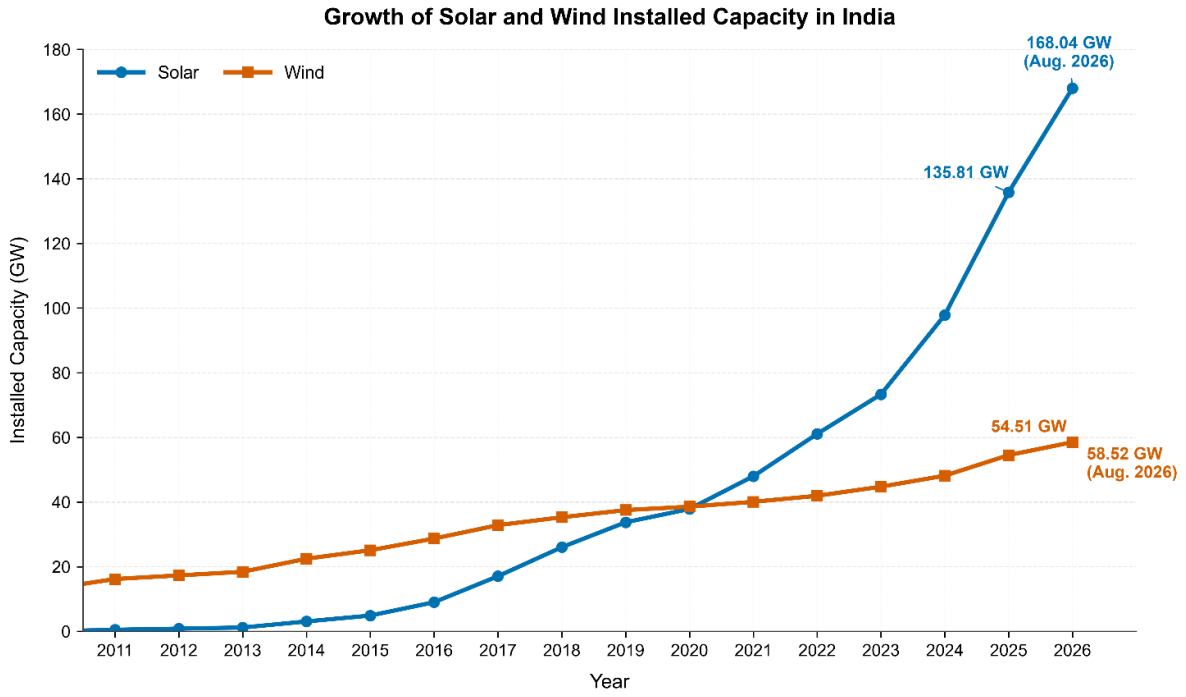
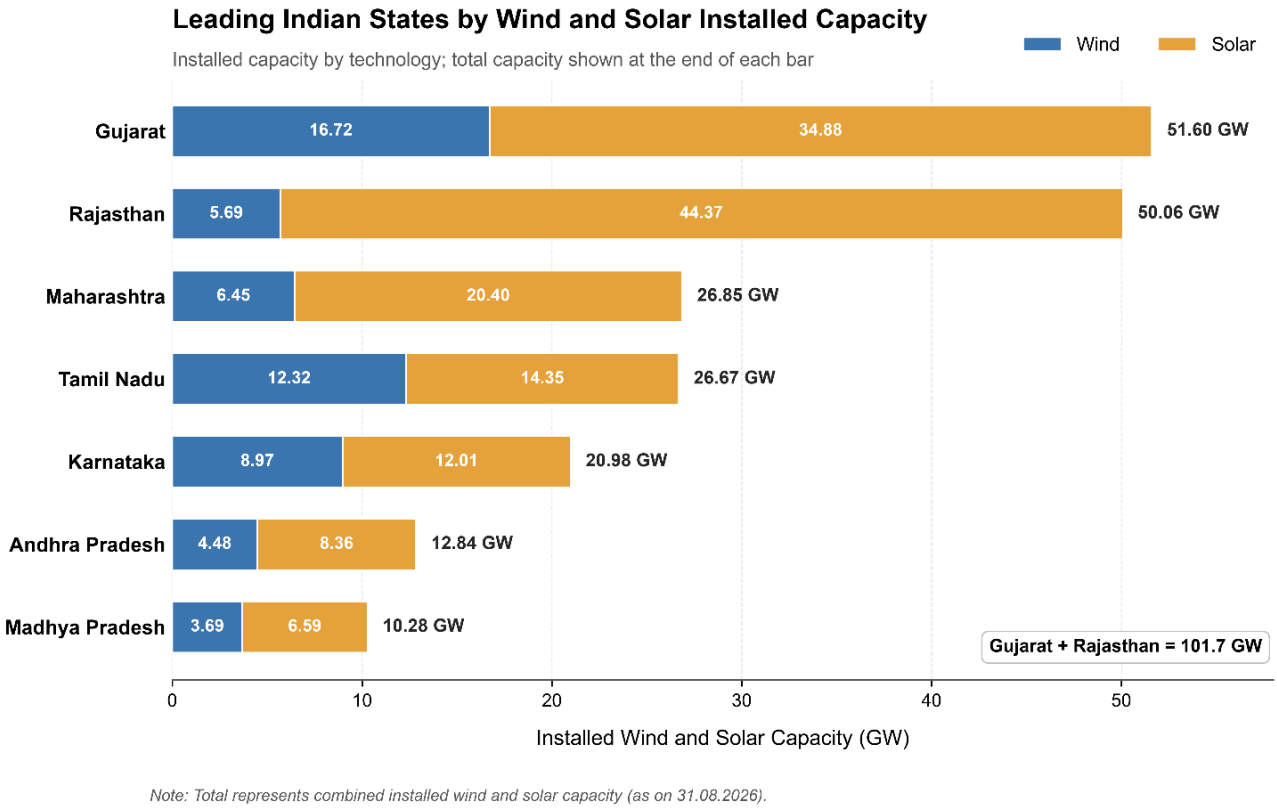


Figure 2: Growth of installed solar and wind capacity in India (Dec. 2011 to Aug. 2026)

(Source: This figure has been plotted using data sources from MNRE and CEA historical installed-capacity releases)



Note: Total represents combined installed wind and solar capacity (as on 31.08.2026).

Figure 3: Leading Indian states by Wind and Solar Installed Capacity as of Aug. 2026*

(Source: This figure has been plotted using data sources from MNRE state-wise wind and solar installed capacity installations)

* Solar includes ground-mounted, rooftop, hybrid-component and off-grid capacity

1.2.2 Power Demand and RE Penetration: New Peaks Being Achieved

Electricity demand in India is growing faster as compared to the projections done by planning studies. It is primarily driven by heat-related cooling load, datacentres, agricultural pumping, urbanisation and industrial activity. All-India peak demand reached 256.1 GW at 15:38 hours on 25 April 2026, surpassing the previous record of 250 GW occurred on30 May 2024, and then an all-time high of 270.8 GW on 21 May 2026, as presented in

Figure 4.[6] Although maximum demand of 270.8 GW occurred during solar hours, demand remained high after sunset, requiring greater output from dispatchable generation. At the moment of peak, thermal generation supplied about 171.7 GW, wind about 13.6 GW and RE (including hydro) about 34% of demand; after sunset, demand stayed close to 250 GW until midnight, while thermal output rose to 184.9 GW. The CEA's Long-Term National Resource Adequacy Plan (LT-NRAP, April 2026) projects peak demand of 289 GW in 2026-27, 388 GW in 2031-32 and 459 GW in 2035-36, with energy requirement rising from 1,929 BU to 3,365 BU over the same period [7].

Renewable generation has also reached new operational highs as shown in Table 2. Solar output reached an all-time high of 93.81 GW on 3 October 2026, and it supplied roughly one-third of all-India demand at its peak generation as seen from Figure 5[8]. Wind generation peaked at 36.64 GW on 12 July 2026, at the height of the south-west monsoon, with 36.58 GW recorded in the 17:15 block as shown in Figure 6. Because strong monsoon wind coincided with good late-summer irradiance, combined variable renewable energy reached its highest output of 105.24 GW on 27 August 2026, with 105.04 GW in the 12:30 block, about 75 GW of solar and 30 GW of wind as shown in Figure 7. On all three days, the thermal generation was reduced to roughly 115-150 GW at midday and ramped back up by 50-60 GW in the evening, illustrating the dependency on coal based generation. These observations indicate the increasing contribution of VRE to meeting instantaneous demand. They also highlight the need for greater flexibility and adequate grid-support capabilities as the generation mix changes.

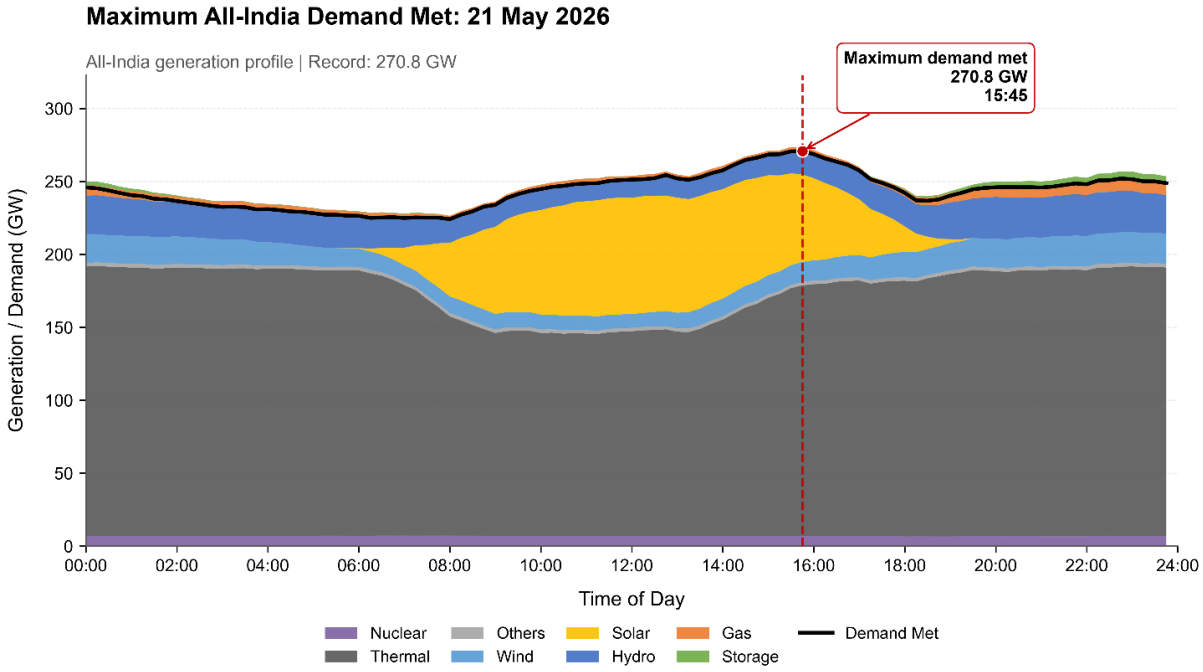


Figure 4: All-India generation profile on 21 May 2026, the day of maximum demand met

[6] Grid Controller of India Limited (GRID-INDIA), "Daily Power System Performance (PSP) Report," National Load Despatch Centre (NLDC), Ministry of Power, Government of India.

[7] Central Electricity Authority, Long Term National Resource Adequacy Plan (2026–27 to 2035–36), Report (Central Electricity Authority, Ministry of Power, Government of India, 2026).

[8] Grid Controller of India Limited (GRID-INDIA), "NLDC Renewable Energy Management Centre Report," National Load Despatch Centre (NLDC), New Delhi, India, Oct 2026.

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

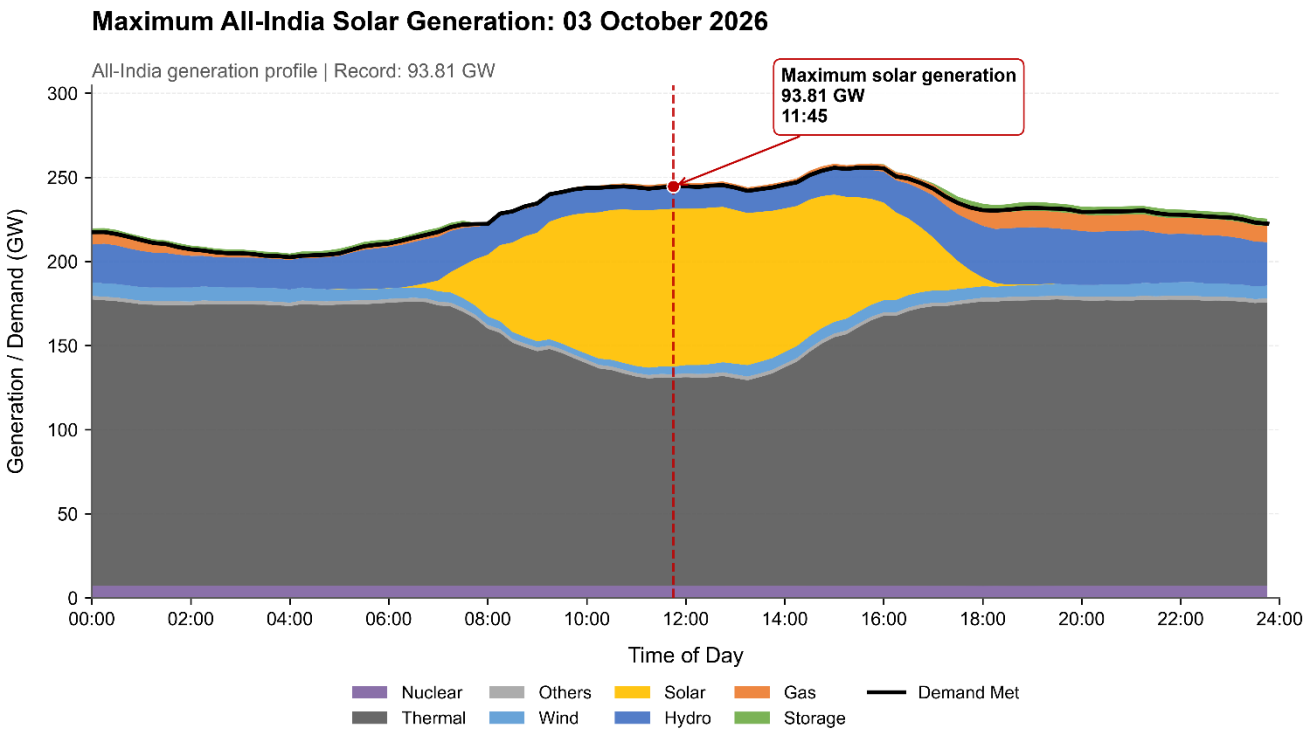


Figure 5: All-India generation profile on 3 October 2026, the day of maximum solar generation

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

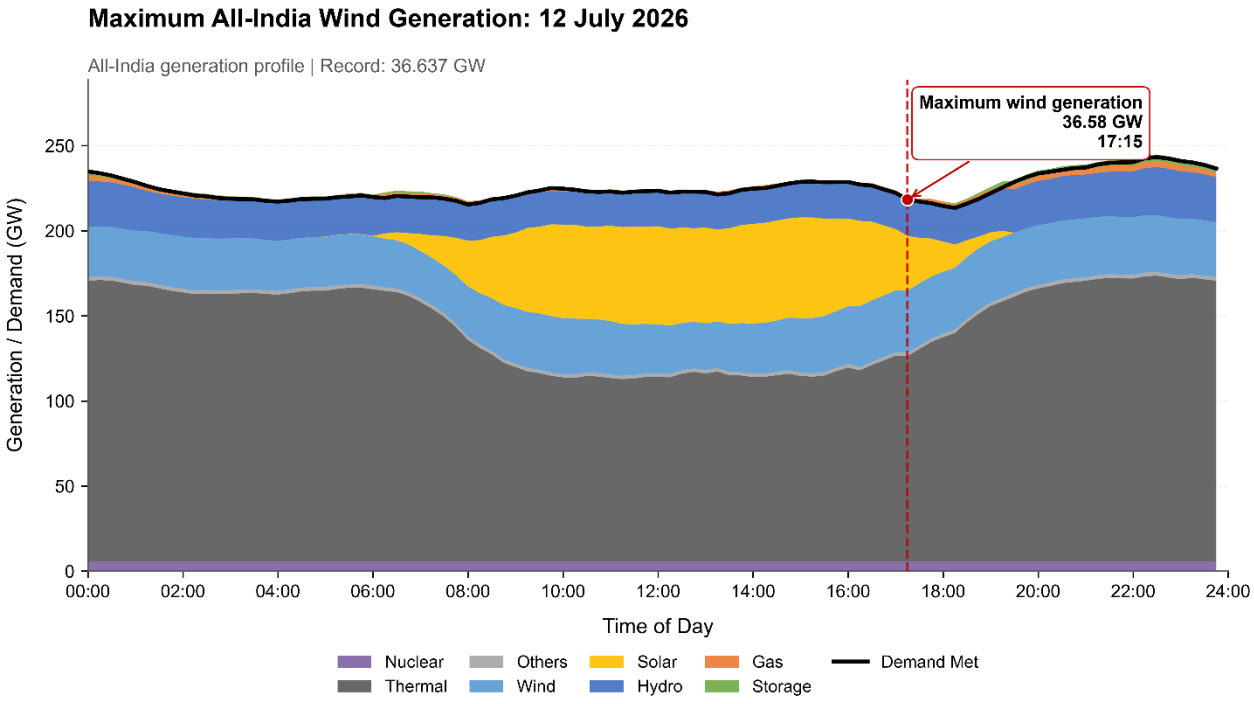


Figure 6: All-India generation profile on 12 July 2026, the day of maximum wind generation

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

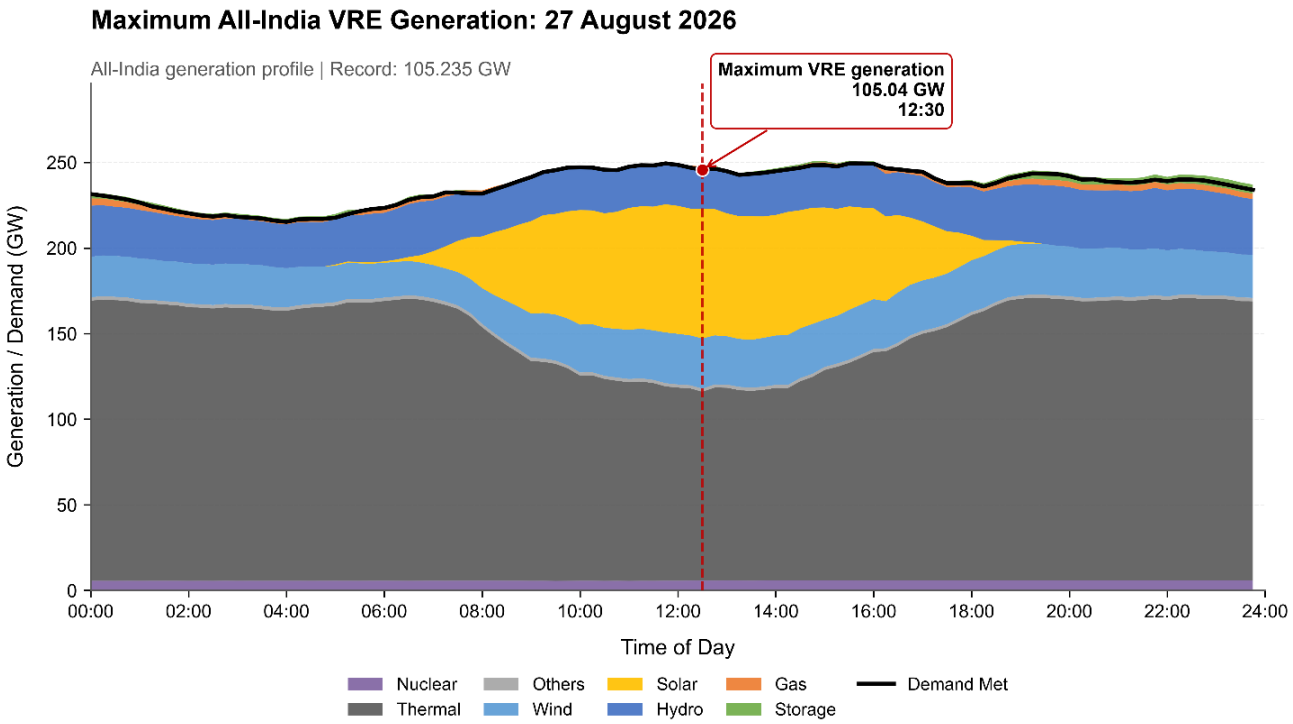


Figure 7: All-India generation profile on 27 August 2026, the day of maximum VRE generation

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

Penetration represents the share of demand met by VRE at a given moment. It is an important operational metric because it determines how much synchronous generation remains online to provide inertia, voltage control, and ramping. The highest solar penetration occurred not on the day of maximum solar generation but on 3 March 2026, a mild spring day with modest demand. Generation form Solar PV met 39.1% of all-India demand, with 39.0% i.e. about 81 GW against roughly 207 GW of demand in the 13:30 block as represented in Figure 8. These increasing penetration of solar and wind is also changing India's net-load profile as shown in Figure 9. Net demand reduced from about 201 GW at 07:15 to a minimum of 123.4 GW at 13:30, a decline of about 77 GW in six hours, and then increased to 205.4 GW by about 19:15, a rise of about 82 GW in under six hours i.e. an average of roughly 14 GW per hour. The thermal generation accommodated a substantial part of this variation Such steep ramps increase the requirements for flexible generation and demand-side flexibility.

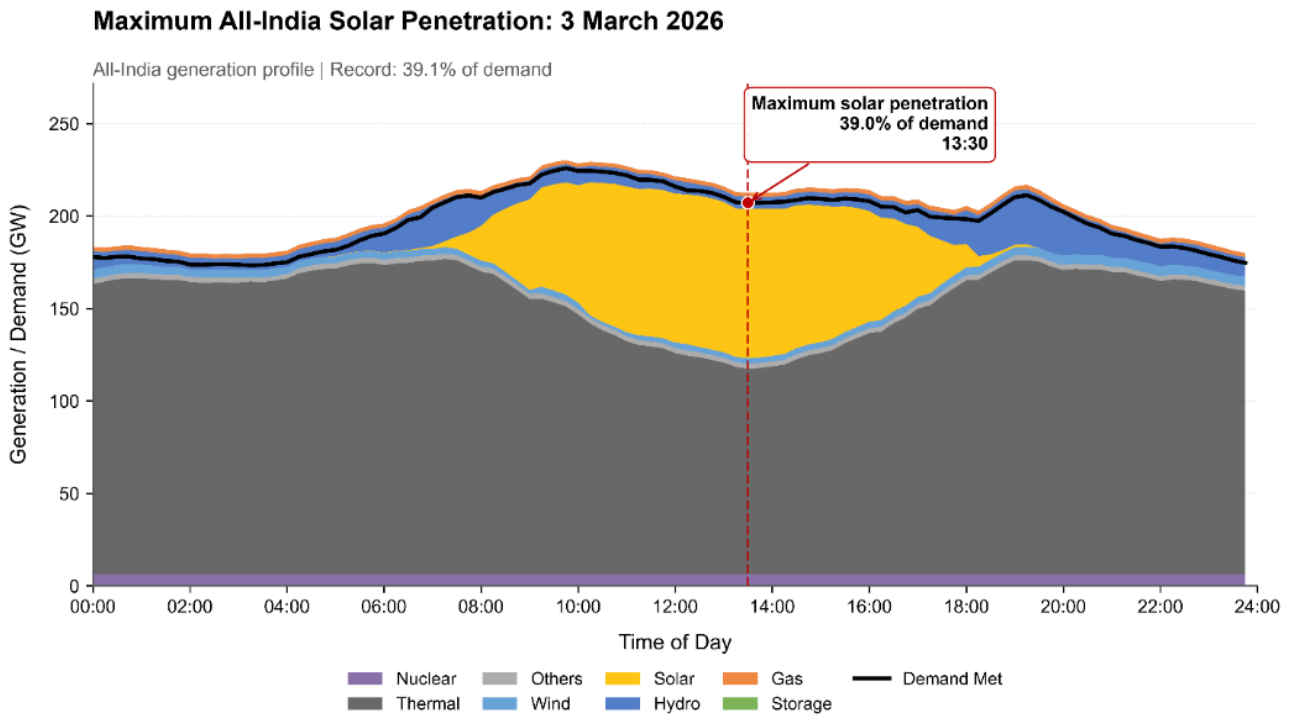


Figure 8: All-India generation profile on 3 March 2026, the day of maximum solar penetration

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

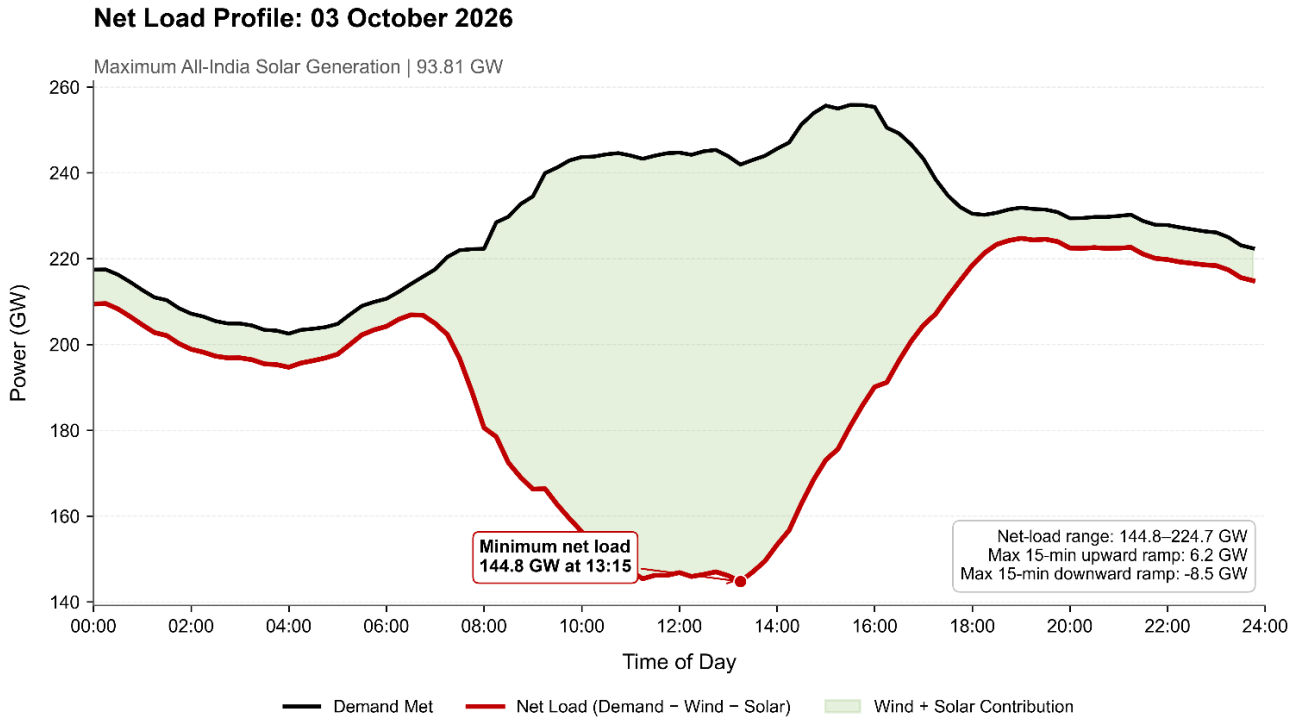


Figure 9: Net load profile during maximum all-India solar penetration on 3 March 2026

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

Wind penetration peaked on the same day as wind generation, i.e. 12 July 2026, at 17.13% of demand; in the 18:15 block, wind supplied 17.0% of demand just as solar output was fading, so that wind carried a substantial part of the evening transition as shown in

Figure 10. The highest combined VRE penetration, 42.87% of demand, was recorded on 27 August 2026, with 42.76% in the 12:30 block as shown in Figure 11, surpassing the 41% midday share observed on 6 March 2026.[9] Taken together, the records show that VRE output mostly exceeds 100 GW at midday and covers more than two-fifths of national demand at its peak, while thermal and hydro generation fulfil the demand in non-solar hours.

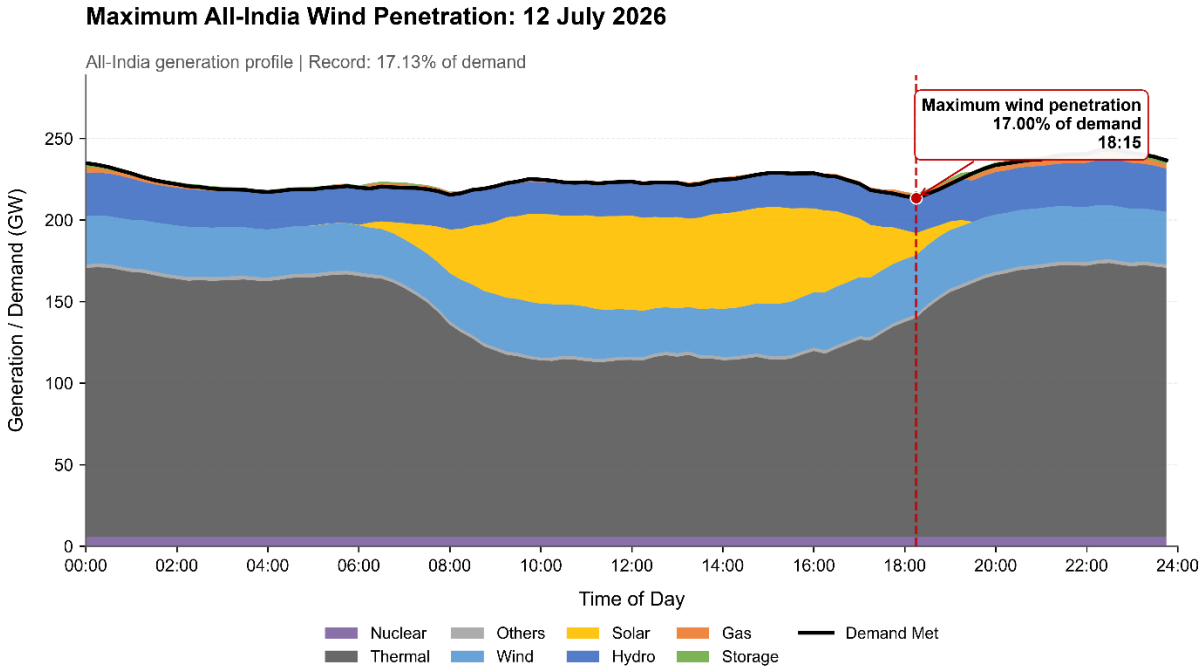


Figure 10: All-India generation profile on 12 July 2026, the day of maximum wind penetration

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

[9] Grid Controller of India Limited, "Daily Power System Performance (PSP) Report," National Load Despatch Centre, Ministry of Power, Govt of India.

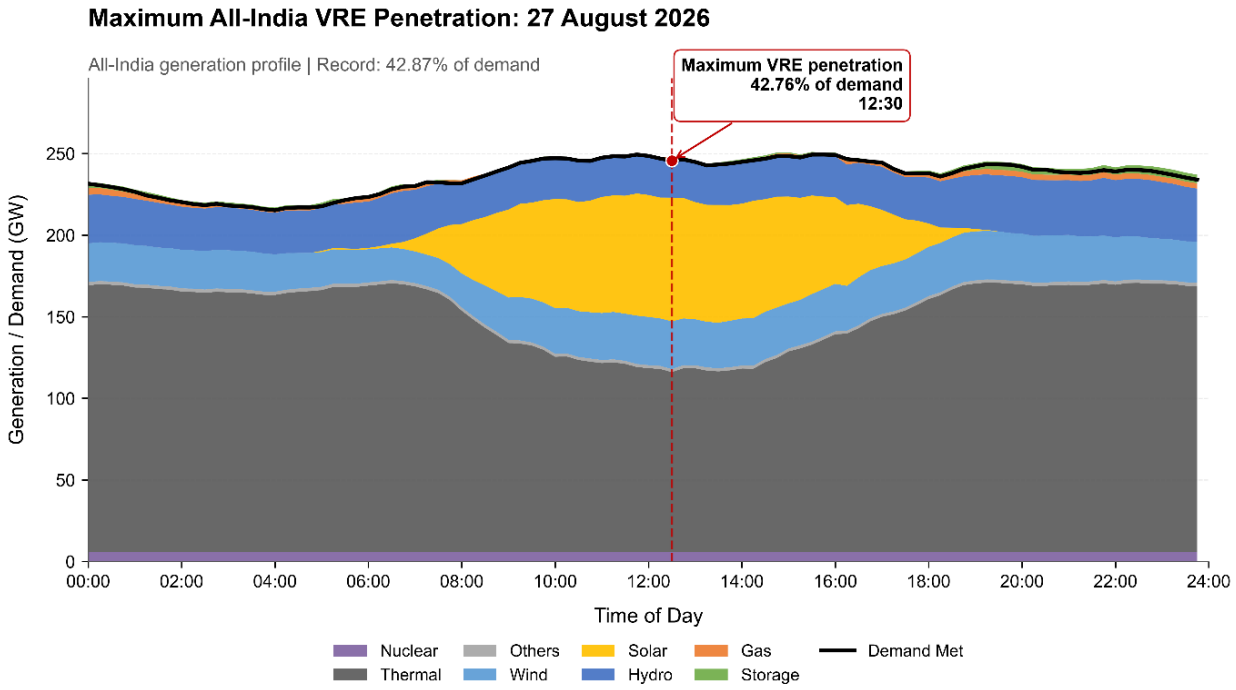


Figure 11: All-India generation profile on 27 August 2026, the day of maximum VRE penetration

(Source: This figure has been plotted using data sources from NLDC operational generation and demand data)

The difference between solar-hour and non-solar-hour demand further illustrates the emerging adequacy challenge. In April-May 2026, shortages at peak occurred on only 6 of 61 days during solar hours but on 36 of 61 days during non-solar hours, with the largest non-solar shortfall reaching 5,405 MW on 24 April 2026[2]. These observations indicate greater adequacy stress during evening and nighttime periods, when solar generation is unavailable. Energy storage can help address such requirements by shifting energy from periods of surplus generation to periods of higher net demand.

The combined impact of rising demand and increasing VRE penetration is creating requirements for both sustained energy supply and faster operational response. BESS and PSP can support evening peak management, load shifting and ramping requirements. Their required power and energy ratings must be determined through detailed time-series assessments that consider demand, renewable availability, network constraints and other flexibility resources.

Table 2: Key demand, RE generation and flexibility indicators for India, 2026

Indicator	Value	Significance for Storage Planning
Demand		
Maximum Demand met	270.8 GW at 15:45 on 21 May 2026	Peak-power adequacy and dispatchable capacity requirements
Peak shortages, April-May 2026	36 of 61 days in Apr–May 2026 with maximum 5.4 GW	Evening/night adequacy is the binding constraint - an *energy-shifting* problem
RE generation records		

Indicator	Value	Significance for Storage Planning
Maximum solar generation	93.81 GW (3 Oct 2026)	About one-third of the demand from solar at midday, the scale of surplus available for charging
Maximum wind generation	36.64 GW (12 Jul 2026)	Contribution of wind during monsoon and non-solar periods
Maximum VRE (solar + wind) generation	105.24 GW (27 Aug 2026);	VRE output now exceeds 100 GW at midday
Highest daily solar energy	658 MU (27 Mar 2026)	Daily energy that must be absorbed or shifted
RE penetration records		
Maximum solar penetration	39.1% of demand (3 Mar 2026)	Highest solar share occurs on low-demand spring days and not on peak-output days
Minimum net load and ramps	123.4 GW (3 Mar 2026); range 123.4-205.4 GW; max 15-min ramps +7.7 / −7.8 GW	Approx. 82 GW evening rise in under 6 h (Approx. 14 GW/h); sizes ramping and 4–6 h storage needs
Maximum wind penetration	17.13% of demand (12 Jul 2026)	Wind supports demand during the solar-to-evening transition
Maximum VRE penetration	42.87% of demand (27 Aug 2026)	High instantaneous inverter-based share; stability (inertia, system strength) relevance
Outlook		
Projected peak 2026-27 / 2031-32 / 2035-36	289 / 388 / 459 GW	Long-term capacity and resource-adequacy planning
Projected energy 2026-27 / 2031-32 / 2035-36	1,929 / 2,703 / 3,365 BU	Future electricity supply and energy-adequacy requirements

Data Compiled from Multiple Sources

1.2.3 Growth in Electricity Generation

India's electricity generation has grown by more than half in a decade, from 1,168 billion units (BU) in FY 2015-16 to 1,840 BU in FY 2025-26. That is an increase of about 672 BU, a compound annual growth rate (CAGR) of 4.6% as shown in Figure 12.[10] Generation growth has varied considerably over this period. Following slower growth in FY 2019-20 and FY 2020-21, electricity generation increased sharply between FY 2021-22 and FY 2024-25, driven by rising electricity demand.

[10] Central Electricity Authority, All-India Electricity Generation by Source: Conventional and Renewable Energy Generation Reports, FY 2015-16 to FY 2025-26 and FY 2026-27 (Year-to-Date), Compilation of Annual and Monthly Electricity Generation Reports (Central Electricity Authority, Ministry of Power, Government of India, 2026).

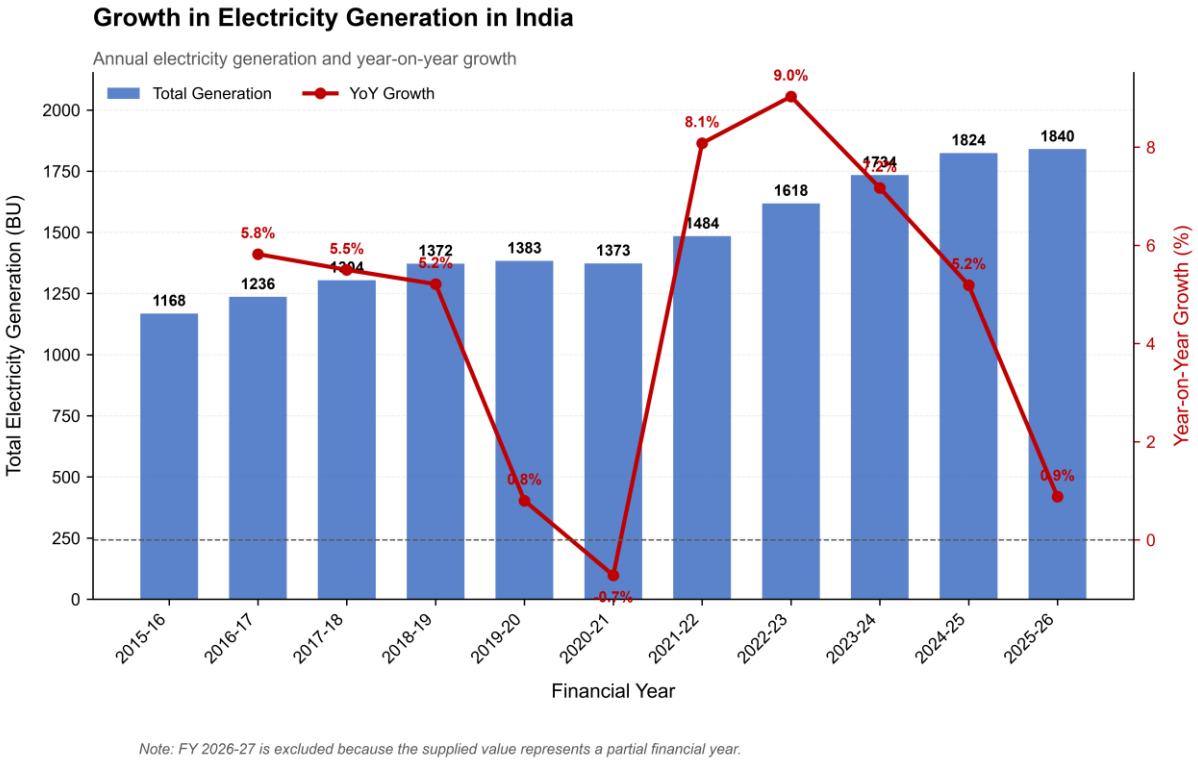


Figure 12: Annual electricity generation in India and year-on-year growth, FY 2015-16 to FY 2025-26

(Source: This figure has been plotted using data sources from CEA annual conventional and renewable generation reports)

Generation growth moderated to 0.93% in FY 2025-26. Early arrival of the monsoon milder temperatures, reduced electricity demand for cooling and agricultural pumping. India's electricity demand grew by only 1.4% in calendar year 2025, after four years of growth above 6%.[11] Demand growth was about 1% in the first half of FY 2025-26.[12] Even in the fourth quarter, generation grew by only about 3% year on year, the slowest quarterly rate in six years. The record peaks in April-May 2026 suggest that further growth in consumption is imminent, and the IEA projects demand growth of about 6.4% per year through 2030. The CEA's Long-Term National Resource Adequacy Plan (LT-NRAP) puts the energy requirement at 1,929 BU in 2026-27.[13]

Source-wise trends: Figure 13 illustrates the changing contribution of conventional and renewable generation sources. Coal (including lignite) supplied 384 BU, or 57%, of the 672 BU added over the decade. Its output increased from 896 BU in FY 2015-16 to a peak of 1,332 BU in FY 2024-25, although its share of generation reduced from 76.7% to 69.6% by FY 2025-26. Despite the increasing contribution of renewable energy, coal remains India's dominant electricity source. Hydropower provides an important source of flexibility, although its generation depends on hydrological conditions. Gas-based generation offers operational flexibility, but fuel availability and cost constrain its utilisation. These limitations increase the importance of additional flexibility resources in the Indian power system.

[11] International Energy Agency, Electricity 2026: Analysis and Forecast to 2030 (International Energy Agency, 2026).

[12] Grid Controller of India Limited (GRID-INDIA), Monthly Operational Report, National Load Despatch Centre (NLDC), Ministry of Power, Government of India, New Delhi, India.

[13] Central Electricity Authority (CEA), Long Term National Resource Adequacy Plan (2026–27 to 2035–36), Ministry of Power, Government of India, New Delhi, India, Apr. 2026.

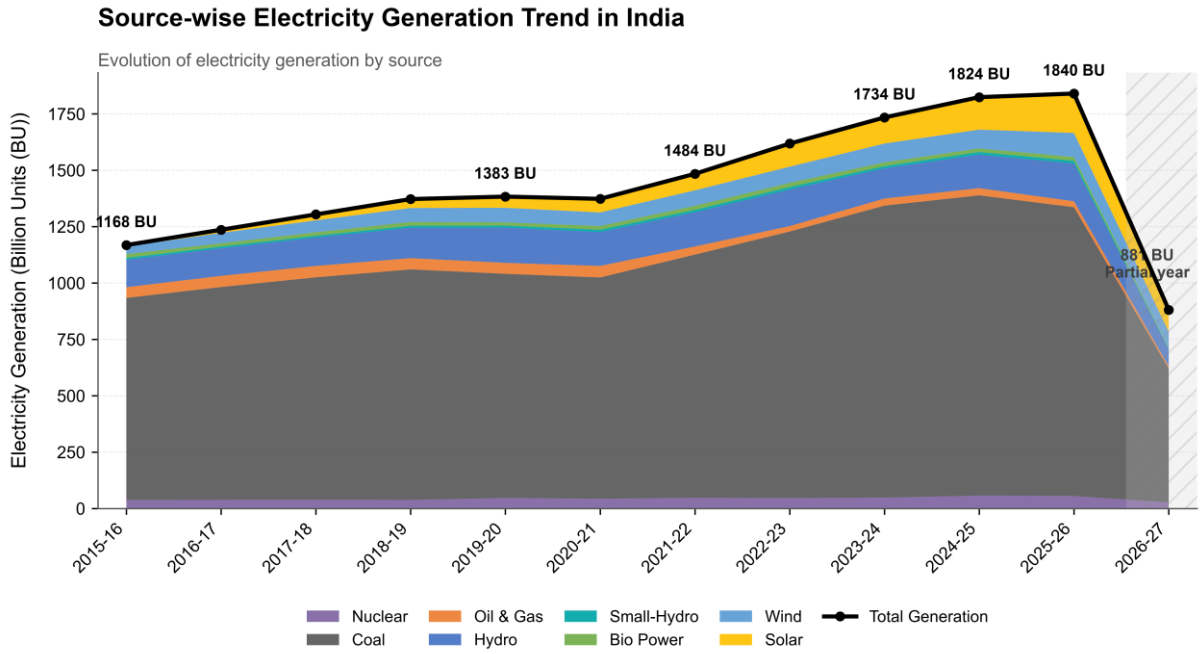


Figure 13: Source-wise electricity generation in India, FY 2015-16 to FY 2026-27 (FY 2026-27 is a partial year, shown hatched)

(Source: This figure has been plotted using data sources from CEA annual and monthly generation reports)

In FY 2025-26 total electricity generation increased marginally, while renewable generation recorded substantial growth. Solar and wind generation increased by approximately 29.4 BU and 22.7 BU, respectively. Large hydro generation also increased by approximately 18.5 BU. Meanwhile, coal and lignite generation declined by approximately 50.5 BU[14]. These changes demonstrate the increasing contribution of renewable energy to India's electricity supply, although coal continues to account for the majority of annual generation.

Growth of Wind and Solar Generation: Figure 14 shows the increasing growth of solar and wind energy generation. Their combined generation increased about sevenfold, from 40 BU in FY 2015-16 to 279.6 BU in FY 2025-26. Generation from Solar increased 24-fold, from 7.4 BU to 173.5 BU, surpassing generation from large hydro of167.2 BU to become India's second-largest source of electricity after coal. Generation from wind increased from 33 BU to 106.1 BU. The combined share of solar and wind in total generation increased from approximately 12.4% in FY 2024-25 to 15.1% in FY 2025-26. This growing contribution of VRE increases the need for flexibility to accommodate variations in generation for both short term and long term time durations.

[14] Ministry of New and Renewable Energy (MNRE), "RE-Statistics 2025–26", Government of India, Delhi, 2026.

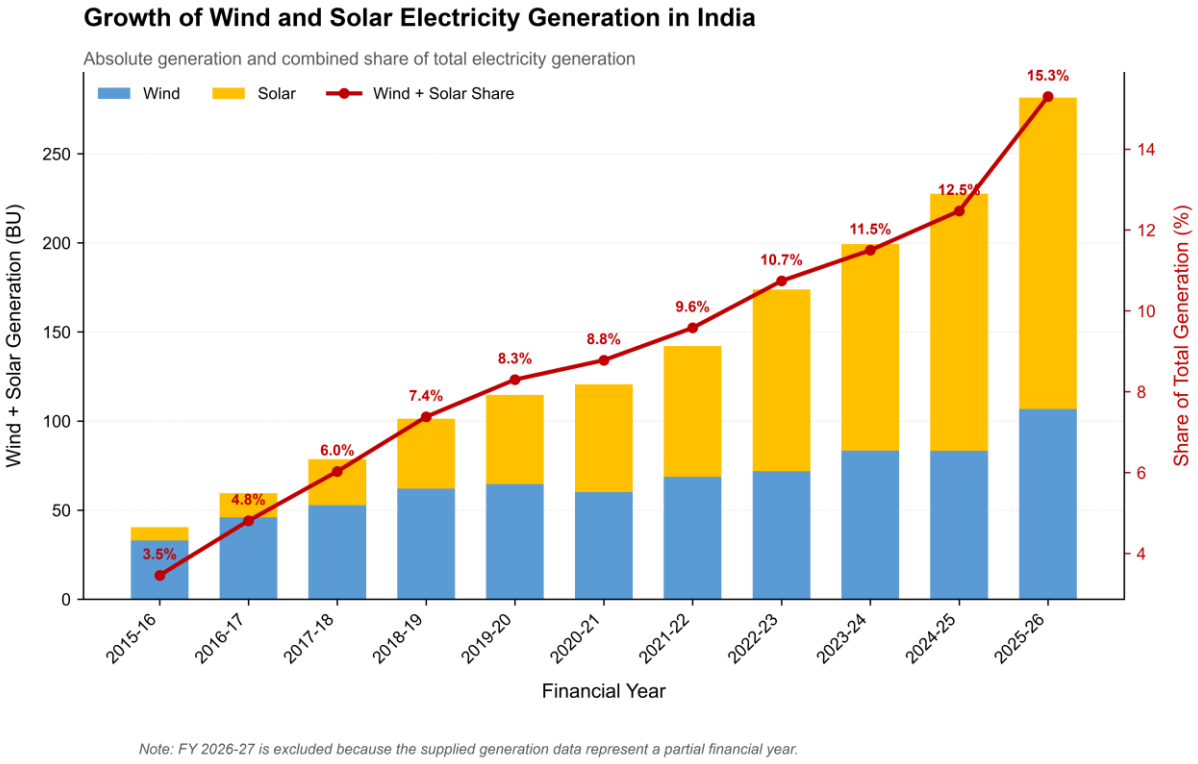


Figure 14: Wind and solar generation in India (stacked) and their combined share of total generation, FY 2015-16 to FY 2025-26

(Source: This figure has been plotted using data sources from CEA annual generation reports)

Installed Capacity versus energy generation: Although non-fossil sources accounted for 53% of India's installed generating capacity by March 2026[14]. Yet in FY 2025-26, their contribution to total electricity generation was only 29%.: Renewable energy including large hydro contributed 26.0%; and nuclear accounted approximately 3.0%. This difference reflects the varying capacity utilisation, resource availability and operating characteristics of generation technologies. It highlights the continued reliance on dispatchable generation and the importance of energy storage for aligning renewable electricity availability with demand.

Implications for energy storage: The increasing share of variable renewable generation creates a growing need to align electricity availability with demand. Energy storage can shift solar generation to non-solar hours, support peak-demand management and reduce the ramping burden on conventional generators. It can also improve renewable energy utilisation where surplus generation and network conditions permit charging. The required storage capacity and duration must be assessed alongside flexible thermal and hydro generation, transmission capability and demand-side flexibility.

1.3. Estimation of Energy Storage Requirement for India

India’s storage requirement has been estimated in successive planning exercises based on different demand projections, RE energy scenarios and technology assumptions. Table 3 consolidates the prominent estimates, distinguishing energy storage power capacity (GW) from energy capacity (GWh). Figure 15 illustrates the projected energy-storage requirements across different planning horizons.

Table 3: Envisaged energy-storage requirement in India: power (GW) and energy (GWh)

Horizon	Source	PSP (GW / GWh)	BESS (GW / GWh)	Total (GW)	Total (GWh)	Implied average duration
2026-27	NEP 2023 (CEA)[15]	7.45 / 47.65	8.68 / 34.72	16.13	82.37	5.1 h (PSP 6.4 h; BESS 4 h)
2029-30	CEA Optimal Generation Mix 2029-30[16]	18.98 / 128.15	41.65 / 208.25	60.63	336.40	Approx.5.5 h
2031-32	NEP 2023 (CEA)	26.69 / 175.18	47.24 / 236.22	73.93	411.40	5.6 h (PSP 6.6 h; BESS 5 h)
2035-36	LT-NRAP 2026 (CEA)[17]	94 / 567	80 / 321	174	888	5.1 h (PSP 6.0 h; BESS 4.0 h)
2047	CEA/MNRE estimate[18]	- / 540	- / 1,840	-	2,380	Energy Not stated
2070 (Net Zero Scenario)	NITI Aayog (2026)[19]	150-165 GW	2,500–3,000 GW	-	-	Scenario ranges

Data Compiled from Multiple Sources

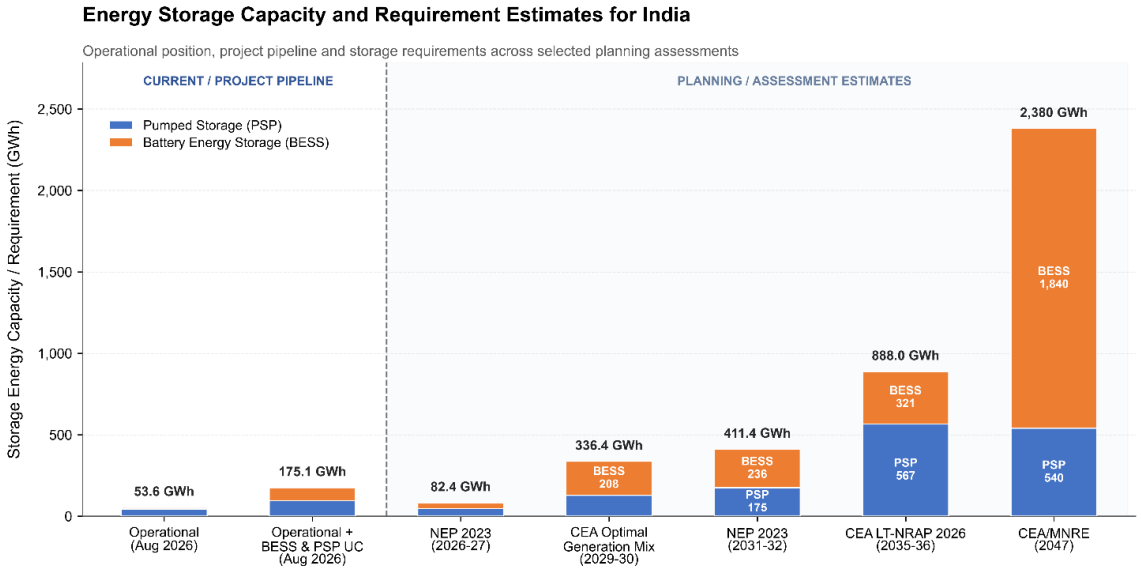


Figure 15: Envisaged storage requirement trajectory in India (GWh), split by PSP and BESS, with the August 2026 operational and pipeline position

(Source: This figure has been plotted using data sources from CEA NEP 2023, Optimal Generation Mix 2030, LT-NRAP 2026, MNRE ESS outlook and CEA project lists, PSP operational energy estimated using assumed duration)

[15]Central Electricity Authority (CEA), National Electricity Plan (Volume I: Generation) for 2022–27 and 2027–32, notified in the Gazette of India, May 2023.

[16]Central Electricity Authority (CEA), Report on Optimal Generation Mix 2030 (Version 2.0), Apr. 2023. Press Information Bureau (PIB), Ministry of Power, "Development and deployment of energy storage capacities to power India's clean energy transition", 18 Dec. 2025.

[17]Central Electricity Authority (CEA), Long-Term National Resource Adequacy Plan (2026-27 to 2035-36), Ministry of Power, Government of India, Apr. 2026.

[18]Ministry of New and Renewable Energy (MNRE), "Energy Storage Systems (ESS) – Overview" (storage requirement for 2026-27, 2031-32 and 2047; ESO trajectory).

[19]NITI Aayog, Scenarios Towards Viksit Bharat and Net Zero: An Overview (Vol. 1) and Power sector volume, Government of India, Feb. 2026. Power Line, "Energy Pathways: NITI Aayog report assesses power scenarios towards Viksit Bharat and Net Zero", 23 Mar. 2026.

The planning estimates indicate a substantial increase in both storage power and energy requirements. The NEP (2023) envisaged 16.13 GW/82.37 GWh of storage by 2026-27, increasing to 73.93 GW/411.40 GWh by 2031-32[15]. The LT-NRAP (2026) envisages 174 GW/888 GWh by 2035-36, while the indicative requirement for 2047 reaches 2,380 GWh[17]. The implied average storage durations are approximately five to six hours across the near- and medium-term estimates. However, the required duration depends on the application, demand profile, renewable availability and resource-adequacy requirements. Storage planning must therefore consider both power and energy capacity rather than relying on aggregate GW targets.

The envisaged requirements are significantly higher than India's existing operational storage capacity. However, installed capacity, storage duration and project commissioning status must be considered when assessing the deployment gap. In particular, the energy capacity of operational PSPs cannot be determined solely from their installed MW capacity. The project pipeline also includes assets at different stages of development, which cannot be treated as commissioned capacity. A detailed assessment of India's operational storage systems and project pipeline is provided in the subsequent deployment chapter.

The relative contribution of PSP and BESS also varies across planning studies. PSP accounts for approximately 43% of the envisaged storage energy in the NEP's 2031-32 estimate and 64% in the LT-NRAP's 2035-36 estimate. In contrast, the indicative 2047 assessment assigns approximately 77% of storage energy capacity to BESS. These differences reflect the assumptions and optimisation results of individual studies rather than fixed technology-specific procurement targets. Future storage planning must therefore account for technology costs, construction timelines, operational requirements and the availability of alternative flexibility resources.

1.4. Definitions: Adequacy, Flexibility, Stability and Resilience

Energy storage is frequently characterised as a source of system flexibility. However, this broad terminology encompasses several distinct system requirements, each associated with specific performance metrics, operational timescales, and storage characteristics. Failure to distinguish among these requirements can result in inappropriate technology selection, suboptimal system sizing, and unsuitable procurement or contractual arrangements. Table 4 summarises five major power-system requirements and the corresponding contributions of ESS.[20] [21]

Table 4: Five system needs and the contribution of energy storage to each

System needs	Definition	Key metrics	Timescale	Storage contribution and critical attributes
Power (capacity) adequacy	Sufficient available capacity to meet demand and reserves requirements at every hour, particularly net-peak hours	LOLP, LOLE, planning reserve margin, capacity credit	Critical peak hours and consecutive high-demand periods	Reliable discharge capacity during system-stress periods, subject to available energy, duration, state of charge (SOC) and availability
Energy adequacy	Sufficient energy to meet electricity demands extended over days, weeks and seasons, including low-wind/low-	Expected unserved energy over extended periods, seasonal energy balance and	Days to seasons	Multi-day to seasonal energy (PSP with large reservoirs, LDES, hydrogen/thermal); BESS contribution depends on available energy and recharging opportunities

[20] IRENA (2020), Electricity Storage Valuation Framework: Assessing system value and ensuring project viability, International Renewable Energy Agency, Abu Dhabi.

[21] N. Hatziargyriou et al., "Definition and Classification of Power System Stability – Revisited & Extended," IEEE Trans. Power Syst., vol. 36, no. 4, pp. 3271–3281, Jul. 2021, doi: 10.1109/TPWRS.2020.3041774.

System needs	Definition	Key metrics	Timescale	Storage contribution and critical attributes
	sun periods and hydro droughts	available stored energy		
Operational flexibility	Ability to respond to net-load ramps and forecast errors	Ramp capability (MW/min, GW/h), ramping reserve margins, curtailment, cycling costs	Seconds to hours	Fast bidirectional power response, ramp management and energy shifting; performance depends on power rating, energy availability and operating constraints
Stability	Ability to remain in synchronism and within acceptable voltage and frequency limits during and post disturbances	RoCoF, frequency nadir, voltage recovery, SCR/system strength, damping ratio	Milliseconds to seconds	Fast frequency response; synthetic inertia dynamic reactive-power support, oscillation damping and grid-forming support where appropriately designed; subject to converter capability and operating limits
Resilience	Ability to withstand, adapt to and recover from high-impact events (extreme weather, cascading outages)	Time to restore, energy not served in events, black-start availability	Minutes to days or longer	Backup supply, black start supports and islanded operation where supported by the system design; requires adequate stored energy, restoration coordination and appropriate controls

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The distinction has three practical consequences. First, a single storage asset can contribute to several needs simultaneous service provision is constrained by available energy, SOC, converter capacity and operating requirements. Second, power adequacy and energy adequacy require different metrics A storage system may provide sufficient discharge power during a short peak event but may not have adequate energy to sustain supply during prolonged shortages. Its contribution to resource adequacy therefore depends on discharge duration, charging opportunities and the duration of system-stress periods This storage saturation effect has been observed in system-planning studies in markets such as California and Australia.[22] Third, stability services as well as available power and energy. Grid-forming capability must therefore be specified through converter performance requirements, rather than inferred from the storage technology alone

1.5. Benchmarking Energy Storage Needs Against the Evolving Grid

Storage requirements should be benchmarked against the physical characteristics of the system they are meant to serve. India's seasonal net-load ramps, non-solar demand and renewable generation patterns are important considerations for determining storage power and energy requirements.

[22] M. G. Aydin and C. O. Aydin, "California Public Utilities Commission Energy Storage Procurement Study," Lumen Energy Strategy and California Public Utility Commission, Oakland, CA, USA, May 31, 2023.

Storage power relative to peak is about 3.3% today (≈9 GW of operational PSP and BESS against a 270.8 GW peak), compared with the NEP 2031-32 requirement of 73.93 GW against a projected peak of 366-388 GW (≈19–20%) and the LT-NRAP's 174 GW against 459 GW in 2035-36 (≈38%).

Storage energy relative to the evening ramp problem is small, and flattening even half of a summer evening ramp would require on the order of 130-155 GWh, while actual energy storage discharge averaged 23.8 GWh/day in May 2026

Curtailment remains modest in aggregate (1.3% of RE generation in FY 2025-26) but is concentrated in specific months, hours, and locations. For instance, more than 7 GW of RE was curtailed during a single event on 21 March 2026, and it was estimated that about 10 GWh of BESS would have consumed most of the curtailed energy[23].

Daily price spread in the day-ahead market has widened to about 9:1 between evening and midday prices in May 2026, which is a strong signal that storage would be valuable at the margin.

Storage planning must therefore consider the magnitude, duration and timing of flexibility requirements rather than aggregate installed capacity alone.

1.6. Energy Storage as a Flexibility Resource

Energy storage is one of the potential solutions to the challenges introduced by increasing share of RE generation, but its economic suitability depends on the required grid service, operating conditions and available alternatives. A credible national strategy must compare storage against, and combine it with, the full set of flexibility and stability resources. The comparison should be made on a service-by-service basis as each option differs in its technical capabilities, operational constraints and costs.

In India, transmission expansion and inter-regional transfers remain essential for relieving network congestion and sharing balancing resources. The Ministry of Power reported 120 GW of inter-regional transmission capacity in January 2026, with expansion to 168 GW planned by 2032[24]. Storage can address temporary network constraints but cannot replace transmission infrastructure required for sustained power transfers.

Flexible thermal generation, hydro and gas plants provide balancing and reserve services. CEA's thermal flexibility programme targets a minimum operating load of 40% for identified coal units through phased implementation. Demand response, time-of-day tariffs and flexible electricity consumption can further reduce the requirement for energy shifting through storage[25].

For voltage stability and system strength, synchronous condensers and STATCOMs provide alternatives or complements to converter-based storage[26]. Grid-forming BESS can combine active-power flexibility with dynamic grid support, subject to converter ratings, control performance and operating constraints.

Storage deployment should therefore be based on service-specific technical and economic assessments. Response time, discharge duration, location, network constraints and lifecycle costs must determine the appropriate combination of storage and alternative flexibility resources.

1.7. Global ESS Perspective

International experience offers useful lessons, provided that differences in system size, market design and resource mix are respected. Table 5 summarises the five systems most frequently cited in Indian policy discussions.

[23]N. Rodrigues, Bottleneck to the Next Phase of Renewable Energy Growth in India, Ember, Jun. 17, 2026.

[24] Ministry of Power, Government of India, "Strengthening Transmission Infrastructure for Integration of Renewable Energy," Press Information Bureau (PIB), Mar. 23, 2026.

[25] Central Electricity Authority (CEA), "Quarterly Review Report: Renovation & Modernisation of Thermal Power Stations, July–September 2025," Thermal Projects Renovation & Modernisation Division, Ministry of Power, Government of India, 2025.

[26] Central Electricity Regulatory Commission (CERC), "Central Electricity Regulatory Commission (Ancillary Services) Regulations, 2022," Notification No. RA-14026(11)/3/2019-CERC, Ministry of Power, Government of India, January 2022.

Table 5: Global storage deployment snapshot and lessons for India

System	Deployment status (latest)	Key policy/market mechanisms	Findings relevant to India
China	66.43 GW / 189.48 GWh of new-type storage added in 2025; 144.7 GW new-type storage by end-2025 (213.3 GW including PSH); average duration 2.58 h; >98% LFP	Provincial mandates for RE-paired storage (later relaxed), capacity compensation, standalone "shared" storage; EPC costs ~US$131–146/kWh	Mandates without market access led to under-utilised co-located storage; standalone storage with market access now dominates (58% of 2025 additions)
United States	~43.6 GW battery storage at end-2025; ~52 GW by June 2026; ~14 GW more expected in H2 2026	Wholesale market participation (FERC Order 841), investment tax credits, state procurement (CA), ERCOT energy-only market	Market access and clear participation models unlock merchant storage; ERCOT (Texas) now requires advanced grid-support (GFM-like) capability for new storage (NOGRR 272)
Australia (NEM)	>9,000 MW grid-scale BESS by Q2 2026; batteries set prices in 36% of intervals (46% in evening peak)	Capacity Investment Scheme, system-strength framework, ARENA funding for 2 GW of GFM batteries, voluntary GFM specification	GFM batteries can provide system strength; 74% of the connection pipeline is GFM; price spreads collapse as storage grows (−85% in one year), revenue risk for merchant projects
Great Britain and Ireland	GB: rapid BESS growth; Ofgem LDES cap-and-floor Window 1: 16 projects, 7.6 GW, 8–22 h (Jun 2026). Ireland: SNSP up to 75%, RoCoF 1 Hz/s	GB Grid Code GC0137 (GBGF), Stability Pathfinders and Stability Market; Ireland DS3 system services and Low Carbon Inertia Services	Procure stability as a service; define GFM performance in the grid code; use regulated revenue floors for LDES
European Union	27.1 GWh added in 2025; 77.3 GWh cumulative; ~750 GWh needed by 2030	NC RfG 2.0 to require GFM capability for new PPMs and storage >1 MW; national capacity mechanisms	Harmonised GFM requirements; Iberian blackout (28 Apr 2025) shows need for dynamic voltage control from CBRs

Data Compiled from Multiple Sources

The key lessons that stand out for India from a global perspective are as follows:

(1) **Market access matters alongside mandates.** China removed mandatory storage co-location as a precondition for new renewable projects in February 2025[27], while the United States established dedicated

[27] National Development and Reform Commission (NDRC) and National Energy Administration (NEA), "Notice on Deepening the Market-Oriented Reform of New Energy Feed-in Tariffs and Promoting the High-Quality Development of New Energy," Government of China, Notice No. 136, Jan. 27, 2025.

wholesale-market participation rules for storage under FERC Order 841[28].India's advisory on co-located storage (February 2025) should therefore be accompanied by clear dispatch and remuneration rules[29].

(2) **Stability must be specified and procured explicitly.** System operators in Ireland and Australia have developed mechanisms for procuring system services and supporting grid-forming BESS. Ireland's DS3 programme demonstrates service-based procurement, while Australia's ARENA programme supports grid-forming battery projects. India can adopt performance-based specifications for stability services rather than relying on storage capacity alone.

(3) **Revenue cannibalisation is an important consideration as storage penetration increases**. In Australia's National Electricity Market, BESS set prices in 36% of dispatch intervals during Q2 2026, compared with 17% in Q2 2025. Increased battery discharge contributed to lower evening prices and a flatter intraday price profile. For India, this highlights the value of contracted capacity payments, revenue floors, or other mechanisms that provide greater revenue certainty during large-scale storage deployment.[30].

(4) **Long-duration storage needs bespoke procurement.** Great Britain's cap-and-floor framework illustrates an approach to managing investment risk for long-duration energy storage (LDES). In June 2026, Ofgem provisionally selected 16 projects representing approximately 7.6 GW under its first application window. Similar mechanisms may be relevant for long-duration projects in India where market revenues alone are insufficient to support investment.

(5) **Voltage control is as important as frequency control.** The Iberian blackout of 28 April 2025 demonstrated the importance of adequate dynamic voltage control in inverter-dominated power systems, with the subsequent ENTSO-E investigation highlighting deficiencies in voltage-control capability among several interacting causes of the disturbance[31]. The grid disturbance at Khavda, India, on 13 May 2026 similarly underscores the growing importance of voltage stability in RE-rich networks. Energy storage, particularly converter-based BESS, should therefore be specified and operated not solely for energy shifting and frequency response, but also to provide dynamic reactive power and voltage support, including during periods when active power charging or discharging is limited.

[28] Federal Energy Regulatory Commission (FERC), "Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators," Order No. 841, 162 FERC ¶ 61,127, Docket Nos. RM16-23-000 and AD16-20-000, Feb. 15, 2018.

[29] Central Electricity Authority (CEA), "Advisory on Co-Locating Energy Storage Systems with Solar Power Projects to Enhance Grid Stability and Cost Efficiency," Ministry of Power, Government of India, Feb. 18, 2025.

[31]Expert Panel on the Grid Incident on 28 April 2025, Grid Incident in Spain and Portugal on 28 April 2025: ICS Investigation Expert Panel Final Report. European Network of Transmission System Operators for Electricity (ENTSO-E), Mar. 20, 2026.

Chapter 2.

Energy Storage Technologies: Performance and Suitability for India's Power System






The suitability of energy storage technologies for India's power system depends on their discharge duration, response capability, efficiency, degradation, safety, technical maturity and deployment constraints. BESS and PSP offer complementary capabilities for energy shifting and grid support. Other storage technologies require evaluation based on their technical readiness, application-specific performance and practical feasibility under Indian conditions.

2.1. Overview of Energy Storage Technologies

Energy storage technologies can be grouped into five families based on the physical form in which energy is stored as shown in Table 6.

For Indian power-system planning, electricity-to-electricity storage must be distinguished from technologies that primarily provide thermal storage or produce chemical energy carriers. CEA's National Electricity Plan (2023) quantifies grid-scale storage requirements for BESS and PSP. Thermal storage and flexible electrolysis can also support grid balancing through demand-side flexibility, but their services differ from those of electricity storage.

Table 6: Overview of energy storage technologies and their relevance to India's power system

Technology Family	Physical principle	Representative technologies	Power-system relevance and constraints
Mechanical	Gravitational potential, pressure or kinetic energy	Pumped storage (fixed/variable speed; open/closed loop), CAES (diabatic, adiabatic, isothermal), liquid-air (LAES), flywheels, solid-mass gravity	PSP supports bulk energy shifting, peak management and reserves, subject to site availability and development constraints. Other technologies have application-specific potential.
Electrochemical	Reversible redox reactions in cells	Li-ion (LFP, NMC/NCA, LMFP), sodium-ion, NaS, lead-acid/lead-carbon, flow batteries (vanadium, iron, zinc-based, organic), metal-air (iron-air, zinc-air), solid-state	BESS supports intraday energy shifting, rapid balancing and ancillary services. Suitability depends on cost, degradation, safety, duration and technical maturity.
Thermal	Sensible, latent or thermochemical heat/cold	Molten salt, concrete/rock/sand, phase-change materials, ice/chilled water, Carnot batteries (pumped thermal)	Primarily supports industrial heat and cooling-load shifting. Electricity-to-electricity applications require suitable energy conversion systems.
Chemical	Energy in the chemical bonds of a fuel	Hydrogen (compressed, cavern, liquid), ammonia, methanol, e-methane, LOHC	Seasonal storage, sector coupling, application in hard-to-abate industry

Electrical	Electric or magnetic fields	Supercapacitors (EDLC, hybrid), SMES	Suitable for rapid power support and power-quality applications, with limited energy-storage duration.

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For India's power system, BESS and PSP are the principal technologies considered in current national grid-scale storage planning. Other technologies may complement them where specific operating requirements, resource availability and economics justify deployment.

2.2. ESS Comprehensive Technology Matrix

Table 7, Table 8, and Table 9 compares different energy storage technologies. Values are indicative ranges compiled from cost and performance figures from multiple sources and peer-reviewed literature, adjusted where Indian evidence is available (e.g., the CEA's estimate of about ₹6 crore/MW for PSP). Cost estimates represent different source years, markets, project scopes and operating assumptions. They should be treated as screening values rather than directly comparable project costs.

Table 7: Technology matrix (A): Mechanical and electrical storage

Parameter	PSP – fixed speed	PSP – variable speed	CAES (diabatic / adiabatic)	Liquid-air (LAES)	Flywheel	Gravity (solid mass)	Supercapacitor	SMES
Power rating (per plant)	100-4,000 MW	100-2,000 MW	50-400 MW	5-300 MW	0.1-20 MW	5-100 MW	kW-30 MW	kW-10 MW
Discharge duration	4–24 h (India 6–8 h)	4–24 h	4–24 h	4–12+ h	seconds–15 min	2–12 h	seconds–1 min	seconds
Response time	Gen: 60–180 s from standstill; mode change minutes	Faster; pump-mode power regulation	Minutes (≈10 min cold start)	Minutes	< 5–10 ms	Seconds–minutes	< 10 ms	< 5 ms
Round-trip efficiency (AC)	70–80%	72–82%	42–54% (diabatic, with supplemental fuel); 60–70% (advanced concepts).	50–60% (≈70% with waste heat/cold)	85–95% (short cycles)	75–85% (claimed)	90–95%	90–95%
Self-discharge	≈0 (evaporation, seepage)	≈0	Low (cavern leakage, heat loss)	0.1–0.5%/day	3–20%/hour	≈0	10–40%/day	10–15%/day (cryogenics)
Energy density	0.5–1.5 Wh/kg of water (300–500 m head)	Same	2–6 kWh/m^3 of cavern	50–200 Wh/kg of liquid air	5–100 Wh/kg	≈0.3–1 Wh/kg	5–10 Wh/kg	0.5–5 Wh/kg
Power density	Low (civil works)	Low	Low	Medium	High (1–5 kW/kg)	Low	Very high (5–15 kW/kg)	Very high
Cycle life	> 20,000 (mechanical wear only)	> 20,000	> 10,000	> 10,000	10^5–10^7	> 20,000 (claimed)	10^5–10^6	> 10^5
Calendar life	50–100 years (civil); 30–40 (E&M)	50–100 / 30–40	30–40 years	30–40 years	20 years	30–50 years	10–20 years	20 years

Parameter	PSP – fixed speed	PSP – variable speed	CAES (diabatic / adiabatic)	Liquid-air (LAES)	Flywheel	Gravity (solid mass)	Supercapacitor	SMES
Usable DoD	≈100% of live storage	≈100%	≈100% of working pressure range	≈100%	75–90% (speed range)	≈100%	75% (voltage window)	≈100%
C-rate equivalent	0.04–0.25C	0.04–0.25C	0.04–0.25C	0.1–0.25C	4–100C	0.1–0.5C	> 60C	> 100C
CAPEX – power (US$/kW)	700–3,500 (India ≈700–850, ₹6 cr/MW)	+10–30% vs fixed	800–2,000	1,000–2,500	1,500–3,000	1,000–2,500	200–500	1,000–10,000
CAPEX – energy (US$/kWh)	50–300	60–350	30–150	50–300	3,000–10,000	150–500	10,000–30,000	> 10,000
Fixed O&M	0.8–1.5% of capex/yr	1–2%	1.5–2.5%	1.5–2.5%	1–2%	1–2%	0.5–1%	High (cryogenics)
Indicative LCOS (use-case-dependent)	US$100–200/MWh (daily cycling)	US$110–220/MWh	US$120–250/MWh	US$150–300/MWh	Service-based (US$/MW)	US$150–300/MWh (early)	Service-based	Service-based
TRL / commercial status	9 – commercial	9 – commercial	9 (diabatic) / 7–8 (adiabatic)	7–8 – first commercial	9 (niche)	6–8 – demonstration	9 (niche)	6–7
Construction time	4–7 years	4–7 years	3–5 years	2–4 years	< 1 year	1–3 years	< 1 year	1–2 years
Geographic dependence	High (head, water, geology)	High	High (caverns)	Low	Low	Medium (height, mines)	Low	Low
Degradation	Negligible (maintenance)	Negligible	Negligible	Negligible	Bearing wear	Low	Capacitance fade	Low
Safety risk	Dam breach, flooding, tunnelling	Same	High-pressure vessels/caverns	Cryogenic, pressure	Rotor burst (containment)	Structural	Low (electrolyte)	Magnetic field, cryogens

Parameter	PSP – fixed speed	PSP – variable speed	CAES (diabatic / adiabatic)	Liquid-air (LAES)	Flywheel	Gravity (solid mass)	Supercapacitor	SMES
Environmental impact	Land, forest, aquatic ecology (lower for closed loop)	Same	Gas use (diabatic); cavern	Low	Low	Materials, land	Low	Low
Black-start capability	Yes	Yes	Yes (with gas)	Possible	Limited energy	Possible	No (energy)	No
Grid-forming / inertia	Inherent synchronous inertia and fault current	Synchronous (DFIM) or via converter (full-converter)	Synchronous machine	Synchronous machine	Via GFM PCS; very fast	Via generator/converter	Via GFM PCS	Via PCS
Scalability	GW scale	GW scale	100s MW	100s MW	Modular MW	10s–100s MW	Modular	Limited
Indian maturity	Commercial; 7.43 GW installed	Tehri PSP reported as India's first variable-speed units	None; potential in hard-rock caverns	None; LNG-cold synergy potential	Niche UPS	R&D / proposals	Niche (industrial, EV)	R&D

Data Compiled from Multiple Sources

Table 8: Technology matrix (B): electrochemical storage

Parameter	Li-ion LFP	Li-ion NMC/NCA	Sodium-ion	Sodium–sulphur (NaS)	Lead-acid / lead-carbon	Vanadium redox flow	Iron flow (all-iron)	Zinc-based (Zn-Br, Zn-hybrid)	Iron-air
Power rating (per project)	kW–GW (multi-GWh sites)	kW–100s MW	kW–100 MW	1–100s MW	kW–10s MW	kW–200 MW	kW–10s MW	kW–10s MW	1–10s MW (100 h)
Discharge duration	0.5–8 h (typ. 2–4)	0.5–4 h	1–4 h	6–7 h	1–8 h	4–12 h	4–12 h	3–12 h	≈100 h
Response time	< 100 ms (PCS-limited)	< 100 ms	< 100 ms	< 1 s	< 1 s	< 1 s	seconds	seconds	minutes
Round-trip efficiency (AC)	85–90%	85–90%	83–90%	75–85%	70–82%	65–78%	60–70%	65–75%	35–45%
Self-discharge	1–3%/month	2–5%/month	2–5%/month	Heat loss when idle (~20%/day to maintain temperature)	2–5%/month	Low (shunt currents)	Low	Medium	Medium
Cell energy density	150–205 Wh/kg; 300–450 Wh/L	200–280 Wh/kg	100–175 Wh/kg	150–240 Wh/kg	30–50 Wh/kg	15–30 Wh/L (electrolyte)	15–30 Wh/L	30–80 Wh/kg	High (low cost)
Power density	High	Very high	High	Medium	Medium	Low	Low	Low	Low
Cycle life (to 70–80% SOH)	6,000–12,000	3,000–6,000	3,000–10,000 (claimed)	4,500–6,000	500–3,000	> 15,000–20,000	> 10,000	3,000–10,000	Low cycling duty
Calendar life	15–20 years	10–15 years	10–15 years (est.)	15 years	5–12 years	20–25 years	20 years	10–20 years	20 years (target)
Usable DoD	90–100% (usable 80–95%)	80–90%	≈100%	≈90%	50–80%	≈100%	≈100%	≈100%	≈100%

Parameter	Li-ion LFP	Li-ion NMC/NCA	Sodium-ion	Sodium–sulphur (NaS)	Lead-acid / lead-carbon	Vanadium redox flow	Iron flow (all-iron)	Zinc-based (Zn-Br, Zn-hybrid)	Iron-air
C-rate	0.25–2C	0.5–3C	0.25–3C	0.15C	0.1–0.5C	0.1–0.25C	0.1–0.25C	0.1–0.3C	0.01C
CAPEX – power-related (US$/kW)	80–200 (PCS + BOP)	80–200	80–200	300–600	150–400	400–1,000	400–1,000	400–1,000	1,000–2,000
CAPEX – energy / turnkey (US$/kWh)	73–220 turnkey 4 h (China–US range, 2025)	150–300	90–200 (early)	300–500	150–300	250–500	200–400	250–450	≈20–40 (target)
Fixed O&M	1.5–2.5% of capex/yr	1.5–2.5%	1.5–2.5%	2–3%	2–4%	1.5–3%	2–3%	2–3%	2%
Indicative LCOS (daily cycling)	US$65–180/MWh	US$100–220/MWh	US$80–200/MWh (projected)	US$150–300/MWh	US$200–400/MWh	US$150–300/MWh	US$150–300/MWh	US$150–300/MWh	Multi-day adequacy
TRL / status	9 – commercial	9 – commercial	8 – early commercial	9 – commercial (single supplier)	9 – mature	8–9 – commercial	7–8	7–8	7 – first commercial
Construction time	6–18 months	6–18 months	6–18 months	1–2 years	< 1 year	1–2 years	1–2 years	1–2 years	1–3 years
Geographic dependence	Low	Low	Low	Low	Low	Low	Low	Low	Low (large footprint)
Degradation	1.5–3% capacity/yr	2–4%/yr	2–3%/yr	≈1–2%/yr	High	Low (electrolyte rebalanced)	Low	Medium	Low
Safety risk	Thermal runaway (lower than NMC); off-gas explosion	Higher thermal-runaway risk	Lower; can ship at 0 V	High temperature (300–350 °C); sodium fire	H_2 evolution; acid	Low fire risk; acid electrolyte	Low	Bromine handling	Low

Parameter	Li-ion LFP	Li-ion NMC/NCA	Sodium-ion	Sodium–sulphur (NaS)	Lead-acid / lead-carbon	Vanadium redox flow	Iron flow (all-iron)	Zinc-based (Zn-Br, Zn-hybrid)	Iron-air
Environmental impact	Li, graphite, P mining; recyclable	Ni, Co mining	Abundant materials	Na, S (low)	Lead toxicity; high recycling	Vanadium mining; electrolyte reusable	Benign	Zinc; bromine	Iron, benign
Black-start capability	Yes (with GFM PCS)	Yes	Yes	Yes	Limited	Yes	Yes	Yes	Limited
Grid-forming capability	Yes – PCS/control property	Yes (PCS)	Yes (PCS)	Yes (PCS)	Yes (PCS)	Yes (PCS)	Yes (PCS)	Yes (PCS)	Yes (PCS)
Scalability	Very high (modular)	High	High	Medium	Medium	High (decoupled)	Medium	Medium	High (land-intensive)
Indian maturity	Commercial; 9.1 GWh operational (Aug 2026)	EV, BTM	R&D and pilot manufacturing	None	Mature (telecom, UPS)	Pilots	None	None	None

Data Compiled from Multiple Sources

Table 9: Technology matrix (C): thermal and chemical storage

Parameter	Molten-salt TES (CSP / electric-heated)	Carnot battery / pumped thermal	Industrial heat battery (solid media)	Ice / chilled-water TES	Hydrogen (P2H2P: electrolyser + storage + turbine/fuel cell)	Ammonia (P2$NH_3$2P)
Power rating	50–300 MW_e	10–100s MW	1–100 MW_{th}	kW–100s MW_{th} (cooling)	MW–GW	100s MW
Discharge duration	6–15 h	6–24+ h	hours–days	4–12 h	days–months	weeks–months
Response time	Minutes (steam cycle)	Minutes	Seconds (heat)	Minutes	Seconds (fuel cell) to minutes (turbine)	Minutes–hours

Parameter	Molten-salt TES (CSP / electric-heated)	Carnot battery / pumped thermal	Industrial heat battery (solid media)	Ice / chilled-water TES	Hydrogen (P2H2P: electrolyser + storage + turbine/fuel cell)	Ammonia (P2NH$_3$2P)
Round-trip efficiency	35–45% (E2E via heater); >90% heat-to-heat	40–70%	90–98% (heat out); E2E low	85–95% (vs direct chilling)	25–40%	15–30%
Self-discharge	1%/day	1–2%/day	0.5–2%/day	1–5%/day	≈0 (caverns); boil-off if liquid	≈0
Energy density	100–250 kWh/m^3 (thermal)	100–300 kWh/m^3 (thermal)	200–500 kWh/m^3	20–90 kWh/m^3	33 kWh/kg; ~1 kWh/L at 700 bar	5.2 kWh/kg; 3.5 kWh/L (liquid)
Cycle life	> 10,000	> 10,000	> 10,000	> 10,000	Electrolyser stacks 60,000–90,000 h	Plant life
Calendar life	30 years	25–30 years	20–30 years	20–30 years	20–30 years (stack replacement)	25–30 years
CAPEX – power (US$/kW)	3,000–6,000 (CSP incl. power block)	1,000–2,500	200–600 (per kW$_{th}$)	100–300 (per kW$_{th}$)	Electrolyser 500–2,000 + reconversion 800–1,500	1,500–3,000
CAPEX – energy (US$/kWh)	20–40 per kWh$_{th}$	20–60	10–40 per kWh$_{th}$	10–60 per kWh$_{th}$	1–5 (salt cavern); 15–30 (tanks)	0.1–1 (tanks)
TRL / status	9 (CSP)	5–7 – demonstration	7–9 – early commercial	9 – commercial	7–9 by component; P2H2P at scale 6–7	6–7
Geographic dependence	High DNI for CSP	Low	Low	Low	Caverns for bulk storage	Ports/industry
Safety risk	Hot salt; freeze	Moderate	High temperatures	Low	Flammability (4–75% in air), embrittlement	Toxicity
Grid-forming / inertia	Synchronous turbine	Synchronous turbine	n/a	n/a	Synchronous turbine or GFM fuel-cell inverter	Synchronous turbine

Parameter	Molten-salt TES (CSP / electric-heated)	Carnot battery / pumped thermal	Industrial heat battery (solid media)	Ice / chilled-water TES	Hydrogen (P2H2P: electrolyser + storage + turbine/fuel cell)	Ammonia (P2$NH_3$2P)
Indian relevance	CSP pilots (e.g., 50 MW Godavari)	R&D	Industrial clusters (textiles, food, chemicals)	Cooling-dominated peaks in commercial buildings	NGHM pilots; P2H2P long-term	Export-oriented green ammonia; fuel for co-firing

Data Compiled from Multiple Sources

Comparison notes: Round-trip efficiency, CAPEX and LCOS are comparable only when measurement boundaries, operating assumptions and project life are consistent. Costs expressed per kWth or kWhth cannot be directly compared with electricity-storage costs per kWe or kWhe. Fuel-storage costs for hydrogen and ammonia exclude conversion and reconversion equipment unless explicitly stated. Power-related and turnkey CAPEX must not be combined without checking their scope. Values identified as claimed, projected or targeted are not verified commercial performance benchmarks.

A few broad conclusions emerge from the included matrix:

a. No single storage technology demonstrates superiority across all performance attributes. Lithium-ion batteries offer advantages in efficiency, response speed, modularity, and deployment time; pumped-storage hydropower (PSP) provides long operational life, large-scale capacity, synchronous inertia where the generator is electrically coupled to the grid, and comparatively low energy-related costs; flow BESS offer potential advantages for longer-duration cycling, while iron-air systems remain an emerging option for multi-day storage. Hydrogen-based storage may address very long-duration requirements, subject to reconversion efficiency, infrastructure and cost constraints; and thermal storage can achieve high efficiencies for heat-to-heat applications.
b. Grid-forming capability is fundamentally a characteristic of the power-conversion and control system rather than the storage medium itself and can, in principle, be implemented across converter-interfaced storage technologies.
c. Technology maturity and deployment experience in India remain below global levels for several emerging storage technologies, with LFP BESS, PSP, and lead-acid systems being notable exceptions. This gap highlights the need for a structured demonstration and validation programme for promising long-duration storage technologies under Indian grid and operating conditions before large-scale commercial procurement.

2.3. Electrochemical Energy Storage

The suitability of BESS technologies for Indian grid applications depends on lifecycle cost, operating conditions, safety, commercial maturity and supply-chain availability. Lithium-ion batteries, particularly LFP, currently offer a commercially established option for utility-scale BESS. Emerging chemistries may provide alternatives for longer-duration applications and supply-chain diversification. Lithium-ion batteries: LFP and NMC/NCA

LFP has become a commercially preferred chemistry for grid-scale stationary energy storage due to its cost, cycling capability and comparatively favourable thermal stability. These characteristics are relevant for Indian BESS projects operating under high ambient temperatures and repeated daily cycling. Table 10 summarises the comparison between LFP and NMC/NCA BESS technologies and their implications for Indian stationary energy storage.

Table 10: LFP versus NMC/NCA for stationary storage

Attribute	LFP	NMC / NCA	Implication for Indian stationary storage
Project economics	Generally cost-competitive for stationary storage	Higher material cost exposure	Compare turnkey system costs and lifecycle economics rather than cell prices alone
Lifecycle performance	Generally suited to frequent cycling	Greater sensitivity to some operating conditions	Assess warranted degradation, augmentation

Attribute	LFP	NMC / NCA	Implication for Indian stationary storage
			and energy-delivery obligations
Thermal stability	Comparatively favourable thermal stability	Higher thermal-runaway propagation concerns	BESS installations in hot regions such as Rajasthan and Gujarat. Both require appropriate thermal management and fire protection.
Space requirements	Lower energy density so requires more space	Higher energy density. So required high space	LFP Relevant where land availability or site footprint is constrained
Critical minerals	Li, graphite, phosphate, iron - no Ni or Co	Li, Ni, Co, Mn, graphite	LFP reduces exposure to Ni/Co supply risks, but Li and graphite remain
Manufacturing base	Dominated by China, Domestic cell manufacturing capacity is developing	EV-oriented supply chains	India's ACC PLI supports technology-agnostic domestic cell manufacturing, including stationary-storage applications

Data Compiled from Multiple Sources

Implications for India. The shift to LFP simplifies India's critical-mineral challenge (no nickel or cobalt) but does not remove it: lithium, graphite and high-purity phosphate remain largely imported[32], so majority of battery cells used in Indian BESS are imported. India's National Critical Mineral Mission (2025) and the production-linked incentive (PLI) scheme for 50 GWh of advanced chemistry cell (ACC) capacity aim to build domestic capability, but the Ministry of Heavy Industries reported only 1 GWh of installed capacity under the scheme in March 2026.[33,34]. For a stationary-storage market that is likely to exceed 30–50 GWh per year before 2030, domestic LFP cell and cathode manufacturing is a strategic priority.

2.3.1 Sodium-ion batteries

For India, sodium-ion is strategically interesting because it could reduce dependence on imported lithium while using manufacturing processes similar to LFP. MNRE published a dedicated assessment of sodium-ion battery technologies and their potential in India. It is best classified as early commercial globally and R&D/pilot manufacturing in India[35]. For Indian grid-scale deployment, commercial validation should prioritise lifecycle cost, safety, degradation and supplier reliability. Sodium-ion is a potential complement to LFP rather than an immediate replacement.

[32] NITI Aayog, Government of India, Scenarios Towards Viksit Bharat and Net Zero: Critical Mineral Assessment: Demand and Supply, vol. 10, Feb. 10, 2026.
[33]Ministry of Mines, Government of India, "National Critical Mineral Mission," *The Gazette of India: Extraordinary*, Part I, Sec. 1, No. 173, F. No. 28/15/2024-CMM-Part (1), Jun. 24, 2025.
[34] Ministry of Heavy Industries, Government of India, "The Ministry of Heavy Industries invites bids through Global Tender for the selection of beneficiaries to set up giga-scale Advanced Chemistry Cell (ACC) manufacturing facilities of 10 GWh cumulative capacities, under PLI ACC Scheme," Press Information Bureau (PIB), Jul. 15, 2026.
[35] Ministry of New and Renewable Energy (MNRE), Government of India, and UK Government, "Assessment of the Global Landscape for Sodium-Ion Batteries and Their Potential in India," ASPIRE Programme, Dec. 2024.

2.3.2 Sodium–sulphur (NaS) batteries

NaS BESS have demonstrated commercial storage applications internationally. However, the high operating temperature, thermal-management energy during idle periods, single-supplier market and past fire incidents limit their relevance for India. Their use would require careful assessment of safety, supplier support and lifecycle economics under Indian operating conditions.

2.3.3 Lead Acid Batteries

Lead-acid BESS remain the workhorse of India's telecom, UPS and inverter markets and benefit from a mature domestic manufacturing and recycling industry regulated under the Battery Waste Management Rules, 2022[36]. Despite improvements in lead-carbon designs, lifecycle and operating limitations constrain their competitiveness in utility-scale energy-shifting applications. Their continuing relevance lies in low-cost backup, rural and telecom applications their established collection and recycling infrastructure.

2.3.4 Flow batteries: vanadium, iron and zinc-based systems

Flow batteries are potential alternatives for longer-duration and high-cycling stationary applications. Their commercial suitability in India depends on installed cost, supplier availability, electrolyte management and field-proven performance.

- **Vanadium redox flow batteries (VRFB):** VRFBs offer potential advantages in long-term cycling, fire safety and electrolyte reuse, but face cost and supply-chain constraints. NTPC inaugurated India's first MWh-scale VRFB system, rated at 0.6 MW/3 MWh, at its NETRA research centre in Greater Noida in November 2025. This provides a domestic demonstration platform for assessing performance and operating experience.

2.3.5 Metal-air batteries

Metal-air BESs, particularly iron-air systems, are emerging options for multi-day energy storage. Their potential relevance to India lies in meeting prolonged energy shortfalls that cannot be addressed economically by conventional intraday storage. However, lower conversion efficiency, limited deployment experience and uncertain lifecycle costs warrant further demonstration before large-scale procurement. Solid-state and next-generation lithium chemistries

Solid-state and advanced lithium chemistries remain relevant to India's battery manufacturing and R&D ecosystem. However, their suitability for stationary storage depends on demonstrated lifecycle cost, safety, manufacturing scalability and performance under Indian conditions. Established chemistries currently offer a stronger basis for large-scale procurement.

2.3.6 Suitability of Battery Chemistries for Grid-Scale Storage

As illustrated in Figure 16, no single battery chemistry is superior across all performance attributes; technology selection should instead reflect the intended grid service, discharge duration, cycling regime, safety requirements, project footprint, and supply chain considerations. For India's power system, the principal applications include solar energy shifting, evening peak management, renewable ramping, ancillary services and distribution-level flexibility.

[36]Ministry of Environment, Forest and Climate Change, Government of India, "Battery Waste Management Rules, 2022," Notification S.O. 3984(E), The Gazette of India: Extraordinary, Part II, Sec. 3(ii), Aug. 22, 2022.

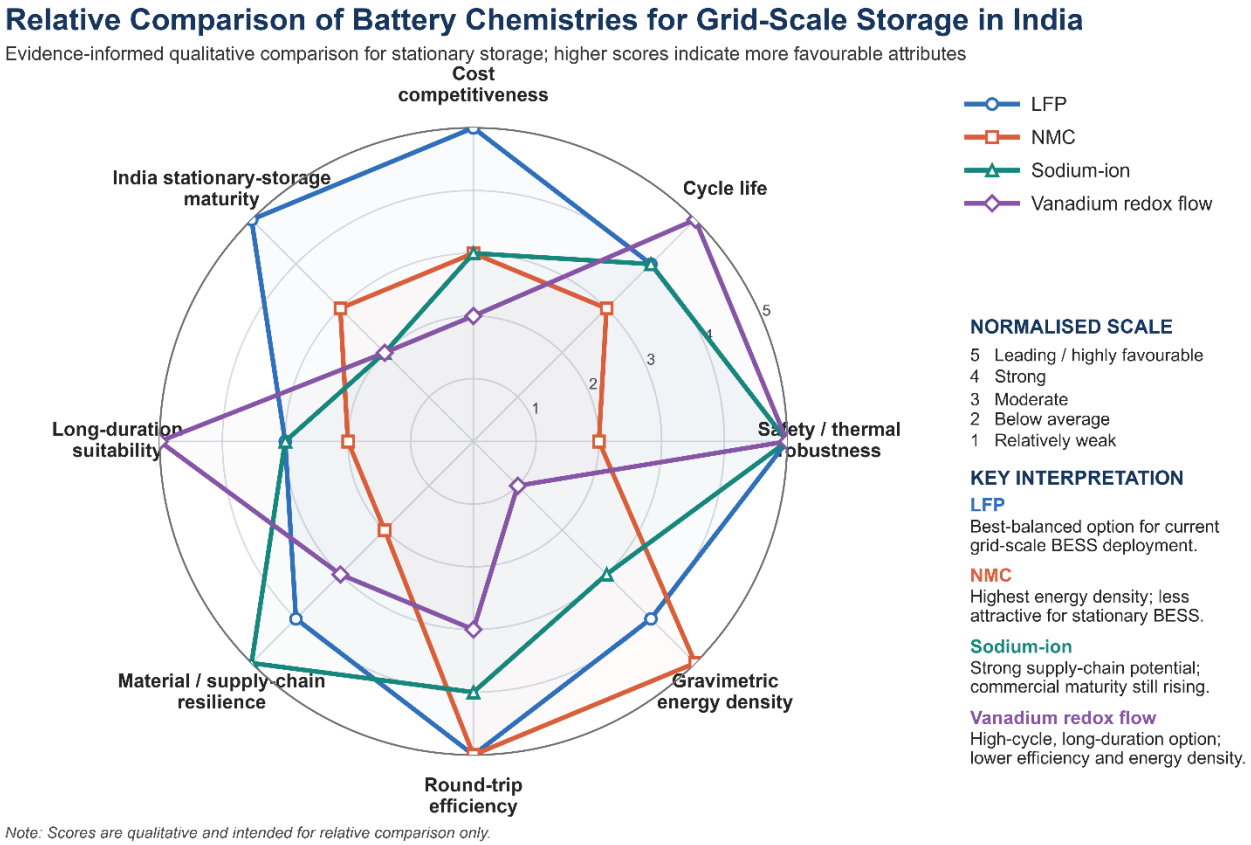


Figure 16: Relative comparison of selected battery chemistries for grid-scale stationary storage in the Indian context. Scores represent an evidence-informed qualitative comparison rather than absolute technology-performance ratings.

(Source: This figure has been plotted using data sources from IEA, Batteries and Secure Energy Transitions (2024), and storage-technology literature; scores are illustrative.)

For the near- to medium-term Indian grid-scale BESS market, LFP presently offers the most balanced combination of cost competitiveness, round-trip efficiency, cycle life, thermal robustness and commercial maturity. This is consistent with the global stationary storage market, where LFP accounted for around 80% of new battery storage deployment as early as 2023, aided by its lower cost, longer lifetime, and lower flammability relative to nickel-rich Li-ion chemistries.[37] These characteristics are particularly relevant in India, where high ambient temperatures, intensive cycling and rapidly expanding utility-scale deployments increase the importance of thermal management, safety and lifecycle economics. LFP-based BESS is particularly suitable for shifting surplus daytime solar generation to non-solar peak hours and supporting rapid changes in net load. It can also provide frequency regulation and other fast-response services when equipped with suitable converters and controls[38]. However, if these BESS are installed at Rajasthan or Gujarat, high ambient temperatures can increase cooling requirements and accelerate degradation if thermal conditions are not adequately controlled.

NMC batteries retain an advantage in gravimetric energy density, but this advantage is considerably less valuable in stationary applications than in electric mobility, where weight and volume are critical. NMC also entails greater exposure to nickel and cobalt supply chains and presents a less favourable thermal-safety profile than LFP; consequently, there is limited rationale for preferring NMC over LFP for most conventional Indian utility-scale BESS applications unless site footprint or energy density is a binding constraint. NMC may therefore be considered for space-constrained installations, such as urban substations and commercial or industrial facilities, where its higher

[37] International Energy Agency (IEA), Batteries and Secure Energy Transitions, World Energy Outlook Special Report. Paris, France: IEA, Apr. 25, 2024.

[38] Ministry of Power, Government of India, National Framework for Promoting Energy Storage Systems, New Delhi, India, Aug. 2023.

energy density provides a meaningful system-level advantage. The IEA similarly identifies the lower energy density of LFP as relatively unimportant for stationary storage and notes the resulting market shift towards LFP. [37]

Sodium-ion batteries represent a potentially important emerging option for India, particularly in terms of technology and raw-material diversification. They eliminate the requirement for lithium and can provide a more geographically diversified upstream resource base; however, their present energy density and manufacturing maturity remain below those of established Li-ion technologies. Moreover, the downstream sodium-ion manufacturing ecosystem remains highly concentrated in China. [39] Sodium-ion should therefore be viewed as a strategically promising complement to LFP rather than an immediate large-scale replacement in the Indian market. In India, sodium-ion batteries could find applications in distribution-level peak management, decentralised renewable energy systems and rural or remote microgrids, where compactness may be less critical. Their suitability for utility-scale deployment requires further validation of lifecycle cost, safety, degradation and performance under Indian operating conditions.

For applications requiring longer discharge durations and very high cycle life, vanadium redox-flow batteries (VRFBs) offer a fundamentally different value proposition. Their independently scalable power and energy components, long electrolyte cycle life, and favourable safety characteristics make them potentially attractive for high-cycling and long-duration applications, although their lower energy density, lower round-trip efficiency, and current cost position limit their competitiveness in mainstream short-duration BESS. For India, VRFBs could be evaluated for longer-duration energy shifting in solar-rich regions and applications requiring frequent cycling over an extended project lifetime. Their value would depend on whether longer discharge duration and cycling capability offset the higher initial cost, conversion losses and larger space requirements.

For India, the appropriate pathway is therefore not to identify a universally preferred battery chemistry, but to match chemistry to application while maintaining technology-neutral procurement wherever feasible. LFP is currently the strongest candidate for the bulk of near-term 2-4-hour grid-scale BESS deployment, while sodium-ion and flow batteries warrant increasing consideration as their domestic ecosystems mature and as demand expands towards longer-duration storage. This diversification is also relevant to India's industrial strategy: the Government's ACC Production Linked Incentive programme is explicitly intended to establish domestic giga scale cell manufacturing and increase domestic value addition, of the 50 GWh manufacturing capacity envisaged under the existing ACC PLI scheme, 10 GWh has been earmarked for grid-scale storage applications. [40] Technology diversification could also reduce dependence on individual battery chemistries and their associated raw-material supply chains, provided alternative technologies become commercially competitive.

Accordingly, future procurement should evaluate technologies on lifecycle cost, warranted degradation, safety, round-trip efficiency, duration, availability and supply-chain resilience, rather than relying solely on upfront ₹/kWh costs. Particular emphasis is required on guaranteed usable energy at the point of interconnection, performance under site-specific climatic conditions and augmentation requirements over the contracted operating life.

2.4. From Cell to System: Architecture of a utility-scale BESS

A utility-scale BESS is a complex system in which the battery cells account for roughly 40-60% of the cost. Performance, safety and lifetime depend at least as much on system integration as on cell chemistry. It is therefore essential to distinguish performance at the levels of cell, module, rack, container (DC block) and complete plant as shown in Figure 17 and summarised in Table 11.

[39] International Energy Association (IEA), “Sodium-ion battery momentum grows, but challenges remain,” Paris, Feb. 2026.

[40] Ministry of Heavy Industries, Government of India, “PLI Scheme for National Programme on Advanced Chemistry Cell (ACC) Battery Storage | Ministry of Heavy Industries.”

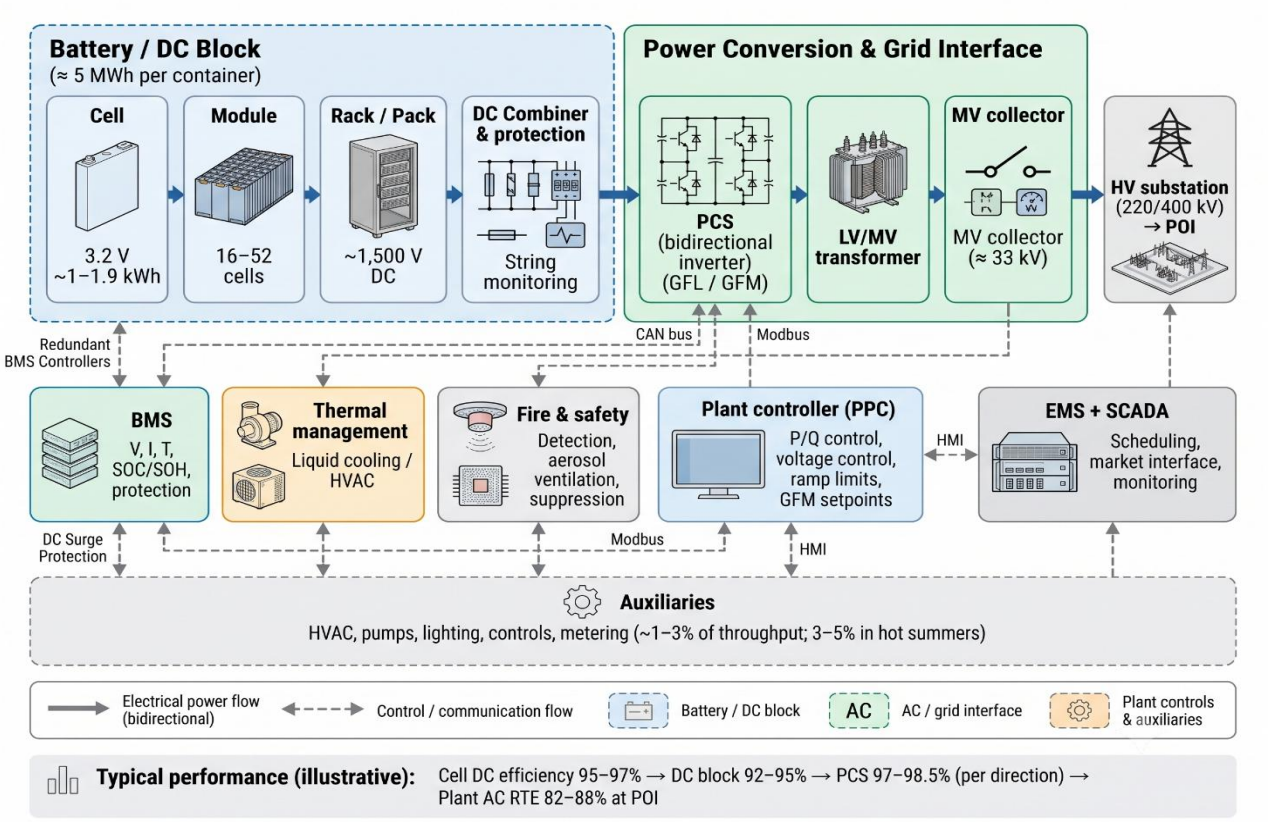


Figure 17: Cell to grid architecture of a typical utility-scale BESS

(Source: This figure has been plotted using data sources from IEC 62933, Electrical energy storage systems; component ratings are indicative.)

Table 11: Performance hierarchy of a BESS from cell to plant

Level	Composition	Typical efficiency/ performance	Key design issues
Cell	Prismatic LFP cell, 280–587 Ah, 3.2 V (0.9–1.9 kWh)	Coulombic efficiency > 99.5%; DC energy efficiency 95–97% at 0.5C	Cell-to-cell variation, grading, and supplier quality
Module	16–52 cells in series with busbars, sensors, cell-level monitoring	Minor resistive losses	Thermal uniformity, busbar joints, cell monitoring
Rack/cluster	8–10 modules in series (≈1,000–1,500 V DC) with battery control unit and switchgear	DC efficiency 94–96%	Imbalance between racks; DC protection (fuses, contactors)
Container / DC block	5–12 racks; liquid or air cooling; HVAC; fire detection and suppression; typical 3.7–6.25 MWh per 20-ft	DC-side efficiency 92–95% including thermal auxiliaries	Thermal management (cell ΔT < 3–5 °C), gas detection, deflagration venting

Level	Composition	Typical efficiency/ performance	Key design issues
Power conversion system (PCS)	Bidirectional inverter, 1–6 MVA per unit, 1,500 V DC; LV/MV transformer	97–98.5% per direction	MVA rating vs MW (reactive headroom), GFL/GFM control, harmonics, and derating at high ambient temperature
MV collection and HV substation	33 kV collector system; HV step-up to 220/400 kV	99–99.5% per transformer per direction	Losses, reactive compensation, protection
Plant (at POI)	EMS + power-plant controller (PPC) + SCADA + auxiliaries	AC RTE 82–88% including auxiliaries	Auxiliary consumption (1–3% of throughput; higher in hot climates), control coordination

Data Compiled from Multiple Sources

Battery management system (BMS): The BMS operates in a three-tier hierarchy (module, rack and system level). It measures cell voltages, currents and temperatures. It estimates SOC and SOH, balances cells, enforces safe operating limits, and communicates alarms and limits to the PCS and EMS. For LFP batteries, accurate SOC estimation is particularly challenging because of its flat voltage curve, and SOC errors of 3-5% translate directly into uncertainty in dispatchable energy, which matters for reserve and capacity contracts.

Power conversion system (PCS): The PCS converts DC to AC and back and critically determines how the BESS plant behaves electrically on the grid, including its active and reactive power capability, ride-through capability, harmonic injection, and whether it operates in grid-following or grid-forming mode. PCS ratings are often specified in kVA or MVA at a stated power factor and ambient temperature; at 45-50 °C, some PCS derate by 10-20%, which must be accounted for in Indian procurement.

Energy management system (EMS) and power-plant controller (PPC): The EMS schedules charging and discharging in accordance with contracts, markets, and dispatch instructions, while the PPC regulates active and reactive power at the POI in real time. Under the August 2025 VGF amendments, the application software of the EMS for VGF-supported projects must be developed indigenously in India[41], which has both industrial-policy and cybersecurity benefits.

Thermal management and auxiliaries: Cell temperature is the single most important determinant of degradation and safety. Liquid cooling, now standard for large LFP containers, limits the spread of cell temperatures to a few degrees and reduces auxiliary consumption compared with air cooling. Nevertheless, in Rajasthan and Gujarat, where ambient temperatures exceed 45 °C for weeks, auxiliary load can rise to 3-5% of throughput in summer. Auxiliary consumption should be included in the RTE guarantee or separately metered and settled.

Fire protection and safety systems: Modern containers include cell-level and container-level temperature sensing, off-gas (H_2, CO, VOC) detection, deflagration venting or explosion-prevention ventilation, and suppression (aerosol, clean agent or water-based).

As illustrated in Figure 18, the RTE of a grid-scale BESS reflects losses across the entire AC-to-AC energy-conversion pathway, rather than battery-cell efficiency alone. Energy losses occur at the grid interface and in transformers, the bidirectional power conversion system (PCS), the battery/DC system, and auxiliary loads such as thermal management and controls. Consequently, high cell-level or DC efficiency does not translate directly into equivalent efficiency at the point of interconnection (POI). The illustrative example shows how 100 MWh of AC charging energy could yield about 87 MWh on discharge, corresponding to an AC-AC RTE of approximately 87%; the individual loss

[41]Ministry of Power, Government of India, "Amendment in Operational Guidelines for Viability Gap Funding Scheme for Development of Battery Energy Storage System Supported Through Power System Development Fund (PSDF)," Order No. 48-15/7/2025-NRE Section, Aug. 4, 2025.

allocations are illustrative rather than representative of a specific project. Actual plant RTE varies with loading, SOC operating window, ambient temperature, battery ageing, HVAC demand and operating strategy, making POI-to-POI measurement under consistent initial and final SOC conditions important for meaningful performance assessment.

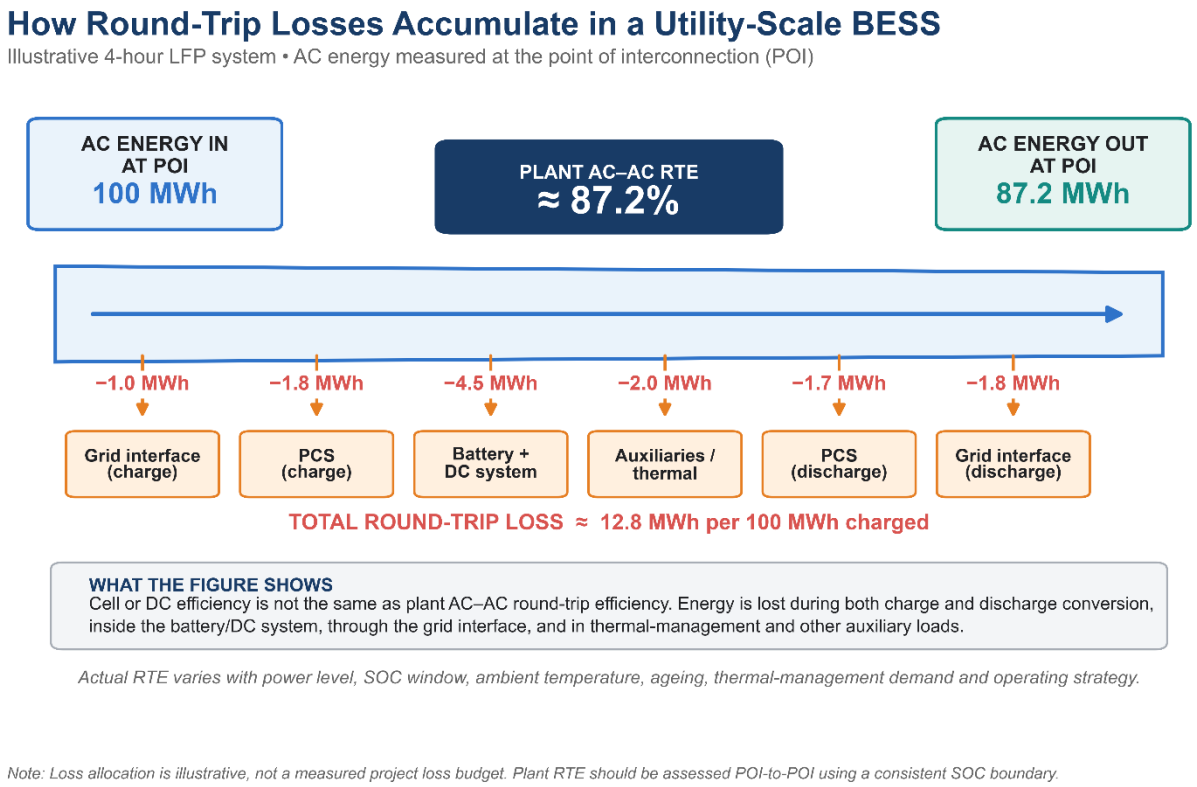


Figure 18: Illustrative accumulation of round-trip energy losses across a utility-scale 4-hour LFP battery energy storage system (BESS), from AC energy input to AC energy returned at the POI

2.5. Battery Degradation, Warranties and Augmentation

Battery degradation is a fundamental engineering and commercial consideration for BESS deployment, as it directly influences the energy and power capability available over the project lifetime, the cost of sustaining contracted performance, and the design of warranties, augmentation strategies, and long-term contractual obligations.

2.5.1 Mechanisms and stress factors

Lithium-ion cells lose capacity and gain internal resistance through several mechanisms, including growth of the solid-electrolyte interphase (SEI) on the anode, consuming cyclable lithium; lithium plating at low temperature or high charge rate; particle cracking and loss of active material from repeated volume changes; electrolyte decomposition and gas generation; and, for NMC, transition-metal dissolution. Two modes are usually distinguished in this aspect[42]:

- **Calendar ageing**: degradation with time, independent of use, accelerated by high temperature and high state of charge.
- **Cycle ageing**: degradation with use, driven by charge throughput, depth of discharge, charge/discharge rate and temperature.

Table 12 summarises the main stress factors and mitigation options. A widely used rule of thumb is that each 10 °C increase in average cell temperature roughly doubles the rate of calendar ageing (an Arrhenius dependence), making thermal design very important in India's hot climate zones.

[42]B. Xu, et al., "Modeling of lithium-ion battery degradation for cell life assessment," IEEE Transactions on Smart Grid, vol. 9, no. 2, pp. 1131–1140, 2018.

Table 12: Degradation stress factors for LFP BESS and mitigation measures

Stress factor	Effect	Typical sensitivity	Mitigation
Temperature	Accelerates SEI growth and side reactions (calendar and cycle)	Roughly 2× calendar fade per +10 °C above ~25 °C	Liquid cooling; shading; night-time pre-cooling; avoid resting at high SOC in heat
State of charge (resting)	High SOC accelerates calendar fade	Storage at 90–100% SOC can double fade versus 30–50%	Schedule charging close to discharge; avoid prolonged full charge
Depth of discharge	Deeper cycles cause more wear per cycle	LFP is relatively tolerant; still non-linear	Operate within 5–95% or 10–90% SOC windows
C-rate	High currents raise temperature and plating risk	Modest at 0.25–0.5C; significant > 1C	Size energy for low C-rate in energy services
Throughput (equivalent full cycles)	Cumulative cycle ageing	Warranties usually specify EFC/year	Throughput caps, degradation-aware dispatch
Low temperature charging	Lithium plating	Rarely binding in India (hill states excepted)	Pre-heating
Cell imbalance	Weakest cells limit rack capacity	Grows with time	Active balancing, rack-level DC/DC, augmentation

Data Compiled from Multiple Sources

A simple semi-empirical representation used in planning studies separates calendar and cycle components:

$$Q_{loss}(t) = a \cdot \exp\left(-\frac{E_a}{RT}\right) \cdot tz + b \cdot f(DoD, C-rate, T) \cdot EFC(t)$$

where $Q_{loss}(t)$ is fractional capacity loss, E_a is the activation energy, R is the gas constant, T absolute cell temperature, t time, z an exponent typically near 0.5, EFC is the number of equivalent full cycles and a, b fitted coefficients. Such models underpin degradation-aware dispatch and augmentation planning.

2.5.2 Metrics, Warranties and Contractual Performance

Degradation must be translated into contractual metrics that protect the procurer without over-constraining operation. The principal metrics for defining it are SOH; usable energy at the POI, guaranteed year-over-year; throughput warranties (e.g., a stated number of equivalent full cycles or MWh over the warranty period); round-trip efficiency guarantees under stated conditions; and availability. Cell suppliers commonly warrant 70-80% capacity after a specified number of cycles or years under specified temperature and SOC conditions; system integrators wrap these into energy retention and availability guarantees at the POI. The April 2026 amendment to the CEA's technical standards for construction introduced minimum capacity-retention requirements for BESS, 90% of original output after five years, 80% after ten years and 70% after fifteen years, effective from April 2027 as shown in Figure 19[43]. These values are reasonable for LFP under two cycles per day in well-cooled containers, but they must be read together with the definition of "original output" (nameplate DC or contracted AC at the POI) and the test protocol.

[43]Central Electricity Authority, "Central Electricity Authority (Technical Standards for Construction of Electrical Plants and Electric Lines) Amendment Regulations, 2026," The Gazette of India, Extraordinary, Part III, Sec. 4, Notification F. No. CEA-TH-17/1/2021-TETD Division, Jun. 22, 2026.

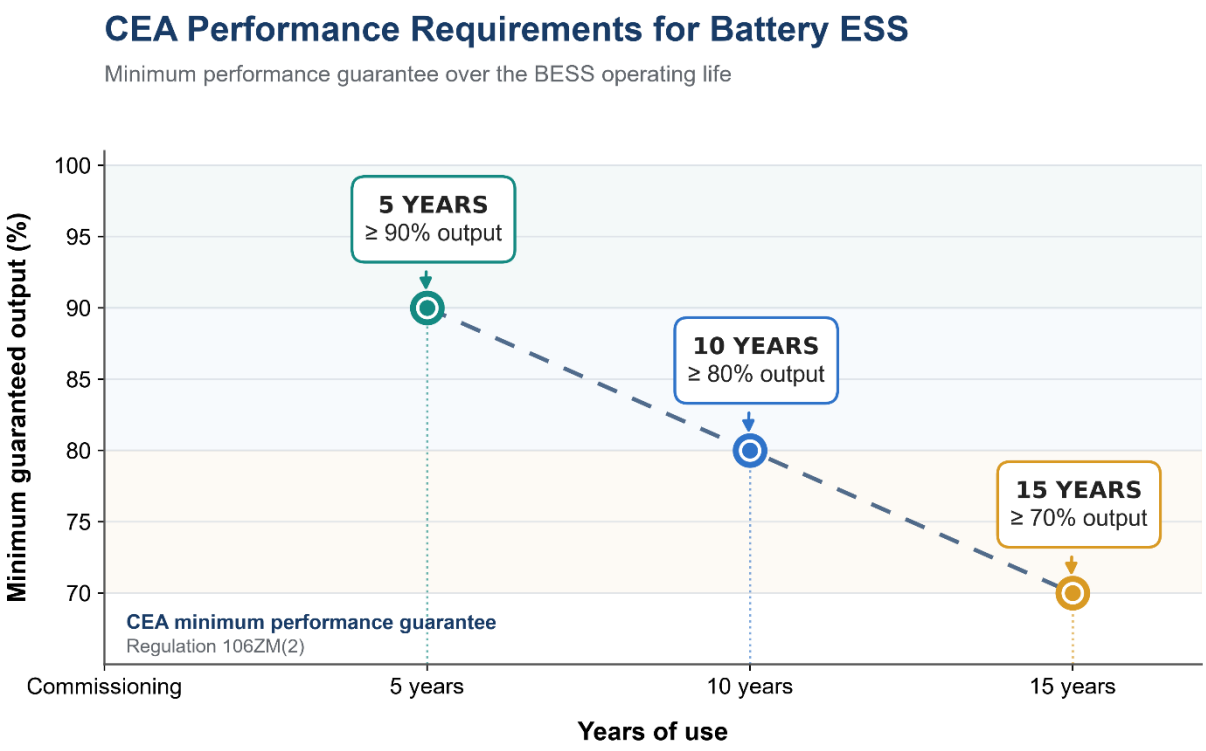


Figure 19: Minimum BESS performance guarantees specified under the CEA (Technical Standards for Construction of Electrical Plants and Electric Lines) Amendment Regulations, 2026

2.5.3 Augmentation Strategies and End-of-Life Capacity

Since capacity fades, a BESS contracted to deliver fixed usable energy for 12–15 years must either be overbuilt at the start (installing, for example, 15-25% more DC energy than contracted) or augmented periodically by adding new modules or containers. Augmentation reduces up-front cost and takes advantage of falling cell prices, but it requires space, electrical capacity in the PCS and collector system, and compatibility between old and new batteries (typically managed with separate DC blocks or DC/DC converters). A combined strategy that requires modest initial overbuild plus one or two augmentation events is usually optimal. At the end of life, typically when capacity reaches 60-70% of BOL, cells can be repurposed for less demanding second-life applications or recycled.

2.6. Mechanical storage

2.6.1 Pumped Storage: Principles and Configurations

Pumped Storage Projects (PSP) are particularly relevant to India's bulk energy shifting, evening peak management and sustained balancing requirements. Their suitability depends on storage duration, reservoir availability, pumping flexibility, grid connectivity and site-specific development constraints. CEA's January 2026 roadmap identified approximately 266.85 GW of assessed PSP potential as of December 2025[44]. This represents identified potential rather than confirmed developable capacity.

PSPs differ along several technical dimensions, summarised in Table 13:

Table 13: Pumped storage configurations and their grid capabilities

Configuration	Operating capability	Advantages	Constraints / Indian relevance

[44] Central Electricity Authority (CEA), Roadmap to 100 GW of Hydro Pumped Storage Projects (PSPs) by 2035–36, Ministry of Power, Government of India, New Delhi, India, Jan. 2026.

Open-loop (on-stream), fixed speed	Generation regulation; fixed pumping power per unit	Uses existing reservoirs so may reduce new reservoir requirements	River ecology, flood design, water-sharing; e.g., Srisailam, N J Sagar relevant where existing reservoirs and suitable head are available
Closed-loop (off-stream), fixed speed	As above	Potentially lower direct river-system impacts and greater siting flexibility	Initial fill and make-up water; land and forest; e.g., Pinnapuram (1,680 MW) Important in assessing off-stream PSP potential across suitable Indian terrain
Variable speed (DFIM or full converter)	Pumping power adjustable (±20–30%) where supported by design; faster response; wider head range	Frequency regulation in pump mode; better absorption of variable solar surplus	10–30% higher E&M cost; converters; Tehri (reported variable speed) Additional converter and control costs; relevant to variable solar generation and changing reservoir heads
Ternary / hydraulic short-circuit	Continuous net power from −P to +P; fast transitions Greater flexibility in pumping and generating modes, depending on hydraulic configuration	Potentially faster operating-mode changes and power regulation	Higher cost and space; not yet used in India
Synchronous-condenser capable	Inertia, fault current and reactive power with no active power exchange	System strength near RE complexes	Requires dewatering systems; operational protocols and verified operating capability
Seawater / mine-void schemes	Site-dependent bulk storage	Uses coastal sites or abandoned mines	Corrosion, sealing, water quality; geotechnical, environmental and water-management constraints require validation

Data Compiled from Multiple Sources

For Indian grid operation, variable-speed pumping is particularly relevant where renewable generation varies substantially within the charging window. Synchronous-condenser capability can also provide system-strength support, but it must be explicitly specified and verified rather than assumed for all PSPs.

Response times and operating modes: Transition times vary depending on the PSP's design. A modern unit can typically reach full generation from standstill in about one to three minutes, and changing from pumping to generating can take several minutes for conventional fixed-speed units, but less for variable-speed or ternary designs. These times make PSP highly suitable for secondary and tertiary reserves and ramping, but less suitable than BESS for sub-second fast frequency response. During the Khavda event of May 2026, most PSPs did not provide the automatic load relief that was expected from tripping the pumping load, highlighting the need to specify and test such protection and control schemes explicitly. Hence, pumping-load interruption, reserve activation and mode-change performance should be specified and tested where these services are required by the system operator.

Siting and constraints: PSP siting depends on topography (head and head-to-length ratio), geology (for tunnels and underground powerhouses), water availability (for initial filling and evaporation make-up,), land and forest clearance, seismicity and transmission access. The CEA's 2026 roadmap highlights indicative DPR preparation periods of 690 days for specified non-Himalayan schemes and 840 days for more challenging Himalayan or underground schemes, land-acquisition complexity under the 2013 Land Acquisition Act, scarcity of skilled tunnelling personnel and the need for transmission[45].

2.6.2 Compressed-air Energy Storage (CAES)

CAES stores energy by compressing air into underground caverns (salt, hard rock or depleted reservoirs) or engineered vessels and later expanding it through turbines. For India, the main constraint is geology, the availability and suitability of storage formations must be established through site-specific investigation. Potential options include hard-rock caverns, depleted oil and gas fields, or engineered storage would be needed. CAES is a credible long-duration option for India only after site-specific geological assessment. Its potential relevance lies in bulk RE shifting and longer-duration balancing where suitable storage formations are available. Fuel consumption in diabatic CAES and the resulting emissions must also be considered.

2.6.3 Liquid-Air Energy Storage (LAES)

LAES liquefies air using surplus electricity, stores it at about −196 °C in insulated tanks at low pressure, and regenerates power by pumping, evaporating and expanding the air through turbines. It uses conventional industrial components (air-separation and cryogenic equipment), has fewer geographic constraints compared to cavern based storage, and has a long life, but its efficiency and project economics depend strongly on thermal integration and auxiliary energy consumption. A distinctive Indian opportunity is integration with LNG regasification terminals or industrial facilities with suitable waste-heat and waste-cold streams. Such integration could improve efficiency and support longer-duration electricity shifting, subject to location, thermal availability and techno-economic feasibility.

2.6.4 Flywheels

Flywheels store kinetic energy in a rotor spinning at high speed (typically 8,000-50,000 rpm) in a vacuum enclosure with magnetic or low-friction bearings; the energy stored is $E = 1/2\ I\omega^2$. They respond within milliseconds, tolerate hundreds of thousands to millions of cycles and have high power density, but store only seconds to minutes of energy and suffer high standing losses (several per cent per hour). They are suited to frequency regulation, power-quality support and hybridisation with batteries to absorb high-frequency cycling

For Indian power systems, flywheels may be considered for short-duration, high-frequency power fluctuations, particularly in industrial networks and specialised grid-support applications. Their limited energy duration makes them unsuitable for bulk renewable energy shifting or sustained evening peak support. They should not be conflated with synchronous condensers, whose provision of inertia, fault current and reactive power depends on their electrical-machine configuration.

2.6.5 Gravity Storage

Gravity storage raises and lowers solid masses (composite blocks in towers or buildings, weights in disused mine shafts, or rail cars on inclines). Claimed round-trip efficiencies are 75–85%, with long life and minimal degradation. India's abandoned mine infrastructure and favourable topography in selected regions may provide opportunities for mineshaft and inclined-rail configurations. Nevertheless, gravity storage should presently be regarded as an emerging technology requiring further demonstration and techno-economic validation under Indian conditions. Particular attention is required to usable elevation, structural integrity, site rehabilitation, land requirements and the cost of delivering electricity at the grid connection point.

[45]Central Electricity Authority (CEA), Report on Roadmap to 100 GW of Hydro Pumped Storage Projects by 2035-36, Jan. 2026.

2.7. Thermal, Chemical and Electrical Energy Storage

2.7.1 Thermal Energy Storage (TES)

Thermal storage takes three forms: **sensible** heat (raising the temperature of water, molten salt, concrete, sand, or rock); latent heat (phase change of materials such as paraffins, salt hydrates, or ice); and **thermochemical** storage (reversible reactions such as hydration-dehydration). TES has three applications are relevant to India:

1. **Concentrated solar power (CSP) with molten-salt storage** (typically 290–565 °C), which provides dispatchable solar power at sites with suitable direct-normal irradiance. CSP has had limited success in India because of cost and direct-normal-irradiance uncertainty, but existing plants such as the 50 MW Godawari plant demonstrate the technology. However, its competitiveness depends on solar resource quality, capital cost and alternative renewable-plus-storage options.
2. **Industrial heat batteries** that convert surplus midday electricity into high-temperature heat i.e. up to 1,000 °C or more in solid media, for industrial processes. With industrial heat accounting for a large share of industrial energy use in clusters such as textiles, food processing, chemicals and ceramics, electric heat storage could become a large, *flexible demand* resource and a route to decarbonising process heat[46]. Its grid value depends on the ability to schedule electricity consumption independently of industrial heat demand.
3. **Cooling-load shifting with ice or chilled-water storage**. As India's peak demand becomes increasingly driven by air-conditioning loads, ice and chilled-water storage can shift cooling demand from evening peaks to solar-rich midday hours. In commercial buildings, campuses, data centres, and district-cooling systems, this can reduce evening net-peak demand, without converting the stored thermal energy back into electricity. The Bureau of Energy Efficiency's district-cooling roadmap identifies TES and time-of-day tariffs as potential instruments for grid flexibility. India's Cooling Action Plan targets a 25–40% reduction in cooling energy requirements by 2037-38 relative to its reference trajectory. Thermal storage can complement these efficiency measures through load shifting, but its contribution to peak reduction must be assessed separately.
4. **Pumped thermal energy storage** convert electricity to heat (and cold) using heat pumps or resistive heaters, then reconvert it via a heat engine, achieving round-trip efficiencies of 40-70%. Pumped thermal electricity storage remains a potential longer-duration option. Its relevance to India depends on electricity-to-electricity efficiency, project cost and the availability of suitable thermal integration.

2.7.2 Distinguishing Electricity Storage, Heat/ Cold Storage and Sector Coupling

The distinction has important consequences for metrics, planning and regulation as summarised in Table 14. Heat and cold storage cannot be credited as equivalent dispatchable electrical capacity without assessing the resulting reduction in electricity demand, but by shifting demand, they reduce the E2E storage requirement. Power-to-X technologies convert electricity into fuels or feedstocks, and their flexibility value lies primarily in when they consume electricity, not in reconverting it.

Table 14: Electricity storage and demand-side flexibility options for India

Dimension	E2E storage (BESS, PSP, CAES, LAES, flow)	Heat / cold storage (TES, ice, heat batteries)	Sector coupling / power-to-X (electrolysers, EV charging, e-fuels)
Output	Electricity back to the grid	Heat or cold used on site	Fuel, feedstock or transport service

[46]World Economic Forum, Accelerating India's Energy Transition through Industrial Clusters, Apr. 2025.

Dimension	E2E storage (BESS, PSP, CAES, LAES, flow)	Heat / cold storage (TES, ice, heat batteries)	Sector coupling / power-to-X (electrolysers, EV charging, e-fuels)
Planning contribution	Dispatchable electrical power and usable energy	Reduction or shifting of electrical demand	Controllable electricity consumption and scheduling flexibility
Grid services	Energy shifting, reserves and converter-based grid support where technically equipped	Load shifting, peak reduction, some DR	Flexible demand, midday absorption, DR, possibly reserves where permitted and technically capable
Regulatory treatment	ESS treatment under the Electricity Rules, as amended in 2025	Consumer-side equipment	Consumer / industrial load; open access subject to applicable rules
Potential Indian applications	Evening peak support, renewable shifting, reserves	Commercial cooling, district cooling, process heat	Flexible electrolysis, managed EV charging, industrial demand response

2.7.3 Hydrogen Energy Storage

Hydrogen appears in both storage and industrial-decarbonisation strategies, and the two roles must not be conflated. In power-to-hydrogen-to-power (P2H2P), surplus electricity is converted to hydrogen by electrolysis (60-70% efficiency on a lower-heating-value basis), compressed or otherwise stored (≈90%), and reconverted to electricity using a fuel cell (50-60%) or hydrogen-fired turbine (35–60%), giving an overall round-trip efficiency of only about 25-40%[47]. P2H2P is therefore justified only where its unique attributes, very low marginal cost of stored energy (particularly in salt caverns) and near-zero self-discharge, are essential, i.e., for multi-week and seasonal storage. In direct use, green hydrogen replaces grey hydrogen in refineries and fertiliser plants or serves as a reductant in steelmaking or a feedstock for green ammonia and methanol; here, the conversion losses of reconversion are avoided, and the value per kilogram is much higher.

For India, the implication is that the National Green Hydrogen Mission is primarily an industrial decarbonisation and export strategy, whose main contribution to power-system flexibility is the flexible electrolyser load it creates, rather than a source of electricity storage. The Mission envisages at least 5 million metric tonnes of annual green hydrogen production by 2030, supported by approximately 125 GW of associated renewable capacity. This represents a potentially significant additional electricity demand. Scheduling electrolysis during periods of high RE generation could improve renewable utilisation and reduce balancing requirements. However, flexibility depends on electrolyser operating limits, hydrogen storage, industrial offtake commitments and electricity supply arrangements.

Bulk hydrogen storage for the power sector is further constrained by geology and the availability of suitable underground storage formations. Hydrogen-to-power applications also face significant reconversion losses and require dedicated infrastructure. Accordingly, flexible electricity consumption is a more immediate system-planning consideration than large-scale reconversion of hydrogen into electricity[48]. The hydrogen value chain and its relevance to India are summarised in Table 15.

[47] A. Risco-Bravo, C. Varela, J. Bartels, and E. Zondervan, "From green hydrogen to electricity: A review on recent advances, challenges, and opportunities on power-to-hydrogen-to-power systems," Renewable and Sustainable Energy Reviews, vol. 189, p. 113930, Jan. 2024.

[48] International Energy Agency (IEA), Global Hydrogen Review 2025, Paris, Sep. 2025.

Table 15: Hydrogen value chain: Efficiencies and Indian considerations

Stage	Technology options	Indicative efficiency/metric	Indian considerations
Electrolysis	Alkaline, PEM, solid-oxide, AEM	60–70% (LHV); 50–55 kWh/kg	3 GW/yr electrolyser manufacturing awarded under SIGHT; alkaline slower to ramp than PEM
Compression / storage	350–700 bar vessels; salt or lined-rock caverns; pipelines	88–95%	Limited salt formations; lined-rock caverns and pipelines at study stage
Carrier conversion	Ammonia (Haber–Bosch), methanol, LOHC	Ammonia synthesis 10–15% energy penalty; cracking back to H_2 adds losses	Green ammonia auctions discovered ≈₹49.75/kg (2025–26)
Reconversion	Fuel cells (PEM, SOFC), H_2/NH_3 turbines, co-firing	35–60%	Ammonia co-firing trials in coal plants; long-term P2H2P
Overall P2H2P	—	≈25–40% round trip	Seasonal/strategic reserve only; direct industrial use is higher value

2.7.4 Electrical Energy Storage: Supercapacitors and SMES

Supercapacitors store energy electrostatically and can deliver very high power for seconds to minutes, with 10^5–10^6 cycles and millisecond response times. They are useful for power quality, ride-through, smoothing of very fast PV fluctuations and hybridisation with BESS. Superconducting magnetic energy storage (SMES) stores energy in the magnetic field of a superconducting coil. Its cryogenic requirements and cost limit its use to niche and research applications.

In India, supercapacitors may be useful for industrial power quality, rapid power fluctuations and specialised hybrid storage applications. Their limited energy duration restricts their role in bulk grid balancing. SMES remains a niche option with significant cost and cryogenic-system constraints.

2.8. Safety of Storage Technologies and Applicable Standards

2.8.1 BESS Hazards

Thermal runaway, fire propagation and accumulation of flammable gases are important safety risks for grid-scale lithium-ion BESS. These risks are particularly relevant to Indian BESS installations that are exposed to high ambient temperatures, dust, humidity and site-specific environmental conditions. Appropriate thermal management, ventilation, fire protection and emergency access must be incorporated into system design. The three major consequences that may follow are:

- **Propagation** from the failing cell to neighbouring cells, modules and racks, which cell spacing, thermal barriers and cooling design must prevent.
- **Fire**, which may be difficult to extinguish because heat generation continues inside cells.
- **Explosion** caused by ignition of accumulated off gases like hydrogen, carbon monoxide, methane and other hydrocarbons, in an enclosed container, requiring adequate gas detection, ventilation and explosion protection.

The Indian BESS installations, which is being deployed after these lessons were learned, should adopt current-generation standards from the outset. Safety assessments must consider complete BESS installations rather than

relying solely on cell-level certification or the comparatively favourable thermal stability of a particular battery chemistry. The CEA (Measures relating to Safety and Electric Supply) Amendment Regulations, 2026 introduced BESS-specific safety provisions. Compliance assessments should address battery chemistry, enclosure configuration, fault protection, fire and explosion hazards, emergency procedures and applicable safety requirements. For Indian utilities and procurers, fire-safety test reports should be reviewed against the actual container design, battery configuration and installation conditions. International standards such as UL 9540A and NFPA 855 should not automatically be treated as mandatory Indian legal requirements unless incorporated into applicable regulations, approvals or contractual specifications.

2.8.2 Safety Design and Testing

Key elements of BESS safety design include: cell selection and certification (IEC 62619, UL 1973)[49]; large-scale fire testing according to UL 9540A, which characterises cell-, module-, unit- and installation-level thermal-runaway and propagation behaviour and provides the data for spacing and explosion-control design[50]; system certification to UL 9540 or IEC 62933-5-2[51]; installation according to NFPA 855, which specifies separation distances, maximum energy per enclosure, explosion control, detection and suppression, and emergency-response planning[52]; multi-level detection (cell voltage/temperature via BMS, off-gas detection, smoke and heat detection); and suppression suited to lithium-ion fires. Site-level measures include separation from occupied buildings, access for fire services, water supply, drainage and containment of fire-water run-off, and a site-specific emergency response plan developed with local fire services. CEA (Measures relating to Safety and Electric Supply) Amendment Regulations, 2026 introduced BESS-specific safety provisions. Compliance assessments should address battery chemistry, enclosure configuration, fault protection, fire and explosion hazards, emergency procedures and applicable safety requirements.

2.8.3 Safety of other technologies

Other technologies have different hazard profiles: PSP involves dam-safety, flooding, landslide and tunnelling risks governed in India by the Dam Safety Act, 2021[53]; CAES and LAES involve high-pressure and cryogenic equipment; hydrogen is flammable and embrittles some metals, and in India is regulated by PESO under the Gas Cylinders Rules and Static and Mobile Pressure Vessels Rules; ammonia is toxic; flow batteries contain acidic electrolytes requiring bunding and spill control; NaS batteries operate at elevated temperatures with molten sodium; and flywheels require burst containment. In India, site-specific risk assessments are particularly important for PSPs in geologically sensitive terrain, pressure-based storage near industrial facilities and thermal storage integrated with high-temperature industrial processes. The applicable safety framework must reflect the technology and location rather than impose identical requirements on all ESS categories.

2.8.4 Standards and regulations

Table 16 summarises the international and Indian standards relevant to storage. Building on the CEA (Measures relating to Safety and Electric Supply) Regulations, 2023[54], India has made significant progress in 2026: the CEA's (Measures relating to Safety and Electric Supply) Amendment Regulations, 2026, introduced a BESS safety framework, including specific safety requirements for BESS installations[55].

[49]IEC 62619:2022, Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications.

[50]UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (5th ed., 2025), and UL 9540, Energy Storage Systems and Equipment.

[51]IEC 62933 series, Electrical energy storage (EES) systems – Parts 1 (vocabulary), 2-1 (unit parameters and testing), 3-1 (planning and performance assessment), 4 (environmental issues) and 5-2 (safety requirements for grid-integrated electrochemical systems).

[52]NFPA 855, Standard for the Installation of Stationary Energy Storage Systems, National Fire Protection Association, 2026 edition.

[53]Ministry of Law and Justice, Government of India, "The Dam Safety Act, 2021," Act No. 41 of 2021, The Gazette of India: Extraordinary, Part II, Sec. 1, no. 58, Dec. 14, 2021.

[54]Central Electricity Authority (CEA), (Measures relating to Safety and Electric Supply) Regulations, 2023.

[55] Central Electricity Authority (CEA), "Central Electricity Authority (Measures Relating to Safety and Electric Supply) Amendment Regulations, 2026," Notification F. No. CEA-PS-16/1/2021-CEI Division, Ministry of Power, Government of India, New Delhi, Mar. 27, 2026.

Gaps remain in mandatory large-scale fire testing (UL 9540A-type data) as a condition of connection, in harmonised Indian (BIS) adoption of the IEC 62933 series, in explicit separation-distance rules, and in emergency-response training for local fire services. The CEA has also issued guidance for training fire-safety officials for BESS installations. Project specifications should clearly distinguish notified Indian regulations from draft proposals, voluntary international standards and additional contractual requirements.

Table 16: Key standards and regulations for storage safety, performance and grid integration

Area	International standards	Indian regulations/status
Cell and battery safety	IEC 62619; UL 1973; UN 38.3 (transport)	Applicable BIS/IS standards and CEA BESS safety requirements; battery transport requirements to be assessed separately
System safety	IEC 62933-5-1/-5-2; UL 9540; UL 9540A (fire propagation testing)	CEA Safety Amendment Regulations 2026 (BESS safety framework); UL 9540A data increasingly required in tenders
Installation and fire protection	NFPA 855; NFPA 68/69; IEC 62485-2 (lead-acid)	National Building Code (fire); state fire-service NOCs; CEA BESS safety provisions and applicable site-specific fire approvals
Performance and testing	IEC 62933-2-1; IEC 62933-3-1; IEEE 2030.2.1	CEA Technical Standards for Construction Amendment Regulations, 2026; specific BESS performance obligations and commencement provisions require clause-level confirmation
Grid interconnection	IEEE 2800-2022; IEEE 1547-2018; ENTSO-E NC RfG; national grid codes	CEA Technical Standards for Connectivity (2007, amended 2013/2019/2023; draft 2026); IEGC 2023
Grid-forming	AEMO voluntary GFM specification; NESO GC0137; NERC and UNIFI specifications; ERCOT NOGRR 272	CEA advisory (Jul 2026); draft connectivity regulations 2026
Power quality	IEEE 519-2022; IEC 61000 series	CEA connectivity standards refer to IEEE 519 limits
Communications and cybersecurity	IEC 61850; IEC 60870-5-104; IEC 62351; IEC 62443; NERC CIP	CEA cybersecurity guidelines (2021) and draft regulations (2024); CERT-In directions (2022)
Environment and end-of-life	EU Battery Regulation 2023/1542; IEC 62933-4	Battery Waste Management Rules 2022 (EPR)
Dams and hydro	ICOLD bulletins	Dam Safety Act 2021; CEA DPR guidelines for PSP (v3.0, 2024)

Data Compiled from Multiple Sources

Safety compliance for Indian ESS projects must be assessed at the system and installation levels. Applicable requirements depend on technology, connection voltage, location, operating configuration and relevant statutory approvals.

Chapter 3.

RE Growth & Flexibility Requirements in India



India's rapid RE expansion is changing net-load profiles, ramping requirements and power-system operating conditions. Geographic concentration, renewable-generation variability, transmission constraints and emerging demand patterns create distinct flexibility requirements across regions and timescales. Energy storage requirements must therefore be assessed against these operating conditions, including energy balancing, network constraints, system stability and resource adequacy.

3.1. Renewable Growth and Geographic Concentration

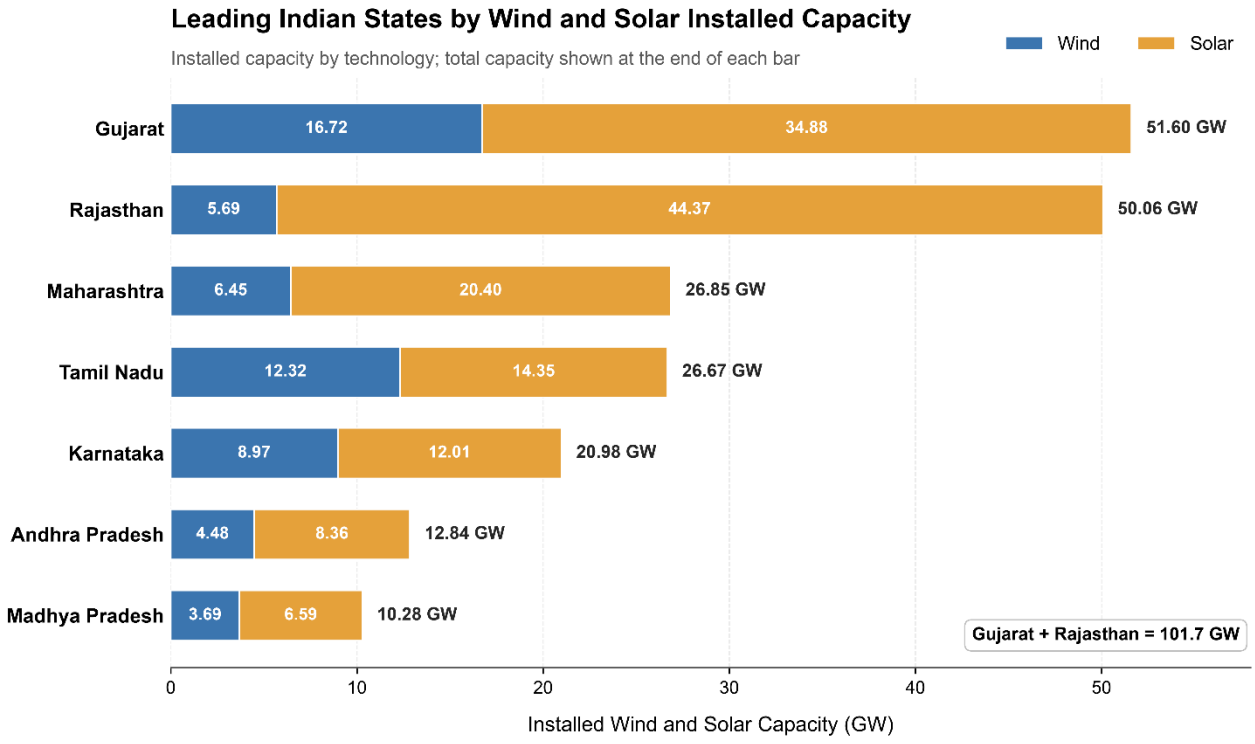
India's RE deployment accelerated markedly after 2023, supported by favourable policy and regulatory measures, the expansion of domestic manufacturing capacity, sustained investment, and a stronger national push towards achieving long-term clean-energy and decarbonisation targets. Installed Solar capacity increased from about 28 GW in March 2019 to 150.26 GW in March 2026 and 168.04 GW in August 2026, while wind increased from about 35.6 GW to 58.52 GW over the same period[56]. FY 2025-26 set records of about 44 GW of solar and 6 GW of wind additions, and India added record solar capacity in the first half of calendar 2026.[57]

RE capacity is heavily concentrated in five western and southern states, as shown in Figure 20.[58] High solar irradiation, favourable wind regimes and land availability contribute to this concentration, particularly in Rajasthan, Gujarat, Karnataka and Tamil Nadu. This geographic concentration contributes to locational flexibility, transmission-congestion and system-strength challenges, particularly where large RE injections are remote from major load centres. Where RE generation evacuation capacity is constrained, high RE injections from pooling substations can increase curtailment and network loading. Weak-grid conditions at certain pooling stations also create distinct system-strength and voltage-control requirements. Storage siting must therefore consider local power-flow constraints, evacuation capability and network stability. Figure 20 shows the state wise installed capacity of solar PV and Wind as of August 2026 in India.

[56]Ministry of New and Renewable Energy (MNRE), "Physical Achievements – cumulative physical progress as on 31.03.2026" and year-end releases for 31 March 2019–2025, Government of India. Ministry of New and Renewable Energy (MNRE), "Physical Achievements – programme/scheme-wise cumulative physical progress as on 31.08.2026", Government of India, Sep. 2026.

[57]Central Electricity Authority, "Monthly installed capacity reports," Ministry of Power, Government of India, New Delhi, India, 2026.

[58]NITI Aayog, India Climate & Energy Dashboard (ICED), 2026.



Note: Total represents combined installed wind and solar capacity (as on 31.08.2026).

Figure 20: Leading states by total installed renewable capacity, 31 August 2026 (GW)

(Source: This figure has been plotted using data sources from MNRE state-wise wind and solar installed capacity)

Distributed solar is also growing rapidly: grid-connected rooftop solar reached 32.59 GW by August 2026, supported by the PM Surya Ghar scheme, and off-grid solar reached 6.63 GW[59]. Agricultural feeder solarisation under PM-KUSUM Component C supports reliable daytime electricity supply for irrigation, although the resulting change in pumping demand depends on feeder operation and agricultural consumption patterns.[60] Distributed solar is largely invisible to system operators in real time; it depresses the midday load seen by the transmission system, making the net-load trough deeper and the evening ramp steeper, and it creates reverse power flows and voltage-rise problems on distribution feeders. Where adequate telemetry is unavailable, behind-the-meter solar generation may not be fully visible to system operators. Rooftop solar reduces daytime metered demand and can increase evening net-demand pickup as its output declines. High local penetration can also introduce reverse power flows and voltage-control challenges, depending on feeder loading and network configuration

3.2. Capacity and Generation Scenarios

Table 17 and Figure 21 present the source-wise installed capacity for the actual August 2026 position and the principal planning horizons considered in this report. Actual capacities are based primarily on CEA and MNRE statistics, while projections for 2026–27, 2031–32 and 2035–36 are drawn from the CEA's National Generation Adequacy Plan (NGAP), 2026, providing a consistent planning basis across these horizons. The Ministry of Power has separately indicated an installed capacity requirement of approximately 2,100 GW against projected peak demand of about 708 GW by 2047.[61] The Nuclear Energy Mission targets of 100 GW of nuclear capacity by 2047[62], and long-term assessments

[59]Ministry of New and Renewable Energy (MNRE), "Physical Achievements – programme/scheme-wise cumulative physical progress as on 31.08.2026", Government of India, Sep. 2026.

[60]Ministry of New and Renewable Energy (MNRE), Government of India, "Guidelines for implementation of Component-C of PM-KUSUM Scheme on Solarization of Grid-connected Agricultural Pumps," Office Memorandum, F. No. 32/645/2017-SPV Division, New Delhi, India, Nov. 8, 2019.

[61] Press Information Bureau (PIB), Ministry of Power, "Shri Manohar Lal addresses Brainstorming Session on the Indian Power Sector Scenario 2047," 14 Oct. 2024.

[62] Government of India, Nuclear Energy Mission for Viksit Bharat, targeting 100 GW of nuclear power capacity by 2047.

indicating very large-scale expansion of solar, wind and energy storage capacity. The 2047 values should therefore be interpreted as an indicative planning envelope rather than an official capacity-expansion scenario.

Table 17: Installed capacity scenarios by source (GW)

Source	Actual, Aug 2026	2026–27 (CEA NGAP 2026)	2031–32 (CEA NGAP 2026)	2035–36 (CEA NGAP 2026)
Coal + lignite	230.8	237	291	315
Gas	19.43	20	20	20
Nuclear	8.78	10	16	22
Large hydro (excl. PSP)	44.64	48	61	78
Solar	168.04	176	356	509
Wind	58.52	63	113	155
Other RE (biomass, waste + small hydro)	16.93	17	20	22
Total generating capacity (excl. BESS and PSP)*	554.54	571	877	1,121
BESS (GW / GWh)	3.03 / 9.08	6 / 24	37 / 147	80 / 321
PSP storage (GW / GWh)	7.43 / —	5 / 27	44 / 263	94 / 567
Peak demand (GW)	—	≈289	≈388	459

Data Compiled from Multiple Sources

**The CEA NGAP generating-capacity totals exclude separately reported ESS capacities. The August 2026 actual installed-capacity total includes installed PSP capacity; therefore, the actual and projected totals are not presented on an identical accounting basis.*

The projected large-hydro and PSP categories follow CEA's planning classifications, which may differ from the installed-capacity classification of existing pumped-storage units. The 2026–27 PSP projection should not be interpreted as a reduction in the physical installed PSP fleet. Rooftop and off-grid solar are already included in total solar capacity.

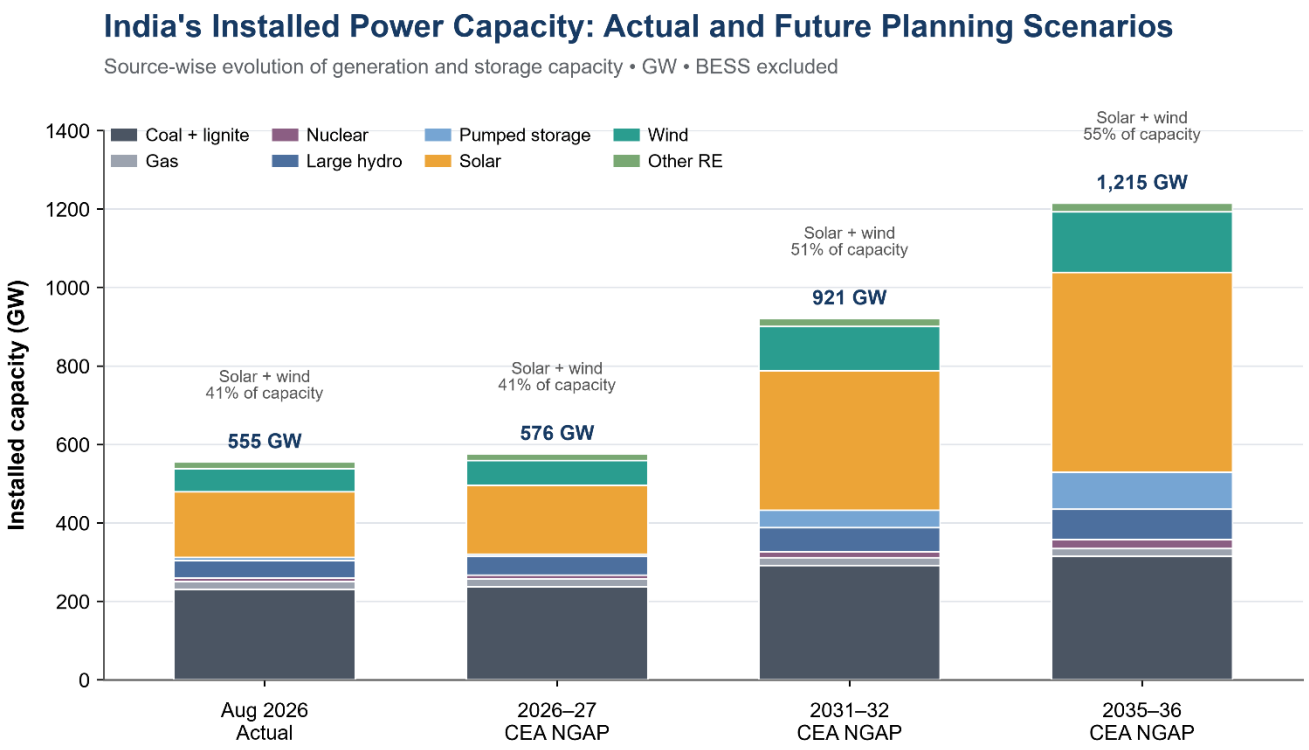


Figure 21: Installed capacity by source: 2026 (actual) and planning scenarios for 2026-27, 2031-32, & 2035-36

(Source: This figure has been plotted using data sources from Compiled from CEA installed-capacity statistics (August 2026), National Electricity Plan (2023), National Generation Adequacy Plan (2026), LT-NRAP (2026), and MNRE ESS outlook)

Capacity does not translate directly into energy. Table 18 converts the capacity scenarios into indicative annual generation shares using representative capacity utilisation factors. These shares are independently calculated illustrations and should not be interpreted as CEA generation forecasts. Under the stated illustrative utilisation assumptions, the combined solar and wind share increases from approximately 24% in 2026–27 to 33% in 2031–32 and 39% in 2035–36. Actual generation shares will depend on dispatch, renewable availability, curtailment, system constraints and storage operation.

Instantaneous RE penetration may be substantially higher than the annual average.By 2031-32, midday solar output on clear days could approach 70–80% of all-India demand, compared with about 41% (wind and solar together) at midday in March 2026. Future magnitude of RE penetration must be assessed using time-resolved generation and demand profiles rather than annual capacity utilisation factors.

Table 18: Indicative annual generation shares by source (%)

Source (assumed CUF for projections)	2025 actual	2026-27	2031-32	2035-36	2047 (indicative)
Coal and lignite (≈55–58%)	≈73 (fossil total)	≈59	≈49	≈46	20–30
Gas (10–15%)	incl. above	≈1	≈1	≈1	≈1
Nuclear (75%)	≈3	≈4	≈5	≈4	≈12–15
Large hydro (≈37%)	≈8	≈8	≈8	≈8	≈6–7

Solar (≈19.5–20%)	9.4	≈16	≈23	≈27	35–40
Wind (≈26–30%)	≈5	≈8	≈11	≈12	13–18
Biomass and small hydro (40–50%)	≈2	≈4	≈3	≈3	≈2
Solar + wind	**14**	**≈24**	**≈34**	**≈39**	**≈50–55**

Data Compiled from Multiple Sources

3.3. RE Penetration Levels

India's non-fossil installed-capacity share reached approximately 54.9% by August 2026, with solar and wind together accounting for 40.9%. However, non-fossil sources contributed 29.2% of electricity generation in FY 2025–26, including approximately 15.1% from solar and wind. The difference highlights the importance of generation profiles and available dispatchable resources alongside installed capacity. These figures represent different reporting periods and should not be treated as contemporaneous measurements.

Instantaneous RE penetration can be considerably higher than its annual generation share. On 29 July 2025, RE generation, including hydro, was reported to meet 51.5% of all-India demand of approximately 203 GW. Such operating conditions increase the importance of ramping capability, reserves and dynamic stability assessment. Table 25 summarises the planning relevance of the three measures.

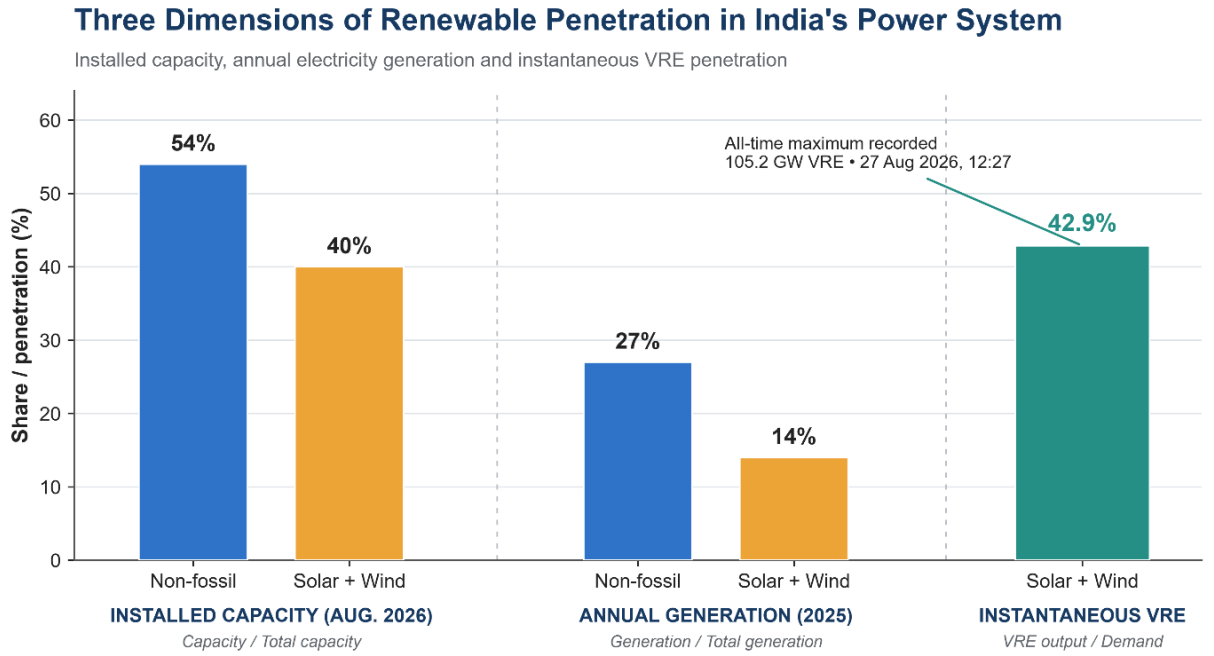


Figure 22: Three measures of renewable penetration in India, 2025-26: installed-capacity share, annual energy share and instantaneous share.

Sources: Data Compiled from Multiple Sources

Table 19: Penetration metrics and their planning uses

Metric	Definition	Value in India	Planning use
Installed-capacity share	[Non-fossil (or VRE) GW] / [total GW]	54.9% non-fossil; 40.9% solar + wind (Jun 2026)	Capacity expansion and long-term resource planning

Annual energy share	[Annual VRE (or clean) TWh] / [total TWh]	29.2% non-fossil; 15.1% solar and wind	Energy adequacy, seasonal balancing and energy-mix assessment
Instantaneous VRE share	[VRE MW] / [demand MW at a moment]	41% (6 Mar 2026 midday); 34% RE at the 270.8 GW peak	Ramping, curtailment, reserve requirements
Short-circuit ratio (SCR) at the pooling station	Three-phase short-circuit capacity (MVA) / rated connected CBR capacity (MVA)	SCR 2 to 5 at pooling stations near major RE complex	Weak-grid assessment, system-strength evaluation and grid-forming capability requirements

Data Compiled from Multiple Sources

3.4. Load, Net load and the Indian Duck and the Camel Curve

3.4.1 All-India Net-Load Curve

Net load is defined as the demand, $D(t)$, remaining after subtracting variable renewable generation, constituting both solar, $P_{solar}(t)$ and wind, $P_{wind}(t)$:

$$NL(t) = D(t) - P_{solar}(t) - P_{wind}(t)$$

It represents the residual demand to be balanced by other conventional generation, storage and power-system exchanges. As generation from solar PV has increased, the Indian net-load curve has developed a pronounced midday trough and steep morning and evening ramps. Because India's winter demand has a morning peak and its summer demand an afternoon-to-night plateau, the net-load curve exhibits a "camel" shape in winter i.e. two humps, morning and evening, and a "duck" in summer. The EAC-PM working paper, *The Duck and the Camel* (July 2026), based on 15-minute Grid-India SCADA data for 2023–2026, provides a detailed public quantification to date as summarised in Table 20[63]. The study uses demand minus solar generation and reports monthly average operating profiles. Its values therefore differ from net load calculated after subtracting both solar and wind.

Table 20: Evolution of all-India net-load ramps and troughs (GW), 2023–2026

Metric (window)	2023	2025	2026	Interpretation
Summer morning ramp-down, 06:00–11:00 (May)	−18.5	−37.4	−52.6	Solar-adjusted net load declines by approximately 53 GW over five hours
Summer evening ramp-up, 13:00–20:00 (May)	35.7	58.3	73.7	Doubled in three years; average ≈10.5 GW/h
Winter morning ramp-up, 04:00–07:30 (Jan)	41.3	53.4	55.5	Pre-dawn ramp ≈16 GW/h
Winter morning ramp-down, 07:30–13:30 (Jan)	−25.5	−49.7	−64.0	Steep solar-driven decline

[63]Economic Advisory Council to the Prime Minister (EAC-PM), "The Duck and the Camel: Tracing the Net Load on the Indian Power Grid", Working Paper, Jul. 2026.

Winter evening ramp-up, 13:30–18:30 (Jan)	27.1	49.7	64.7	≈13 GW/h average; steepest sustained ramp among the listed monthly-average periods
Minimum net load, May (midday trough)	153	147	153	Midday trough remains near 150 GW despite rising demand
Minimum net load, January (midday trough)	—	—	143	Below overnight net load (136–140 GW)

Data Compiled from Multiple Sources

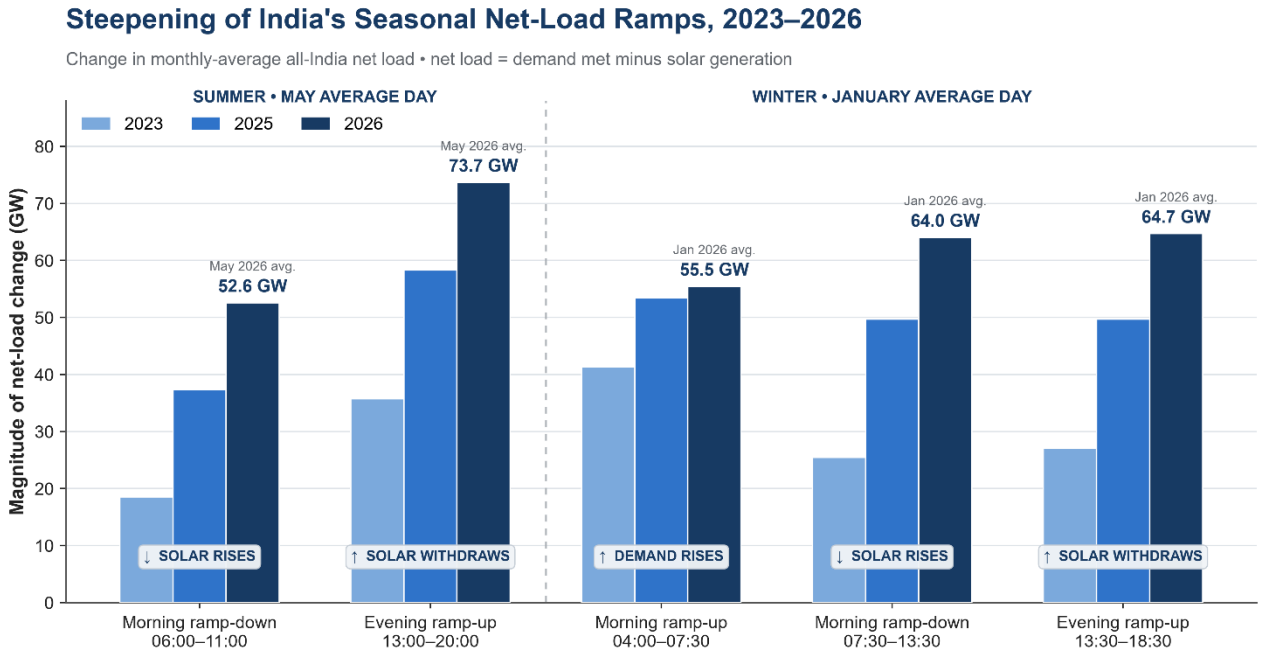


Figure 23: Steepening of all-India net-load ramps, 2023–2026 (GW change over the stated window)

(Source: This figure has been plotted using data sources from EAC-PM, The Duck and the Camel: Tracing the Net Load on the Indian Power Grid (July 2026))

Representative 15-minute demand and net-load profiles illustrate the increasingly pronounced intraday flexibility requirement of the Indian power system under different seasonal and renewable-generation conditions. The principal characteristics of the five representative operating days are summarised in Table 21. On 21 May 2026, when all-India demand reached a record 270.8 GW at 15:45, net load declined to 159.4 GW at 11:15 before recovering by 71.3 GW to 230.7 GW at 22:45, equivalent to an average recovery of ≈6.2 GW/h[64]. The challenge becomes considerably sharper on high-renewable days. On 3 March, solar generation reached 80.9 GW, corresponding to 39.0% of demand at 13:30, while net load fell to 123.4 GW before increasing by ≈82.0 GW towards the evening. Similarly, on 27 August, combined solar and wind generation reached 105.0 GW, or 42.76% of all-India demand at 12:30, with net load reaching 140.6 GW and subsequently recovering by ≈73.4 GW.

The profiles also demonstrate that the flexibility requirement is not confined to high-solar summer conditions. On 23 January, VRE supplied 37.43% of demand at 12:00, and net load subsequently recovered by ≈76.3 GW. On the 12 July maximum wind-penetration day, wind generation reached 36.3 GW (17.0% of demand), while the daily net-load minimum of 135.0 GW was followed by a ≈75.0 GW recovery. Across these representative conditions, the Indian grid

[64]Economic Advisory Council to the Prime Minister (EAC-PM), "The Duck and the Camel: Tracing the Net Load on the Indian Power Grid", Working Paper, Jul. 2026.

therefore exhibits recurrent intraday net-load recoveries of roughly 70–82 GW, although their timing and composition vary substantially with season, demand and the solar–wind generation mix.

Table 21: Net-load characteristics and renewable-energy penetration across representative Indian grid operating conditions in 2026

Representative day	System condition	RE / Demand milestone	Minimum net load	Subsequent net-load recovery
23 Jan. 2026	High-VRE winter day	37.43% VRE	126.1 GW	76.3 GW
3 Mar. 2026	Maximum solar penetration [Till July 2026]	39.0% solar	123.4 GW	82.0 GW
21 May 2026	Record-demand day	Peak demand: 270.8 GW	159.4 GW	71.3 GW
12 Jul. 2026	Maximum wind penetration	17.0% wind	135.0 GW	75.0 GW
27 Aug. 2026	Maximum VRE penetration	42.76% VRE	140.6 GW	73.4 GW

Data Compiled from Multiple Sources

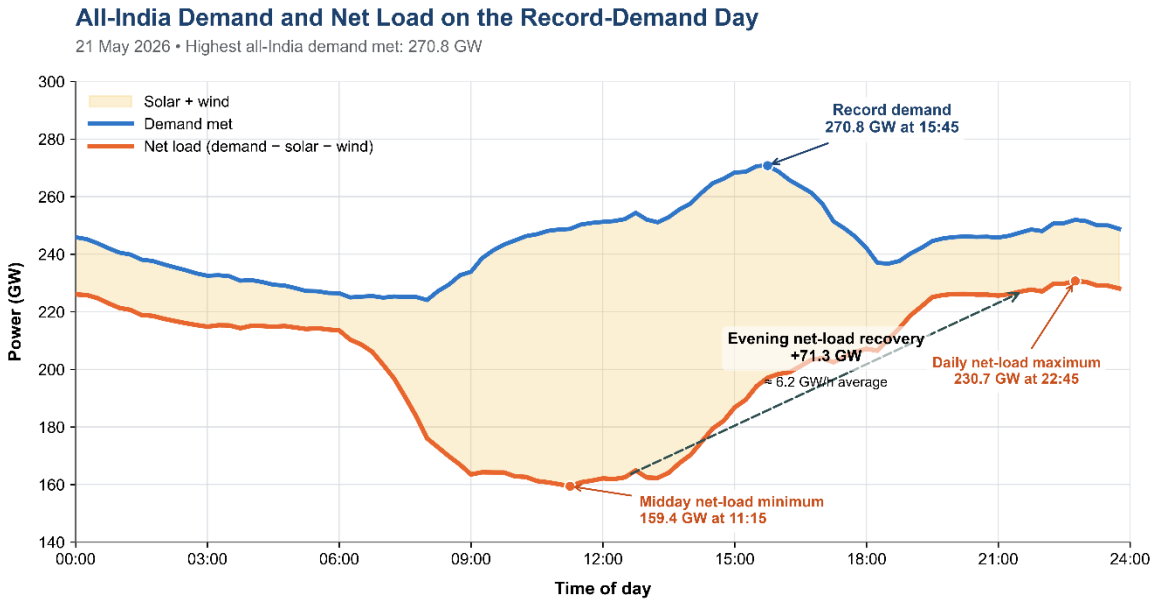


Figure 24: Schematic reconstruction of all-India net load achieved on record-demand day on 21 May 2026

(Source: This figure has been plotted using data sources from data sourced from NLDC)

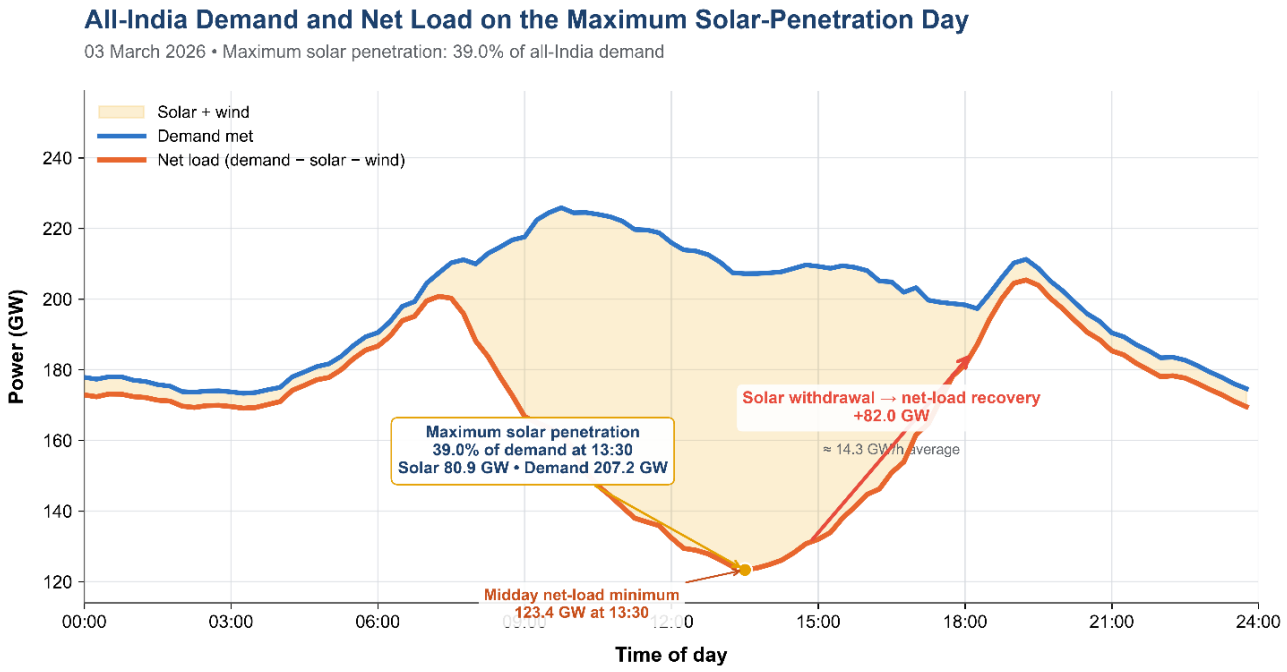


Figure 25: Schematic reconstruction of all-India net load achieved on record-demand day on 3 March 2026

(Source: This figure has been plotted using data sources from data sourced from NLDC)

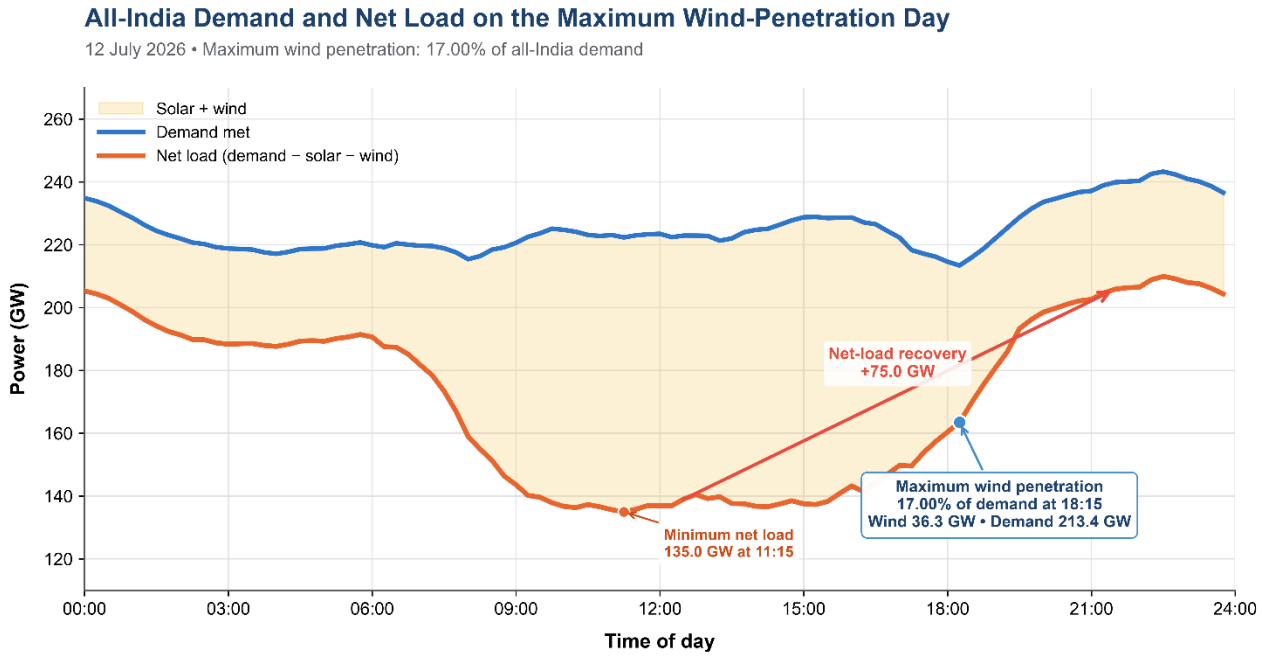


Figure 26: Schematic reconstruction of all-India net load achieved on record-demand day on 12 July 2026

(Source: This figure has been plotted using data sources from data sourced from NLDC)

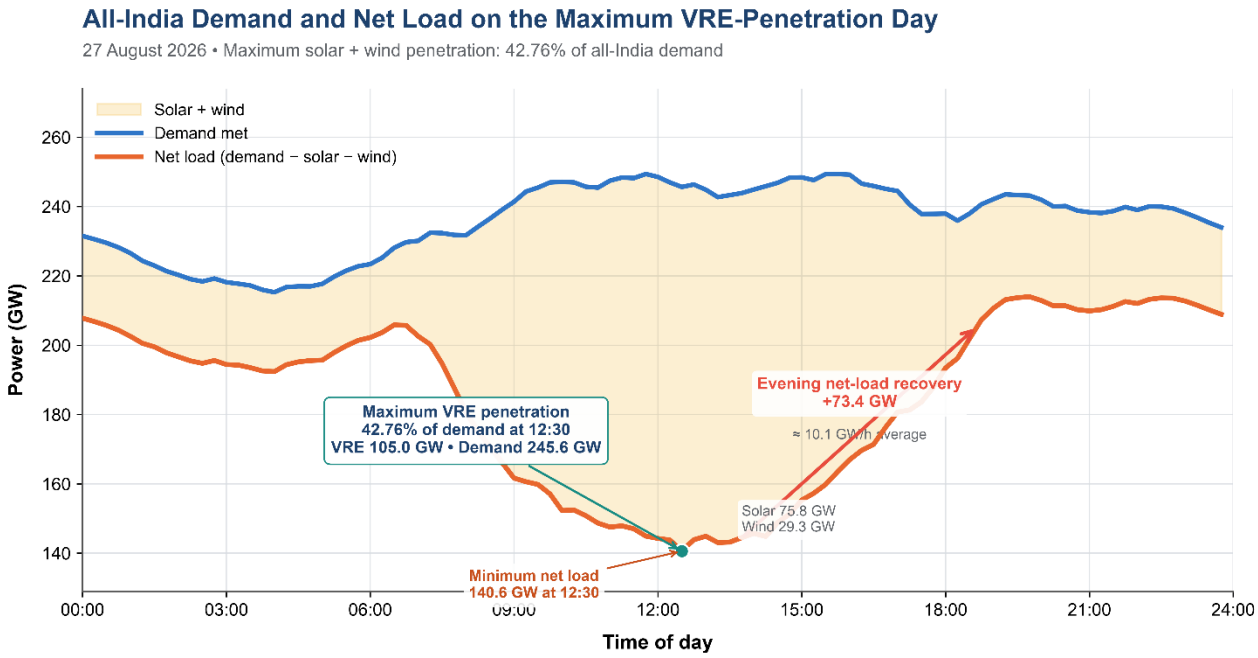


Figure 27: Schematic reconstruction of all-India net load achieved on record-demand day on 27 August 2026

(Source: This figure has been plotted using data sources from data sourced from NLDC)

These characteristics have direct implications for energy-storage planning and system flexibility. The emerging requirement cannot be expressed solely in terms of installed storage capacity; it must consider the required power rating, energy capacity, discharge duration, response capability and cycling profile. Storage can consume energy during periods of depressed net load and subsequently discharge during the recovery period, thereby reducing thermal-generation ramping requirements, RE curtailment and dependence on other flexible resources. The achievable benefits of ESS depend on available charging energy, storage location and dispatch constraints.

Importantly, however, the magnitude of the observed net-load recovery should not be interpreted directly as the required storage power capacity. The flexibility requirement can be shared among energy storage, flexible conventional generation, hydropower, demand response, inter-regional transfers, and RE generation controls. Storage requirements should therefore be determined from the residual flexibility requirement after accounting for these complementary resources, together with the magnitude, rate and duration of the net-load variation.

3.4.2 State-level patterns: Rajasthan, Gujarat, Karnataka and Tamil Nadu

State-level net-load behaviour varies with renewable generation, demand patterns and inter-state power transfers. The analysis of 2025 SLDC data ranks Rajasthan as the state with steepest evening net-load ramp of 19.6 GW and the deepest midday turn-down, which reached such a depth that its midday net load becomes negative of about −32% of peak load, making it India's first "negative-net-load" state in practice, as illustrated in Figure 28, for a typical summer day in March for the years 2021-2025 [65]. Gujarat is following a similar trend with11.1 GW evening ramp and 53% midday turn-down, followed by Karnataka and Tamil Nadu with about 5.0 GW evening ramp each, with turndowns of 46% and 31% respectively [65]. Table 22 summarises the distinctive characteristics of these four states and their implications for energy storage.

[65]EnergyMap.in, "India's duck & camel — net load, 2021–2026" (state-level net-load indicators derived from Grid-India/SLDC data), accessed Sep. 2026. https://www.energymap.in/duck-curve [Accessed: 29 Sep 2026]

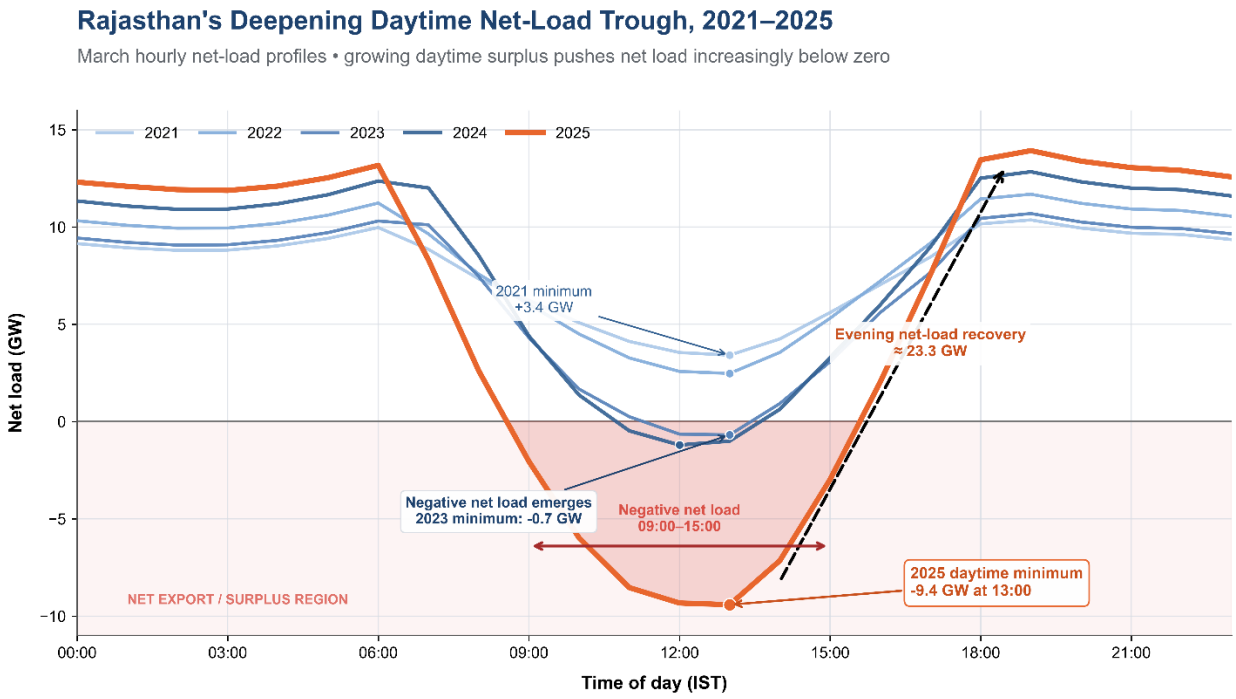


Figure 28: Deepening daytime net-load trough for Rajasthan for 2021-2025 (data presented for a typical day in March)[65]

Table 22 Net-load characteristics of four high-RE states and storage implications

State	Net-load characteristics (2025–26)	Principal constraints	Storage implications
Rajasthan	Evening ramp ≈19.6 GW; midday net load negative (exports); ≈50.7 GW RE installed; severe midday curtailment in 2025 (up to 50–55% at some sites)	Evacuation (23 GW connected vs ≈18.35 GW effective capability in late 2025), low SCR at pooling stations, oscillations	Storage near RE pooling stations where charging and subsequent evacuation are feasible. Load-centre storage for peak support where justified by network studies. Compare storage with transmission reinforcement and other flexibility resources.
Gujarat	Evening ramp ≈11.1 GW; turn-down 53%; ≈53.6 GW RE; Khavda complex >15 GW	Weak grid at Khavda (SCR 2.58–4.65), 8,963 MW loss event (May 2026), long evacuation corridors	GFM BESS at Khavda; synchronous condensers/STATCOMs; state VGF BESS (4 GWh); evening-peak BESS near Ahmedabad–Surat load centres
Karnataka	Evening ramp ≈5.0 GW; turn-down 46%; RE met up to ~80% of demand on some 2025 days	Minimum-load constraints of thermal plants; intra-state congestion	Sharavathy (2,000 MW) and Saundatti (1,600 MW) PSPs; standalone BESS (VGF 2 GWh)
Tamil Nadu	Evening ramp ≈5.0 GW; turn-down 31%; strong monsoon wind (Jun–Sep)	Seasonal wind surplus; curtailment disputes; limited export capacity	Kundah PSP (500 MW); 4-h, 1.5-cycle BESS (TNGECL); seasonal complementarity with solar

Data Compiled from Multiple Sources

The state-level comparison shows that storage requirements cannot be inferred from renewable penetration or evening ramp magnitude alone. Effective storage deployment depends on transmission constraints, the location of available charging energy, demand profiles and the required operating services.

3.4.3 Quantifying the Duck: Metrics and Storage Implications

A duck curve should be characterised using a consistent set of quantitative metrics to support operational planning and ensure that sufficient flexible resources are available across critical periods. Table 23 defines the key metrics required to characterise net-load behaviour and translate the resulting flexibility requirements into appropriate energy-storage sizing and planning decisions. These metrics must use consistent net-load definitions, time intervals and operating conditions.

Table 23: Recommended metrics for quantifying the net-load curve and their storage relevance

Metric	Definition	All-India 2026 value (where available)	Storage relevance
Minimum net load	Lowest net load in the day/season	January midday net-load minimum of approximately 143 GW; morning and evening ramps remain important.	Identifies minimum-load constraints and potential ESS charging periods, subject to network availability.
Maximum net load	Highest net load (usually night)	Approximately 252.0 GW (21 May 2026)	Contributes to non-solar-hour capacity and dispatch requirements.
Maximum 15-minute ramp	Largest change between consecutive 15-min blocks	Not independently calculated from the available 15-minute records.	Sizes fast-ramping MW (BESS, hydro)
Maximum 1-hour and 3-hour ramps	Largest change over 1 h and 3 h	≈10-16 GW/h averages over evening/morning windows	Sizes ramping reserves and MW of storage
Evening net peak duration	Hours during which net load exceeds a threshold (e.g., 90% of daily max)	≈5–7 h in summer	Sets minimum storage duration for capacity credit
Surplus energy	Energy by which RE exceeds the absorbable level (demand − must-run minimum)	≈24 GWh/day curtailment in May 2026	Sets charging energy available; sizes MWh
Peak-to-off-peak spread	Net-load maximum minus minimum; price spread	≈83 GW (21 May 2026); DAM ₹1.11–9.71/kWh (May 2026 average range)	Arbitrage value
Net-load duration curve	Sorted hourly net loads over a year	To be published	Dimensions the storage fleet for adequacy

Data Compiled from Multiple Sources

Energy storage requirements depend on the residual flexibility needed after accounting for available conventional generation, hydropower, demand response and inter-regional transfers. Sizing must consider the required power response, usable discharge energy, charging availability, state-of-charge constraints and network location.

It is estimated that halving a single summer day's evening ramp would require about 130 GWh of discharge in the 13:00–20:00 window. An energy storage gap of about 155 GWh against the May 2026 evening ramp was estimated according to an analysis, compared with only 23.8 GWh/day of actual storage discharge[66]. The implication is that India will need an order of 100-150 GWh of *daily-cycling* storage in the late 2020s just to moderate the evening ramp, consistent with the NEP requirement of 236 GWh of BESS and 175 GWh of PSP by 2031-32. The comparison illustrates the increasing scale of India's flexibility challenge but does not establish a national storage-capacity requirement. Storage MW, usable MWh and operating duration must be determined through chronological system studies that account for available flexibility, charging opportunities, network constraints and storage performance.

3.5. Price Signals: Widening Daily Spread

Power-exchange prices increasingly provide a market-based signal of the value of intraday energy shifting. As illustrated in Figure 29, the IEX Day-Ahead Market (DAM) shows a pronounced widening of the price differential between solar-rich daytime periods and late-evening hours. The comparison uses monthly average prices for each 15-minute delivery block in May.

Based on the average 15-minute DAM price profile for May, the minimum-to-maximum price spread increased from ₹5.27/kWh in 2023 to ₹8.08/kWh in 2025 and ₹8.60/kWh in 2026. In May 2026, the minimum and maximum average prices were ₹1.11/kWh and ₹9.71/kWh, respectively. Thus, the gross intraday price spread increased by approximately 63% between May 2023 and May 2026, reflecting lower daytime prices and higher nighttime prices in the analysed profiles. The May 2026 maximum also approached the prevailing ₹10/kWh DAM price ceiling, which limits the observable upper price in the standard DAM[63].

On 21 May 2026, when India recorded its then-all-time peak demand of 270.8 GW, DAM power scheduled for 13:00 cleared at ₹1.56/kWh, whereas power scheduled for 18:30 cleared at the ₹10.00/kWh market ceiling, a difference of ₹8.44/kWh over 5.5 hours. This price pattern is consistent with the underlying net-load dynamics discussed in the preceding section. High solar output reduces daytime residual demand, while declining solar generation and evening demand recovery increase the need for dispatchable supply.

[66]Economic Advisory Council to the Prime Minister (EAC-PM), "The Duck and the Camel: Tracing the Net Load on the Indian Power Grid", Working Paper, Jul. 2026.

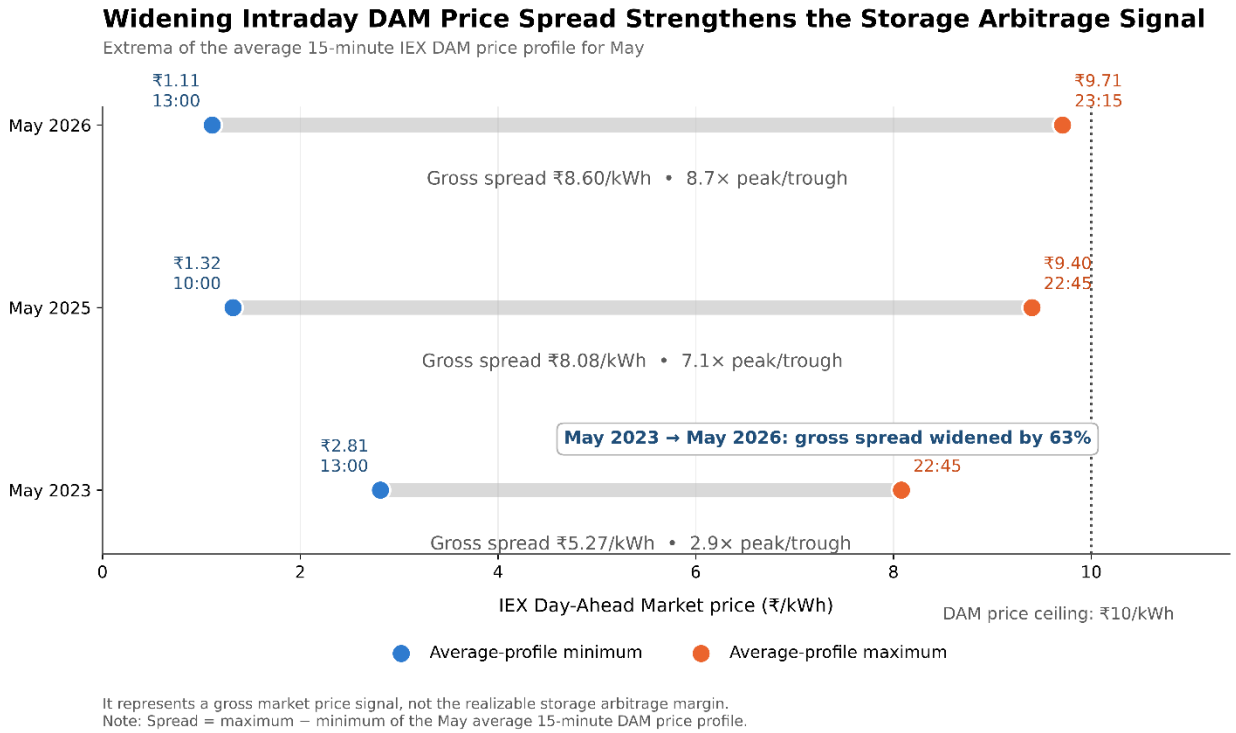


Figure 29: Widening intraday price spread in the IEX Day-Ahead Market (DAM), illustrating the strengthening market signal for energy shifting and storage arbitrage, May 2023–2026.

(Source: This figure has been plotted using data sources from EAC-PM, The Duck and the Camel: Tracing the Net Load on the Indian Power Grid (July 2026), using IEX Day-Ahead Market prices)

For energy storage, this widening temporal price differential creates a progressively stronger economic signal for energy arbitrage: storage can charge during low-price, solar-rich periods and discharge when net load and market prices recover. The value extends beyond arbitrage alone. Charging during periods of renewable surplus can reduce curtailment and provide downward flexibility, while subsequent discharge can reduce evening thermal ramping requirements and contribute to peak capacity and system adequacy. This role is already becoming relevant in India; Ember estimated that approximately 2.1 TWh of renewable generation was curtailed in FY2025–26 due to coal-fleet minimum-generation constraints, and that around 10 GWh of appropriately operated battery storage could have absorbed the identified surplus[67].

The price spread shown in Figure 29 should, however, be interpreted as a gross market signal rather than a directly realisable storage margin. Actual arbitrage revenues depend on the complete sequence of charging and discharging prices, round-trip efficiency, market charges, cycling and degradation costs, state-of-charge constraints, availability and the volume that can be cleared in each settlement block. Moreover, as storage deployment increases, arbitrage itself can compress the price differential by increasing demand during low-price periods and supply during high-price periods. Price spreads, therefore, demonstrate the potential market value of temporal flexibility, but do not by themselves establish the economic viability or required capacity of a storage project.

3.6. Variability, Uncertainty and Contingencies

India's growing RE penetration creates distinct flexibility requirements arising from predictable generation variability, forecast uncertainty and major grid disturbances. Solar withdrawal during evening hours and seasonal wind variations require energy balancing and ramping capability. Forecast errors during cloudy conditions, monsoon variability and heatwaves increase the need for operating reserves and intraday redispatch. Large generation-loss

[67] N. Rodrigues, Bottleneck to the Next Phase of Renewable Energy Growth in India, Ember, Jun. 17, 2026.

events, including those involving multiple inverter-based plants, introduce additional frequency-stability and system-security requirements. Three distinct phenomena drive the need for flexibility, as listed in Table 24[68]:

- **Variability:** It is the expected change in RE output and demand over time, the diurnal solar cycle, seasonal wind patterns and predictable load shapes. It is managed by proper unit commitment and economic dispatch, and energy storage addresses it by facilitating energy shifting.
- **Uncertainty:** It is the unexpected deviation of actual RE output or demand from forecasts, arising from cloud cover, convective storms, wind-speed changes, temperature-driven load and forecast model error. It is managed by reserves and intraday re-dispatch, and storage addresses it by providing fast, bidirectional reserves.
- **Contingencies:** These are sudden, discrete events, such as large generator or transmission line outages, or, increasingly, the simultaneous outages of many inverter-based plants during a fault. They are managed by inertia, fast and primary frequency response and contingency reserves. ESS addresses them via fast frequency response and grid-forming capability.

Table 24: Variability, uncertainty and contingency: characteristics and storage responses

Phenomenon	Examples in India	Metric	Timescale	Storage response
Variability	Solar diurnal cycle; monsoon wind; winter morning peak; summer evening peak	Net-load ramps; seasonal energy balance	Hours to seasons	Energy shifting (2–10 h); long-duration and seasonal storage
Uncertainty	Cloud-driven solar drops; monsoon wind forecast errors; heatwave demand surprises	Forecast error (MAE, RMSE, quantiles); reserve deployment	Minutes to day-ahead	Regulating and tertiary reserves (SRAS, TRAS); intraday rescheduling
Contingency	Unit trips; line trips; RE loss events (e.g., 9-GW event at Khavda, 13 May 2026)	RoCoF, nadir, reference contingency (4,500 MW)	Milliseconds to minutes	FFR, synthetic inertia (GFM), primary response, contingency reserve

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Forecasting horizons map onto these phenomena and onto different flexibility responses. Indian scheduling operates in 15-minute time blocks, with day-ahead and real-time markets and limited intraday schedule revisions for RE generators under the applicable grid code[69].

The NREL–POSOCO *Greening the Grid* study was among the first to show, for India, that forecasting, faster scheduling and balancing-area coordination substantially reduce the flexibility needed to integrate large RE shares[70]. Improved forecasting can reduce balancing costs and reserve deployment. However, reserve capacity and storage requirements must also account for credible forecast errors, contingencies and resource adequacy. Table 25 identifies the relevant Indian operational processes and potential storage applications across different planning horizons.

[68] P. J. 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, 100482, 2020.

[69] Central Electricity Regulatory Commission (Indian Electricity Grid Code) Regulations, 2023.

[70] National Renewable Energy Laboratory (NREL) and POSOCO, Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I – National Study, 2017.

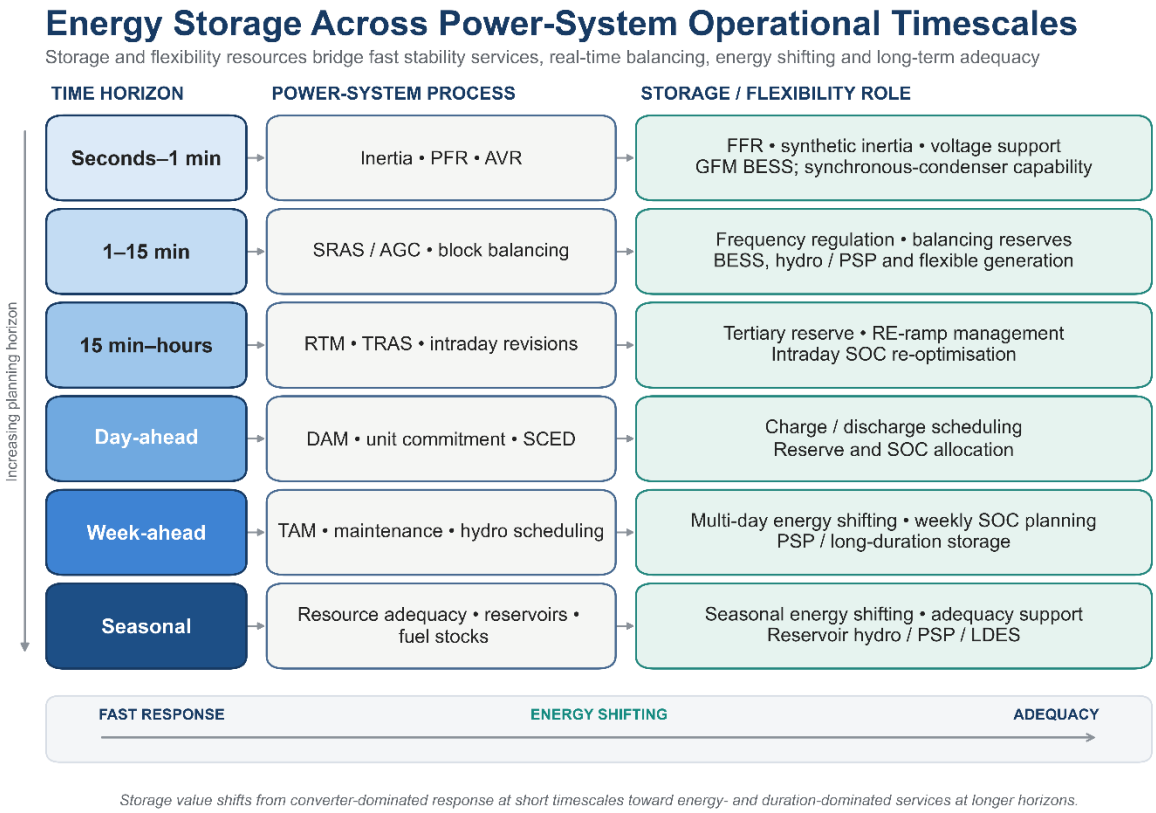


Figure 30: Forecasting horizons mapped to operational processes, flexibility products and storage responses

(Source: This figure has been plotted using data sources from CERC, Ancillary Services Regulations (2022), and Indian Electricity Grid Code (2023))

Table 25: Forecast horizons, operational processes and storage roles

Horizon	Operational process in India	Principal uncertainty	Storage / flexibility role
Seconds to 1 minute	Inertial and primary frequency response; AVR	Cloud transients, faults, and trips	FFR, synthetic inertia, voltage support (GFM BESS, PSP condenser mode)
1–15 minutes	SRAS (AGC), within-block balancing, DSM	Ramp errors, cloud fronts	Regulation (BESS, hydro, PSP), ramp-rate control at RE plants
15 minutes–hours (intraday)	RTM (half-hourly auctions), TRAS, intraday revisions	Intraday RE forecast error; demand surprises	Tertiary reserve; intraday re-optimisation of storage SOC
Day-ahead	DAM, unit commitment, SCED	Day-ahead RE and demand forecast error	Scheduling of storage charging/discharging; reserve allocation
Week-ahead	Term-ahead market, maintenance, hydro scheduling	Weather regimes, monsoon onset, heatwaves	Weekly SOC planning for PSP and LDES; fuel planning

Horizon	Operational process in India	Principal uncertainty	Storage / flexibility role
Seasonal / annual	Resource adequacy, hydro reservoir planning, coal stocking	Monsoon strength, drought, wind seasons, demand growth	Seasonal storage (reservoir hydro, H_2); adequacy procurement

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Storage participation in reserve services is subject to technical eligibility, communication, telemetry, available energy and applicable regulatory requirements. The timescales indicate the relevant operating processes rather than guaranteed response capabilities of every storage technology.

3.7. Curtailment: Evidence, Causes and Measurement

3.7.1 Recent evidence

Curtailment is the reduction of renewable output below the generation that would otherwise have been available. In India, it can arise from transmission or local evacuation constraints, system security limits, minimum generation constraints, or economic/downward-balancing actions. The regulatory position is more nuanced than a blanket "must-run" rule: under the CERC Indian Electricity Grid Code (IEGC), 2023, wind, solar, wind-solar hybrid and specified run-of-river hydro are curtailed after other generation within the relevant GNA/T-GNA category when curtailment is unavoidable for transmission constraints or grid security, and RLDCs/SLDCs are required to publish reports of such incidents [71].

Recent studies identify both system-wide flexibility limitations and location-specific evacuation constraints. Ember estimates that keeping coal units above their minimum technical load (MTL) created about 2.1 TWh of renewable curtailment in FY2025–26, around 1.3% of renewable generation, and estimates that roughly 10 GWh of storage charging in the solar window could have absorbed this specific MTL-driven surplus[72]. These are independent modelling estimates, not measured national curtailment or an official storage requirement.

In April 2026, coal was at or below its roughly 55% MTL in more than half of midday dispatch intervals. Curtailment of RE accounted for 37% of the month's downregulation. Emergency TRAS-down curtailment of solar and wind exceeded 3,600 GWh cumulatively by early June 2026, with more than 120 GWh on each of 1 and 3 May [71]. Separately, the EAC-PM working paper reports solar curtailment of about 677 MU in April and 747 MU in May 2026 roughly 24 GWh/day in May while documenting the rapidly deepening midday net-load trough and evening ramp [72].

Quarterly data provide an important distinction between curtailment capacity instances and actual curtailed energy. CREA's Q4 FY2025–26 snapshot, based on GRID-INDIA data, reports approximately 72 MU of direct solar curtailment and 6 MU of direct wind curtailment during January–March 2026. A further 103 MU of solar and 17.5 MU of wind were curtailed through TRAS-down. Thus, the quarter recorded about 78 MU of direct curtailment and 120.5 MU of TRAS-down energy as shown in Figure 31 [73].

[71] Central Electricity Regulatory Commission (Indian Electricity Grid Code) Regulations, 2023.

[72] Ember, "India needs 10 GWh of battery storage now to stop coal's inflexibility wasting clean power," 17 June 2026.

[73] Centre for Research on Energy and Clean Air (CREA), "Quarterly Energy Snapshot for India: Q4 2025–26," April 2026.

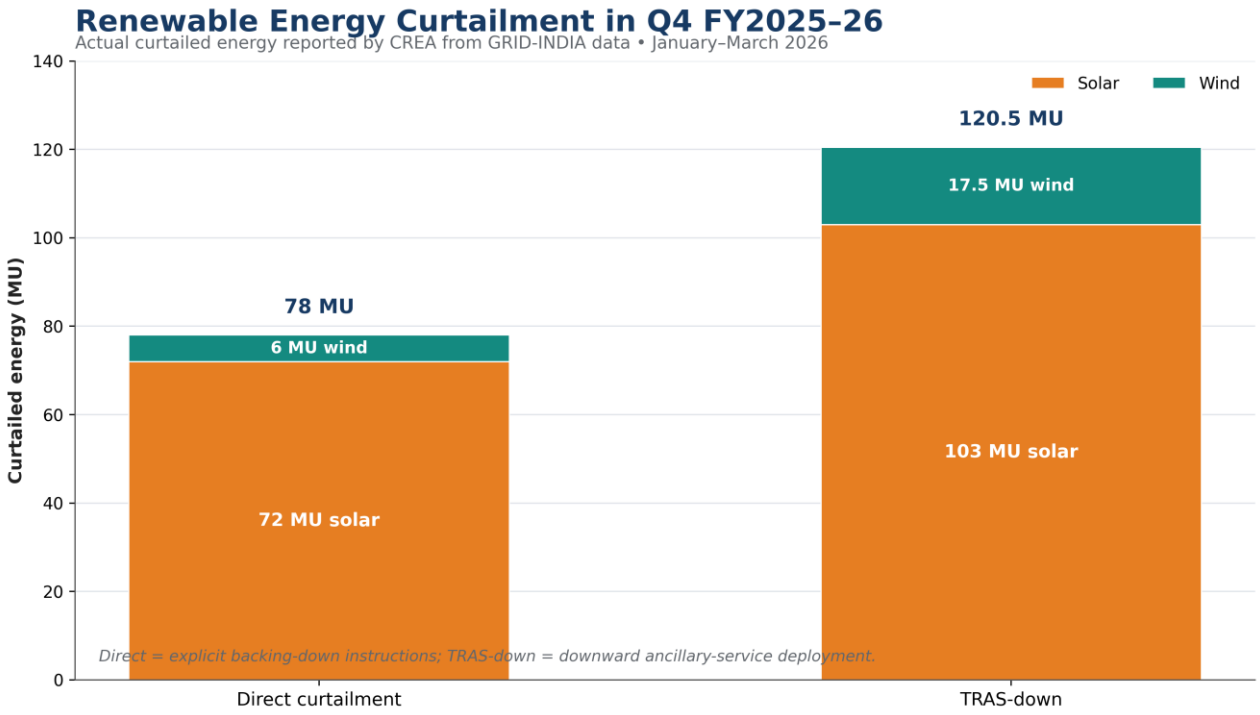


Figure 31: Renewable energy curtailed in Q4 FY2025–26, distinguishing direct curtailment from TRAS-down deployment. Values are actual curtailed energy (MU), not the sum of MW/GW curtailment instructions. Source: CREA, Quarterly Energy Snapshot for India: Q4 2025–26, using Grid India data [73].

(Source: This figure has been plotted using data sources from CREA and NLDC)

Table 26: Selected recent evidence on renewable curtailment and flexibility constraints in India

Indicator	Value
FY2025–26 MTL-driven RE curtailment	Approximately 2.1 TWh of RE generation
Storage needed for that FY26 MTL-driven surplus	Approximately 10 GWh
Q4 FY2025–26 direct curtailment	Solar 72 MU; wind 6 MU
Q4 FY2025–26 TRAS-down curtailment	Solar 103 MU; wind 17.5 MU
April–May 2026 solar curtailment	677 MU (Apr); 747 MU (May)
TRAS-down solar + wind, by early Jun 2026	>3,600 GWh cumulative; >120 GWh on 1 and 3 May
Rajasthan transmission-access gap, Jul 2025	22.24 GW operational ISTS RE; 7.97 GW non-effective GNA; ~3.8 GW solar curtailed at peak hours
July–August 2026 reported VRE curtailment	1,166.52 MU (Jul; 3.3% of RE generation) → 667.76 MU (Aug; 1.89%)

The latest monthly market-tracking data available for this update suggests that the problem remained material after the summer peak. JMK Research reports total VRE curtailment of 1,166.52 MU in July 2026 (3.3% of renewable generation) and 667.76 MU in August (1.89%), a 42.75% month-on-month reduction as shown in Figure 32. Because this is a secondary-source aggregation rather than a harmonised statutory national series, it is best used as a directional indicator and should not be mixed mechanically with Ember's MTL-only estimate or CREA's Q4 categories.

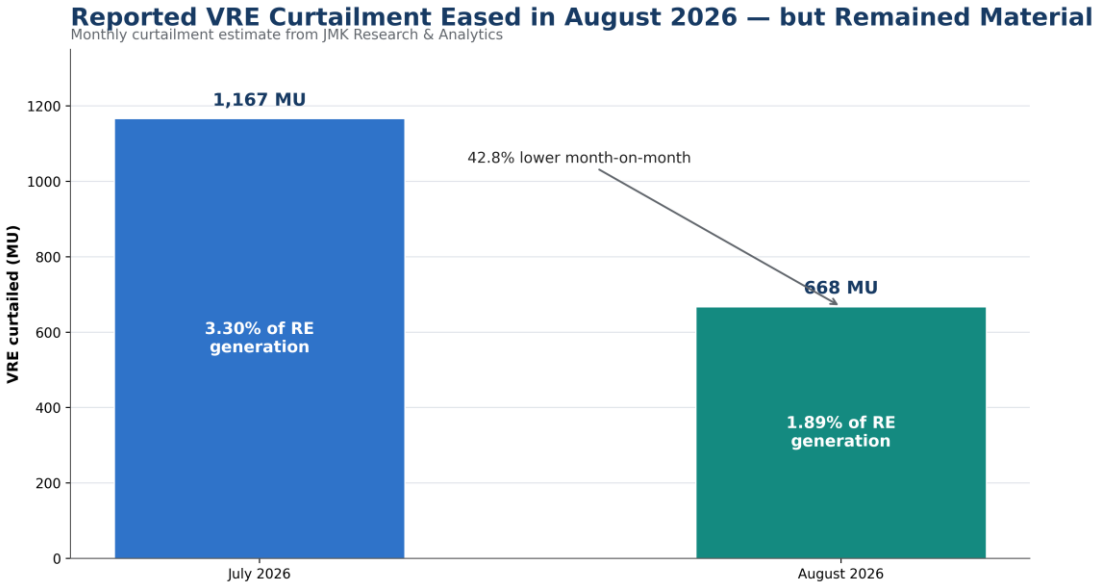


Figure 32: Reported VRE curtailment in July and August 2026.

(Source: This figure has been plotted using data sources from JMK Research & Analytics)

3.7.2 Curtailment is Not One problem: A Taxonomy of Causes

The engineering remedy depends on why RE output is being backed down. A BESS located behind the binding constraint can be useful for consuming a repeatable, hours-long surplus, provided charging and subsequent discharge are electrically feasible. Likewise, grid-forming BESS can contribute to voltage, frequency and system-strength needs, but storage cannot substitute for missing evacuation capacity where the underlying transmission constraint is persistent. Table 27therefore separates the principal mechanisms and the role that storage can realistically play.

Table 27: Taxonomy of RE curtailment causes and the role of storage

Cause	Mechanism	Operational indicator	Storage effectiveness	Complementary remedies
Local evacuation congestion	Pooling station / radial line reaches export limit	Line/ICT loading; T-GNA restrictions; plant-specific backing down	High if short-duration and battery is behind constraint	Transmission augmentation; dynamic line rating; RE power-park reinforcement
Inter-state / inter-regional congestion	Corridor TTC/ATC or stability limit binds	Transfer limits, congestion, and curtailment reports	Moderate; location is decisive	ISTS/HVDC augmentation; topology/market measures
System-wide over-generation / minimum generation	Midday VRE exceeds load net of inflexible generation and reserve needs	Coal at MTL; TRAS-down; very low midday prices	Very high: charging provides downward flexibility and energy shifting	Thermal flexibilisation; demand shifting; exports; hydro/PSP

Voltage / system-strength constraint	Low SCR, reactive limits, oscillations or fault-level issues restrict inverter-based generation	Voltage/reactive limits; oscillation events; operator restrictions	Depends on converter controls, fault performance and validated system-strength studies. Energy capacity alone is insufficient.	STATCOMs; synchronous condensers; GFM controls; network reinforcement
Contingency / N-1 security	Transfer is limited to maintain post-contingency security	Security-constrained dispatch; SPS/RAS arming	Moderate; fast BESS may increase operating margin	Network reinforcement; SPS/RAS; redispatch
Market / economic downward regulation	RE is backed down as the least cost or feasible source of downward regulation	TRAS-down; very low/negative-value periods	High where the battery can charge during surplus and discharge later	Flexible demand; electrolysers; thermal turndown; market redesign
Distribution-level constraints	Reverse flow or voltage rise on distribution feeders	Feeder/DT data; export limits	Potentially useful where suitably located storage relieves the specific feeder constraint	Feeder reinforcement; smart inverters; Volt-VAR/Volt-Watt

3.7.3 Rajasthan: Transmission-driven Curtailment

Rajasthan is an important example of location-specific curtailment. IEEFA/JMK analysis, based on Northern Regional Power Committee data, found 22.24 GW of operational ISTS-connected RE projects in July 2025, but only about 64% had an effective GNA supported by the associated transmission system. About 7.97 GW had non-effective GNA and relied on temporary access; the analysis estimates that roughly 3.8 GW of solar was curtailed during peak solar hours because of corridor unavailability. This is fundamentally different from all-India midday curtailment caused by coal minimum-load constraints: BESS can reduce the duration and peak of congestion if located at the constrained node, but persistent evacuation deficits still require transmission completion and reinforcement.

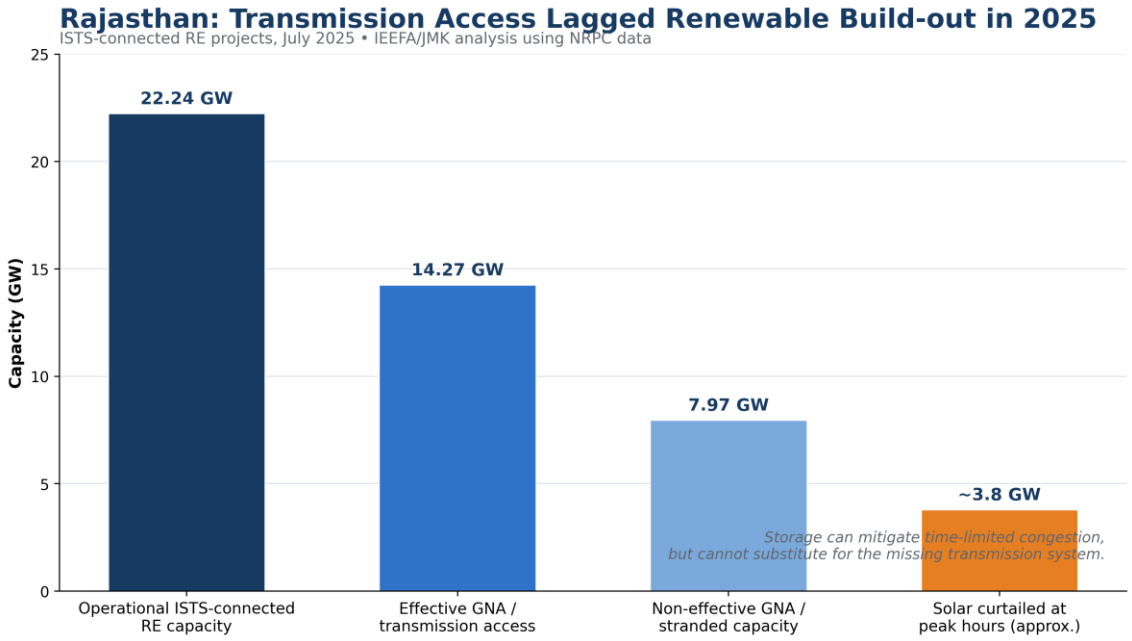


Figure 33: Rajasthan transmission-access gap and approximate peak-hour solar curtailment, July 2025.

(Source: This figure has been plotted using data sources from IEEFA and JMK Research)

3.7.4 Measurement, transparency and compensation

A limitation in India's evidence base on curtailment is that the available datasets measure different things. A "GW curtailed" figure may be a capacity instruction or the sum of MW instances, whereas energy actually not generated must be expressed in MWh/MU/GWh. TRAS-down deployment is also conceptually distinct from direct backing-down instructions, and an estimate of "curtailment risk" from coal MTL constraints is not the same as metered all-cause curtailment. These quantities should therefore not be added unless their time basis, counterfactual available generation and cause codes are consistent.

The IEGC 2023 requires RLDCs/SLDCs to publish reports when scheduled transactions are curtailed for transmission constraints or grid security.[71] The Forum of Regulators' Model Guidelines for Management of RE Curtailment go further, recommending 15-minute/turbine- or inverter-level data, objective grid-security parameters, curtailment records and compensation for curtailment for reasons other than grid security, subject to PPA provisions.[74] Rajasthan SLDC, however, now publishes daily RE-curtailment event files, illustrating the type of disclosure that can support more granular analysis.

For planning energy storage, the minimum useful national dataset should contain, for every 15-minute block: (i) plant/pooling-station identifier and technology; (ii) available generation or a reproducible counterfactual; (iii) scheduled and actual generation; (iv) curtailed MW and MWh; (v) start/end time; (vi) reason code; (vii) binding network element or system-security parameter where applicable; (viii) whether the event was direct curtailment, TRAS-down or another ancillary-service action; and (ix) compensation status. A monthly publication would allow planners to distinguish energy-limited events suited to BESS from chronic network constraints that require transmission.

3.7.5 Implications for storage planning

- ***Size storage against the time profile***, not only annual curtailed energy. A few hundred GWh/year concentrated into recurring 3-6-hour midday windows can imply a very different BESS requirement than the same annual energy spread across seasonal or multi-day events.

[74] Forum of Regulators (FOR), "Model Guidelines for Management of RE Curtailment," November 2022.

- ***Co-optimise location and grid charging***. System-wide MTL-driven curtailment can be absorbed by a grid-connected BESS that is permitted to charge during surplus hours; local evacuation curtailment generally requires the battery to sit electrically behind or at the binding constraint.
- ***Separate energy and stability services***. Where curtailment is triggered by voltage, system strength, or contingency constraints, inverter capability (including grid-forming controls, reactive capability, and short-duration overload) may be as important as MWh duration.
- ***Do not treat storage as a substitute for transmission***. The Rajasthan evidence shows that persistent ATS/corridor deficits can strand several gigawatts of RE. Storage can defer or reduce peak flows, but sustained export capability still requires network reinforcement.
- ***Use curtailment as an economic signal***. Repeated midday TRAS-down deployment, low/near-zero market prices and evening scarcity together create a storage value stack: avoided curtailment, ancillary services, energy arbitrage, capacity/adequacy and potentially transmission deferral.

3.8. Flexibility and Energy Storage Requirements For 2030, 2032 and 2047

Power-system flexibility may be defined as the capability to accommodate variability and uncertainty in electricity demand and generation across multiple operational timescales while maintaining system reliability and an acceptable system cost.[75] This requirement becomes increasingly important as VRE penetration rises. For India's predominantly thermal power system, modelling indicates that meeting this requirement principally through increased cycling and flexibilisation of fossil-fuel generation can entail appreciable cost and emissions penalties at high VRE penetration.[76] Energy storage, therefore, forms part of a broader flexibility portfolio, alongside flexible generation, transmission, demand response, and improved system operation, with the additional advantage of shifting energy over time and providing fast-response balancing and ancillary services.

3.8.1 Demand growth and adequacy context

The CEA Long-Term National Resource Adequacy Plan (LT-NRAP) 2026 places this flexibility requirement within a rapidly expanding, but inherently uncertain, demand outlook[77]. Under Scenario I, based on the mid-term review of the 20th Electric Power Survey (EPS), all-India peak demand increases from 289 GW in 2026–27 to 459 GW in 2035–36, while annual electrical energy requirement rises from approximately 1,929 BU to 3,365 BU over the same period as shown in Figure 34.

The alternative Scenario II, reflecting more recent demand trends, reaches approximately 446 GW of peak demand and 3,215 BU of annual energy requirement by 2035–36. Thus, even the lower trajectory implies very substantial system expansion, while the 13 GW difference in terminal peak demand and 150 BU difference in annual energy requirement between the two scenarios illustrate the demand uncertainty that resource-adequacy planning must accommodate.

[75]M. M. Rahman, et al., "An overview of power system flexibility: High renewable energy penetration scenarios," Energies, vol. 17, no. 24, 6393, 2024.

[76]S. Bhattacharya, et al., "The flexibility dilemma—Managing cost and emissions in a fossil fuel-dominated power sector under increasing penetration of variable renewable energy sources," Applied Energy, vol. 405, 127199, 2026.

[77]Central Electricity Authority (CEA), Long-Term National Resource Adequacy Plan (2026-27 to 2035-36), Ministry of Power, Government of India, Apr. 2026.

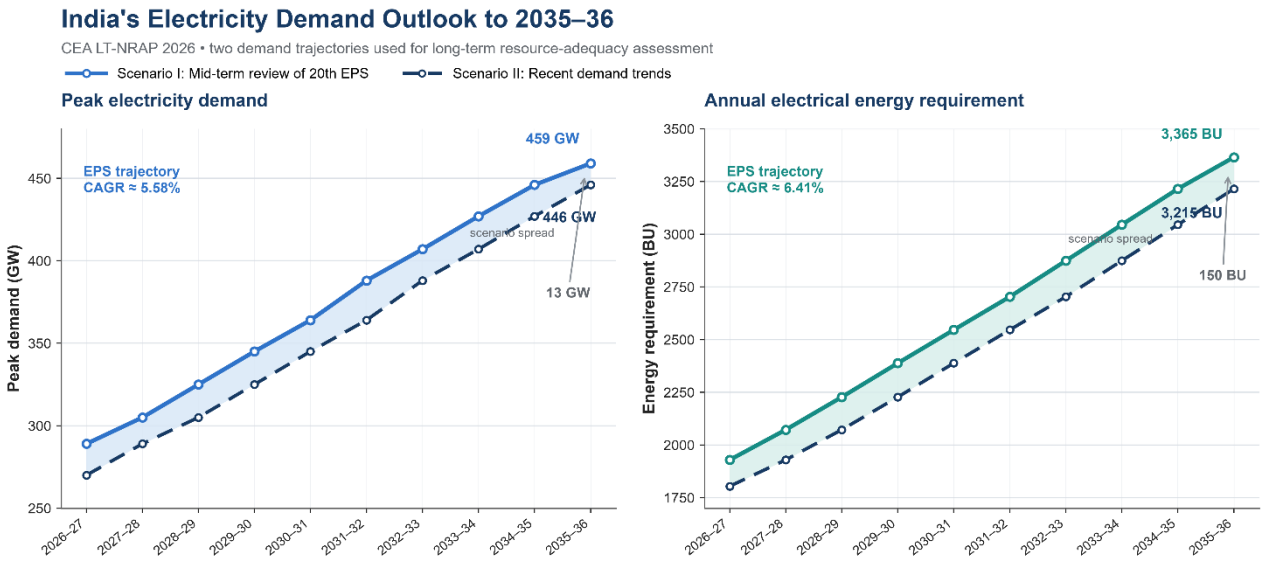


Figure 34: India's electricity demand outlook to 2035–36 under the two demand trajectories considered in CEA's LT-NRAP 2026, showing projected peak electricity demand and annual electrical energy requirement

(Source: This figure has been plotted using data sources from CEA LT-NRAP 2026, demand scenarios and mid-term 20th EPS inputs)

The challenge is not simply one of meeting a higher annual peak. The LT-NRAP's load-duration analysis shows distinct demand distributions during solar and non-solar periods, with demand during non-solar hours concentrated broadly in the 130–230 GW range, compared with approximately 160–240 GW during solar hours.[78] As solar capacity expands, gross daytime demand and the demand that must be served after solar generation declines increasingly become different adequacy problems. Consequently, sufficient resources must be available not only to meet the annual system peak but also to cover evening and non-solar-hour requirements, renewable-energy variability, forecast error and contingencies. This strengthens the value of resources capable of transferring surplus energy from periods of RE abundance to hours of system scarcity.

CEA explicitly incorporates this principle into its resource-adequacy framework through technology-specific capacity-credit assumptions, rather than treating all installed megawatts as equally firm. The LT-NRAP applies indicative capacity credits of approximately 0.8 for coal, 0.7 for nuclear, 0.5–0.6 for hydro and 0.3–0.5 for gas, depending on the relevant category and assumptions.

For storage, adequacy contribution depends on discharge duration, availability during critical periods and the ability to recharge between events. Six-hour storage can provide sustained peak support, but a full capacity credit cannot be assumed without evaluating the relevant demand and resource-availability conditions.[78]As India moves toward the demand levels, the planning question therefore shifts from simply procuring additional capacity to ensuring an adequate portfolio of firm, flexible and sufficiently long-duration resources capable of serving the system during its most critical hours.

3.8.2 Projected Storage Requirements Across Planning Horizons

CEA and the Ministry of Power have published storage-capacity requirements for several planning horizons, as summarised in Table 28. These projections originate from different studies and planning assumptions. They should therefore be interpreted as source-specific estimates rather than a single continuous capacity-expansion trajectory.

[78] Central Electricity Authority (CEA), Long-Term National Resource Adequacy Plan (2026–27 to 2035–36), Ministry of Power, Government of India, Apr. 2026.

Table 28: Storage requirement projections for India

Horizon	Study/Publication Year	Projected Storage Requirement	Evidence Status	Planning Context
2026-27	CEA NEP, 2023	16.13 GW / 82.37 GWh	Official projection	7.45 GW PSP and 8.68 GW BESS
2029-30	Optimal Generation Capacity Mix, 2023	60.63 GW / 336.40 GWh	Official projection	18.98 GW PSP and 41.65 GW BESS
2031-32	CEA NEP, 2023	73.93 GW / 411.40 GWh	Official projection	175.18 GWh PSP and 236.22 GWh BESS
2035-36	CEA NGAP, 2026	174 GW / 888 GWh	Official base-case projection	94 GW / 567 GWh PSP and 80 GW / 321 GWh BESS
2047	Ministry of Power National ESS Framework, 2023	320 GW / 2,380 GWh	Indicative long-term projection	90 GW / 540 GWh PSP and 230 GW / 1,840 GWh BESS

Data Compiled from Multiple Sources

3.8.3 Quantitative flexibility metrics

To plan storage alongside other flexibility options, a small set of quantitative flexibility metrics should be computed and published annually by the responsible authorities. These metrics would provide a consistent basis for assessing whether flexibility capabilities are expanding in step with rising VRE penetration, identifying emerging operational constraints, and determining the type, magnitude and duration of storage required for specific grid services. Recommended quantitative flexibility metrices are summarised in Table 29.

Table 29: Recommended quantitative flexibility metrics

Metric	Definition/formula	Unit	Use
Ramping requirement	$\max_t[NL(t+\Delta t) - NL(t)]$ for Δt = 15 min, 1 h, 3 h; up and down separately	MW/min; GW/h	Sizes ramping capability of flexible fleet and storage
Ramp adequacy margin	Available ramp capability – ramp requirement (P95)	GW/h	Identifies shortfall hours
Reserve requirement	Primary: reference contingency (4,500 MW) and FRO; secondary/tertiary: forecast-error quantiles	MW	Sizes SRAS/TRAS and FFR procurement
Residual-load variability	Standard deviation of hourly changes in NL; P99 of 15-min changes	GW	Tracks growth of short-term variability
Peak-to-off-peak spread	Daily $NL_{max} - NL_{min}$; DAM price spread	GW; ₹/kWh	Arbitrage and shifting value
Net-load duration curve	Sorted annual hourly NL	GW vs hours	Adequacy and storage duration planning

Metric	Definition/formula	Unit	Use
Curtailment rate	Curtailed MWh ÷ available RE MWh, by cause	%	Tracks inflexibility
Minimum synchronous inertia / SNSP	Online kinetic energy; SNSP	GW·s; %	Stability constraint on dispatch
Storage coverage ratio	Daily storage discharge ÷ evening ramp energy	%	Tracks progress (≈13–18% in May 2026)

Data Compiled from Multiple Sources

3.9. Declining Inertia and System Strength

3.9.1 Inertia and the rate of change of frequency

Increasing inverter based RE generation and the reduced commitment of synchronous generators can lower the kinetic energy available to arrest frequency deviations following major generation losses. This increases the importance of monitoring system inertia and securing adequate fast frequency-response capability. When a generator or large block of RE trips, the power imbalance ΔP initially drives the rate of change of frequency, determined by the kinetic energy stored in synchronous machines connected to the grid, defined by the swing equation:

$$RoCoF = \frac{df}{dt} = -\Delta P \cdot \frac{f0}{(2 \cdot E_k)}, \quad E_k = \sum_i H_i \cdot S_i$$

where f_0 = 50 Hz, E_k is the total stored kinetic energy (GW·s) and H_i and S_i are the inertia constant and rating of each synchronous machine. The Grid India-IIT Bombay study of the Indian grid found that the system inertia constant typically ranged from about 5 to 9 seconds over 2014-2021, falling as RE penetration rose, and that for the reference contingency of 4,500 MW, the frequency nadir would be about 49.55 Hz and the quasi-steady-state frequency about 49.71 Hz[79]. Recent research estimates inertia and fast-acting storage requirements for the Indian grid using system data, building on the broader literature on low-inertia systems.

As more coal is backed down at midday, Ember observed coal cycling down by 49 GW in six hours in March 2026; the synchronous kinetic energy online falls precisely when CBR output is highest. A large RE loss at midday therefore produces a faster frequency decline than the same loss at night. During high-RE operating periods, lower synchronous-generator commitment can reduce available inertia. However, the actual frequency response depends on the online generating fleet, the disturbance magnitude, the primary response, and the load characteristics. Time-resolved inertia assessment is therefore necessary for India's evolving generation mix.

The Khavda grid disturbance on 13 May 2026 demonstrated the potential for renewable generation-loss contingencies that substantially exceed conventional planning assumptions. Approximately 8,962 MW of RE generation was lost following inverter HVRT-related tripping and the cascading disconnection of 17 transmission lines within about 17 seconds, nearly twice the 4,500 MW reference contingency[80]. System frequency declined by 0.548 Hz, from 49.946 Hz to 49.398 Hz, triggering Stage-I automatic under-frequency load shedding (AUFLS) at 49.4 Hz. However, the actual load relief was only 5,091 MW, compared with the targeted 12,461 MW. The event highlights that, in grids with high CBR penetration, credible contingencies must account for correlated generation losses arising from common-mode voltage, control and protection interactions, rather than being limited to the largest individual generating unit.

[79]POSOCO (now Grid-India) and IIT Bombay, Assessment of Inertia in Indian Power System, Jan. 2022.

[80]Western Regional Power Committee, Report of the Committee on Grid Disturbance at Khavda Pooling Station occurred on 13.05.2026, WRPC/Prot/GD/2026/2973-298/, 5 Oct 2026.

Consequently, fast frequency response (FFR) requirements and storage sizing must be evaluated against such system-level contingencies, considering available frequency reserves, system inertia and protection performance.

The event highlights the risk of large, correlated generation losses in RE complexes connected through common transmission corridors. Such disturbances require coordinated fault-ride-through compliance, frequency response, protection, and defence schemes. Appropriately controlled BESS can provide fast frequency response, but the required reserve capacity must be established through dynamic contingency studies rather than by directly equating generation loss with the storage power rating.

3.9.2 System strength and the limitations of SCR

System strength describes the network's ability to maintain voltage waveform stability in the face of disturbances. It is closely related to the fault level at a bus. Grid-following inverters rely on a stiff voltage to synchronise via their phase-locked loop (PLL). In weak grids, their controls interact with the network impedance and with each other, causing oscillations, failure to ride through faults, or post-fault instability[81]. The classical measure is the short-circuit ratio:

$$SCR = \frac{S_{SC}}{P_{rated}}$$

where S_{SC} is the three-phase short-circuit capacity (MVA) at the point of connection without the CBR's contribution and P_{rated} the rated active power of the CBR. The CEA's technical standards require an SCR of at least 5 at the interconnection point[82]. At Khavda (KPS-1), an SCR value of 3.8 was recorded as of 31 Jul 2025, signifying a comparatively weak grid with limited system strength.[83]

Classical SCR has important limitations in multi-infeed systems where many CBRs are electrically close. The *CR with interaction factors* (SCRIF), *weighted* SCR, and composite SCR (CSCR) are additional types of SCR metrics that account for interactions among nearby plants. Alongside impedance-based stability analysis, it compares the frequency-dependent output impedance of inverters with the grid impedance, capturing control interactions not captured by SCR. Because SCR also ignores the contribution of grid-forming resources, a network with low SCR but adequate GFM capacity may be stable, while one with apparently adequate SCR may still suffer converter-driven oscillations. Grid-India has recommended a uniform SCR computation methodology as one of the lessons from Khavda.

3.10. Emerging Loads Reshaping the Load Curve

The flexibility challenge depends as much on how demand evolves as on RE growth. Several new loads will reshape India's daily and seasonal load curves over the next two decades, as shown in Table 30. Their impact will depend on when electricity is consumed and the extent to which consumption can be shifted without disrupting the underlying service or industrial process.

[81] A. Boričić, et al., "System strength: Classification, evaluation methods, and emerging challenges in IBR-dominated grids," in Proc. IEEE PES ISGT Asia, 2022, pp. 185–189.

A. Boričić et al., "Voltage vulnerability curves: Data-driven dynamic security assessment of voltage stability and system strength in modern power systems," Int. J. Electrical Power & Energy Systems, vol. 168, 110636, 2025.

X. Wang et al., "Grid-synchronization stability of inverter-based resources—An overview," IEEE Open Journal of Industry Applications, vol. 1, pp. 115–134, 2020.

[82] Central Electricity Authority (CEA), (Technical Standards for Connectivity to the Grid) Regulations, 2007, amended in 2013, 2019.

[83] Grid Controller of India Limited (Grid-India), National Load Despatch Centre (NLDC), Grid-Forming Technology and Possible Applications in the Indian Power System, Discussion Paper, New Delhi, India, Dec. 2025.

Table 30: Emerging loads and their likely effect on net load and flexibility

Load	Scale and trend	Effect on load curve	Flexibility / storage implications
Space cooling	Dominant driver of the 256–271 GW peaks of 2026; rising AC ownership	Raises afternoon and night peaks; heatwave-driven spikes	Higher nighttime demand increases non-solar-hour adequacy requirements. Smart cooling controls and chilled-water or ice storage can provide demand flexibility.
Electric vehicles	Rapid growth in two and three wheelers and e-buses	Uncontrolled home charging adds to the evening peak; workplace/depot charging can shift to midday	ToD tariffs and managed charging to absorb solar; V2G in the longer term; depot BESS
Data centres	Fast-growing (GW scale) predominantly in Mumbai, Chennai, Hyderabad, Noida	Flat, 24×7 load; demand for RTC green power	RTC/FDRE contracts with storage; on-site BESS for backup and grid services
Green hydrogen electrolysers	5 MMT/yr target ⇒ ≈250–275 TWh/yr of electricity if met (at ~50–55 kWh/kg)	Large new load, potentially co-located with RE	Flexible electrolysers can act as midday sinks; alkaline less flexible than PEM
Industry electrification and green open access	Growing C&I procurement of RE	Daytime-weighted if solar-based	Storage for firming C&I contracts; industrial heat batteries
Agricultural pumping	Large share of load in several states; PM-KUSUM feeder solarisation	Shifts pumping to daytime (helps absorb solar)	Reduces evening demand; feeder-level storage for night supply
Distributed solar (rooftop)	32.6 GW (Aug 2026) and growing	Deepens midday trough; creates reverse flows	DT/feeder-level storage; visibility for SLDCs

Data Compiled from Multiple Sources

Two developments are particularly consequential for the evolution of India's flexibility and storage requirements. First, achievement of the National Green Hydrogen Mission's target of at least 5 million metric tonne annual production capacity of green hydrogen. It could translate into approximately 250-275 TWh of electricity consumption per year, equivalent to roughly 14-16% of India's FY 2024-25 electricity requirement. If electrolysers are designed and operated flexibly, this demand could provide substantial controllable electricity demand during solar-rich hours, consuming RE generation that might otherwise be curtailed and reducing the need for electricity storage in some periods. Second, rapidly growing cooling demand is increasingly extending into evening and nighttime hours during hot months. This raises not only the post-sunset peak power requirement but also the volume of energy that must be supplied during non-solar hours, increasing the value of storage with sufficient energy depth and potentially shifting system requirements towards 4–8-hour durations.

The IEA's June 2026 analysis indicates that India's summer net-load peak typically occurs around 20:00, with substantial demand persisting overnight. This reinforces the need to assess storage adequacy against the full non-

solar-hour demand profile rather than the evening peak alone. Storage duration must be determined through chronological adequacy studies, considering discharge requirements and opportunities for recharging between critical periods.

3.11. System needs for multi-timescale storage

India's evolving power system requires flexibility across multiple timescales, from fast frequency and voltage support to intraday energy shifting and longer-duration adequacy. ESS can provide several of these services, depending on their power rating, usable energy, response capability and network location.

Table 31Table 31 consolidates these requirements by linking each operational timescale to the corresponding quantified flexibility need and appropriate storage response. The reported figures represent different operating conditions and analytical bases, not additive national storage requirements.

Table 31: Multi-timescale flexibility needs in India and the corresponding storage response

Timescale	Need	Indicative Indian magnitude (2026)	Storage response
Sub-second to seconds	Inertia, FFR, voltage support, system strength	Contingencies up to ~9 GW; SCR 2.6–4.7 at Khavda; 68 major RE disturbances (2022–25)	GFM BESS; PSP condenser mode; synchronous condensers
Seconds to minutes	Primary and secondary regulation	Reference contingency 4,500 MW; SRAS requirement several GW	BESS (FFR/PFR/SRAS); PSP; hydro
Minutes to hours	Ramping, forecast errors, tertiary reserve	Evening ramps 64–74 GW over 5-7 h; morning ramps 55 GW over 3.5 h	2-4 h BESS; PSP; flexible coal/gas/hydro
Hours (intraday)	Energy shifting from midday to evening and night	130–155 GWh/day to halve summer evening ramp; ≈24 GWh/day curtailment (May 2026)	4-8 h BESS; PSP (6–8 h)
Days	Weather-driven low-RE periods; monsoon cloud cover; wind lulls	Multi-day deficits of several hundred GWh (to be quantified)	PSP with large reservoirs; LDES (flow, iron-air, CAES/LAES)
Seasons	Monsoon wind surplus vs dry-season deficit; hydro variability	Seasonal energy imbalances of tens of TWh	Reservoir hydro; H_2/ammonia; demand-side seasonal flexibility

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Chapter 4.

Grid-Integration Challenges in a Converter-Dominated Indian Grid



The growing share of converter-based resources (CBRs) is changing the Indian grid's dynamic response, network operating conditions and protection requirements. The discussion is structured around four challenge areas: (A) energy balancing and flexibility; (B) frequency, voltage and converter-driven stability; (C) network, protection and power quality; and (D) adequacy and resilience. Addressing these challenges requires matching ESS capabilities to response speed, power and energy requirements, converter performance, location and grid operating conditions.

4.1. Framework For Grid-Integration Challenges

The IEEE/CIGRE classification of power-system stability, revised in 2021 to reflect CBR-dominated systems, provides the organising framework as summarised in Figure 35[84]. In addition to the established categories of rotor-angle, voltage and frequency stability, it introduces resonance stability which includes electrical and torsional resonances including sub-synchronous oscillations), and converter-driven stability, that split into fast interactions i.e. involving inner current controls, at hundreds of Hz to kHz and slow interactions i.e. involving PLLs and outer power controls, typically <10 Hz. Table 32 maps the challenges covered in this chapter to the relevant stability category, timescale and storage service.

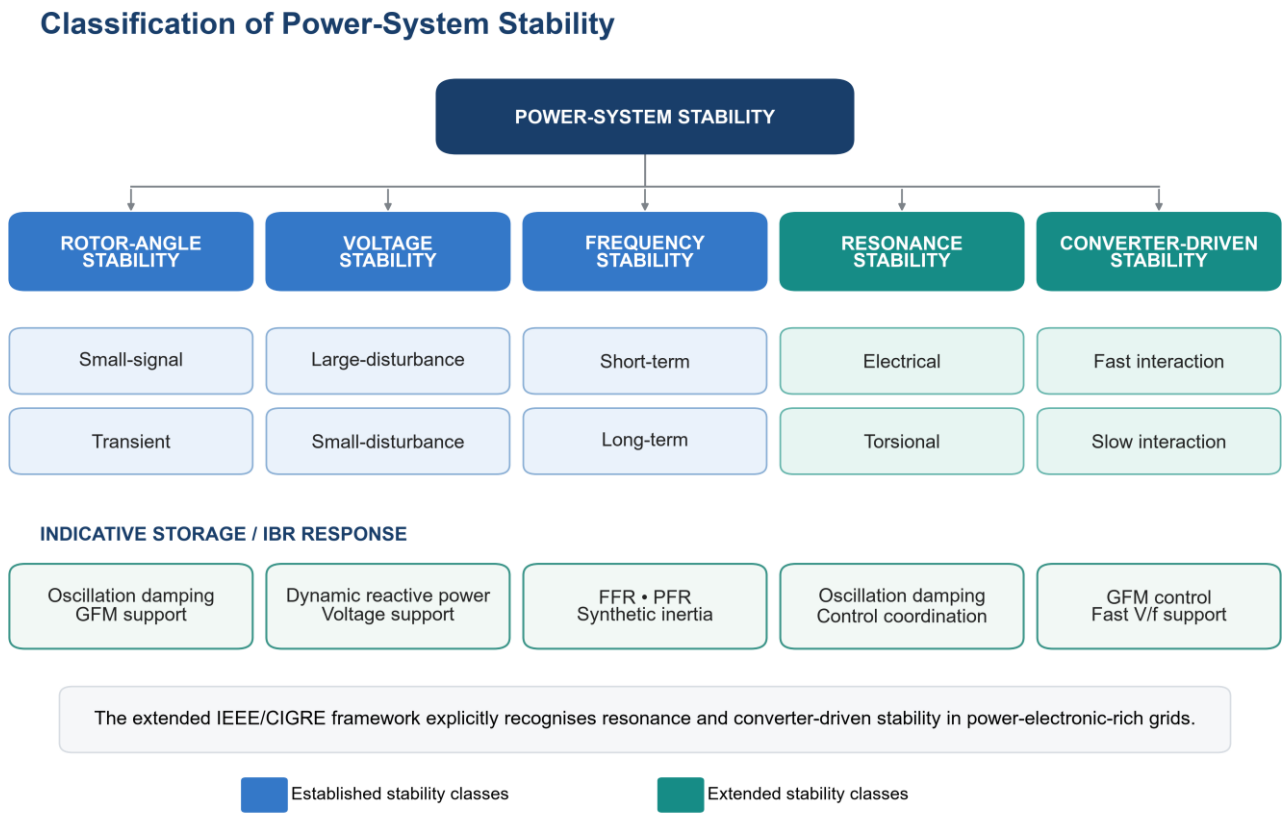


Figure 35: Classification of power-system stability extended for converter-interfaced resources, with indicative ESS support functions

[84] Nikos Hatziargyriou et al., 'Definition and Classification of Power System Stability – Revisited & Extended', IEEE Transactions on Power Systems 36, no. 4 ,2021.

Table 32: Mapping of grid-integration challenges, timescales and storage services

Challenge	Stability category	Timescale	Storage service
Ramping and forecast error	Balancing (not stability)	Minutes–hours	Ramp support, tertiary reserve, energy shifting
Over-generation and minimum load	Balancing	Hours	Charging sink, energy shifting
Low inertia; high RoCoF; deteriorated nadir	Frequency stability (short-term)	0.1–10 s	FFR, synthetic inertia
Primary/secondary frequency control	Frequency stability (long-term)	10 s–15 min	PFR, SRAS, TRAS
Dynamic voltage recovery; FIDVR; post-fault overvoltage	Voltage stability (short-term)	0.1–10 s	Dynamic reactive current; GFM voltage-source behaviour
Steady-state voltage control; midday overvoltage	Voltage stability (long-term)	Minutes–hours	Reactive power scheduling; charging to absorb surplus
PLL/weak-grid instability; control interactions; oscillations	Converter-driven (slow/fast); resonance	ms–10 s	GFM control, damping, sync condensers
Congestion (local, inter-state, distribution)	Thermal / security	Hours	Congestion relief; network deferral
Protection with low fault current	Protection	ms–s	Fault-current contribution (GFM, oversizing)
Harmonics, resonance, flicker	Power quality	Continuous	Active filtering; careful PCS design
Prolonged low-RE periods; extreme weather	Adequacy/ resilience	Days	Long-duration storage; backup
Islanding, restoration, black start	Resilience	Minutes–hours	Black start; island formation (GFM)

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4.2. Energy Balancing and Ramping

Daily balancing of supply and demand is the most immediate operational challenge created by the rapid growth of solar generation. The working paper on India's net load by the Economic Advisory Council to the Prime Minister (EAC-PM) reports two summer trends between May 2023 and May 2026:[85]

- the average evening net-load ramp between 13:00 and 20:00 roughly doubled, from about 36 GW to about 74 GW;
- the morning ramp-down rose from about 18 GW to 53 GW.

[85]S. Sanyal and S. Dev, "The duck and the camel: Tracing the net load on the Indian power grid," Economic Advisory Council to the Prime Minister, New Delhi, India, EAC Working Paper EAC-PM/WP/53/2026, Jul. 2026.

The winter pattern has changed substantially as well. In January 2023, the lowest net load still occurred overnight, at about 136 GW, while midday net load was near 152 GW. By January 2026, the daily minimum had moved to midday, at about 143 GW, and the winter evening ramp had reached about 65 GW.

Grid-India's 15-minute data for 3 March 2026 (Figure 9), the day of highest solar penetration, show how steep these swings can be:[86]

- net load fell from about 201 GW at 07:15 to 123.4 GW at 13:30;
- it then rose to 205.4 GW by about 19:15, an increase of about 82 GW in under six hours;
- the largest 15-minute changes were +7.7 GW and −7.8 GW.

A committee of the Central Electricity Authority (CEA) has similarly noted that the gap between maximum demand and minimum net demand has reached about 82 GW on some days. It puts national ramping requirements at typically 250–300 MW per minute, rising to about 500 MW per minute on certain days.[87] The steepest 15-minute block on 3 March 2026 corresponds to about 510 MW per minute. Forecast errors in wind and solar output introduce uncertainty into these largely predictable ramps.

The thermal fleet still provides most of this ramping. Coal units are routinely cycled between about 55% and full load within a day. An analysis of the 6 March 2026 generation mix shows coal's share of generation falling from 87% at midnight to 54% at midday, a reduction of about 49 GW in six hours. It then recovered by about 51 GW within three hours in the evening.[88] In the same month, coal supplied nearly all upward regulation and more than four-fifths of downward regulation, and midday coal generation averaged about 3.2 GW below the fleet's technical minimum.

Grid-India has likewise observed that thermal units have practically no downward margin left during solar hours. Other sources of flexibility are also limited. Hydro generation is energy-constrained, and its output is already concentrated in the morning and evening peaks. Much of the gas-based capacity has been brought into service through directions under Section 11 of the Electricity Act, 2003. These were issued for the summers of 2024 and 2025 to meet demand in non-solar hours.

The strain shows up in adequacy and price outcomes, as follows:

- Between April and May 2026, peak-hour shortages occurred on 36 of 61 days in non-solar hours, against six days in solar hours.
- Average May prices on the Day-Ahead Market (DAM) fell at midday from ₹2.81/kWh in 2023 to ₹1.11/kWh in 2026. Over the same period evening prices rose from ₹8.08/kWh to ₹9.71/kWh.

Load-following raises heat rates, auxiliary consumption and equipment wear, and minimum-load limits can force curtailment of RE. The CEA (Flexible Operation of Coal-Based Thermal Power Generating Units) Regulations, 2023 require units to reach a minimum power level of 55% within one year of notification and 40% under a phasing plan. They also set minimum ramp rates by load band:[89]

- 3% per minute between 70% and 100% of maximum continuous rating;
- 2% per minute between 55% and 70%;
- 1% per minute between 40% and 55%.

The CEA's flexibilisation roadmap sets out the route to 40% technical minimum load through phased, unit-specific modifications and performance validation.[90] The phasing plan issued in December 2023 covers 493 units of about 197 GW, grouped into a pilot and four phases ending in December 2030.

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[86]Grid Controller of India Ltd. (Grid-India), "All-India demand met and source-wise generation at 15-minute resolution, 3 March 2026," National Load Despatch Centre, New Delhi, India, 2026.

[87]Central Electricity Authority, "Report of the committee on wear & tear, O&M and plant lifespan implications due to flexible operation and analysis of 2-shift operational data," New Delhi, India, Aug. 2026.

[88]N. Rodrigues, "Bottleneck to the next phase of renewable energy growth in India," Ember, London, U.K., Jun. 17, 2026.

[89]Central Electricity Authority, "Central Electricity Authority (Flexible Operation of Coal Based Thermal Power Generating Units) Regulations, 2023," *Gazette of India, Extraordinary*, Jan. 2023.

[90]Central Electricity Authority, *Flexibilisation of Coal-Fired Power Plants: A Roadmap for Achieving 40% Technical Minimum Load*. New Delhi, India: Ministry of Power, Govt. of India, Feb. 2023; Central Electricity Authority, "Phasing plan for flexible operation of coal based thermal power generating units," New Delhi, India, Dec. 15, 2023.

On the regulatory side, the CERC approved a compensation procedure in July 2025 that covers higher heat rate, auxiliary consumption, and secondary fuel oil when units run below 55% of effective capacity and for start-ups beyond seven per unit per year. [91]

The long-term cost of greater flexibility remains debated, as the CEA committee found no significant damage directly attributable to operation at 55% load or to conservative ramping. However, its evidence was drawn from two NTPC units, neither of which operated below 55% under normal conditions, and NTPC recorded a dissent from this finding in the report. The same committee proposed a two-shift operation for 151 units aged 35 years or more, totalling about 34.5 GW. It estimated a retrofit cost of about ₹30,200 crore and a tariff impact of about 62–80 paise/kWh.

The cost of inflexibility is also measurable. It was estimated that coal minimum-load limits caused about 2.1 TWh of RE curtailment in FY 2025-26. That is roughly 1.3% of RE generation, or about ₹629 crore of electricity forgone.

Scheduling and market mechanisms complement these physical measures:

- Security-Constrained Economic Despatch (SCED) of inter-state thermal stations began as a CERC-directed pilot on 1 April 2019.
- Indian Electricity Grid Code, 2023 provides for day-ahead Security-Constrained Unit Commitment (SCUC) and SCED by the National Load Despatch Centre.
- The Real-Time Market (RTM) allows schedules to be revised close to real time.
- The CERC (Ancillary Services) Regulations, 2022 established secondary reserves (SRAS) through Automatic Generation Control (AGC), and tertiary reserves (TRAS).

According to Grid-India, 86 plants (83.63 GW) were under AGC in 2026, the breakup of which is shared below:[92]

- 73.1 GW coal, 6.6 GW hydro and 3.2 GW gas
- 180 MW solar
- one 20 MW/40 MWh battery and 2 × 250 MW of pumped storage

These plants gave a pan-India secondary regulation range of about +2,000 MW to −2,400 MW at a combined ramp rate of 200–250 MW per minute. Grid-India reports that frequency stayed within the IEGC band for 78% of the time with AGC and TRAS in operation during 2024-25, compared with 31% without them. Grid-India has since proposed extending AGC to RE projects above 100 MW, BESS and pumped storage projects.

These mechanisms improve how ramping is scheduled and paid for. The ramping capability itself, however, still comes largely from the same thermal and hydro fleet. The AGC range of about ±2 GW is small compared with daily net-load swings of 70–80 GW, which are met mainly through changes in unit commitment and despatch.

Energy storage complements these measures in two ways. It absorbs the midday surplus, reducing the need to take coal units below their technical minimum, and supplies part of the evening ramp, reducing the rate and depth of coal ramping. A megawatt of BESS provides up to 2 megawatts of ramp rate, from full charge to full discharge. It can move through that range within about a second. A coal unit, by contrast, ramps at 1–3% of rated capacity per minute depending on its loading. At 3% per minute, a 500 MW unit adds about 15 MW per minute and takes roughly 7 minutes to deliver a 100 MW ramp; it is even slower in the lower load bands.

Storage can perform these roles only if it holds matching drawal and injection rights on the transmission system. Since August 2025, CERC's connectivity and general network access regulations have allowed storage of 50 MW or more to seek separate non-solar-hour access to the ISTS and to specify a maximum drawal for charging. [93]

The storage fleet is still small relative to the need, as evident from the following points:

- Operational BESS capacity stood at 3,027.85 MW/9,080.20 MWh on 31 August 2026. [94]

[91] Central Electricity Regulatory Commission, "Procedure for mechanism of compensation for degradation of heat rate, auxiliary consumption and secondary fuel oil consumption due to part-load operation and multiple start/stop of units," Order No. L-1/268/2022/CERC, New Delhi, India, Jul. 14, 2025.

[92] Grid Controller of India Ltd. (Grid-India), CIGRE-India Study Committees C2, C4 and C5, and Forum of Load Despatchers, "Participation of battery energy storage in ancillary services: Challenges and opportunities," presented at CIGRE-India, New Delhi, India, May 2026.

[93] Central Electricity Regulatory Commission, "Central Electricity Regulatory Commission (Connectivity and General Network Access to the inter-State Transmission System) (Third Amendment) Regulations, 2025," Notification No. L-1/261/2021/CERC, New Delhi, India, Aug. 31, 2025.

[94] Central Electricity Authority, "Status of development and deployment of BESS projects in India as on 31.08.2026," New Delhi, India, Sep. 2026.

- EAC-PM estimates that PSP and BESS together discharged an average of about 23.8 GWh a day during 10–31 May 2026. Halving the average summer evening ramp would require about 130 GWh of daily discharge.
- It is estimated that about 10 GWh of storage charging during the midday window would have avoided the curtailment caused by coal inflexibility in FY 2025-26.[95]

On the evidence reviewed, storage will work alongside coal flexibilisation and market reforms in the near term. It is most valuable where the ramp is steepest and where coal units are already at their technical minimum.

Storage mapping: Energy shifting from the midday solar surplus to the evening peak (2-8 h). Fast up- and down-ramping, including midday charging that provides downward flexibility when coal units are already at their technical minimum. Secondary (SRAS/AGC) and tertiary (TRAS) reserves.

Critical attributes: Usable energy (MWh) at the POI during the evening window, after allowing for round-trip losses and degradation; Response time and ramp rate; Availability during the evening peak; Permission to charge from the grid in solar hours; State-of-charge management through the day, so the system starts the evening ramp fully charged while keeping headroom for any reserves it has committed.

4.3. Frequency stability

4.3.1 Frequency-response sequence

After a sudden loss of generation, frequency response proceeds through a sequence of overlapping stages as shown in Figure 36: (1) the inertial response of synchronous machines, which is instantaneous and determines the initial RoCoF; (2) fast frequency response (FFR) from converter-interfaced resources, delivered within a fraction of a second to about two seconds; (3) primary frequency response (PFR) from governors and droop-controlled resources, delivered within seconds and sustained for several minutes, which arrests the frequency decline at the *nadir* and stabilises it at a *settling* (quasi-steady-state) frequency; (4) secondary control (automatic generation control, procured in India as Secondary Reserve Ancillary Service, SRAS), which restores frequency and interchange schedules over minutes; and (5) tertiary control (Tertiary Reserve Ancillary Service, TRAS), which replaces secondary reserves over 15 minutes and longer.[96]

[95] N. Rodrigues, "Bottleneck to the next phase of renewable energy growth in India," Ember, London, U.K., Jun. 17, 2026.

[96] Central Electricity Regulatory Commission, Central Electricity Regulatory Commission (Ancillary Services) Regulations, 2022, Regulations (Central Electricity Regulatory Commission (CERC), Ministry of Power, Govt. of India, 2022).

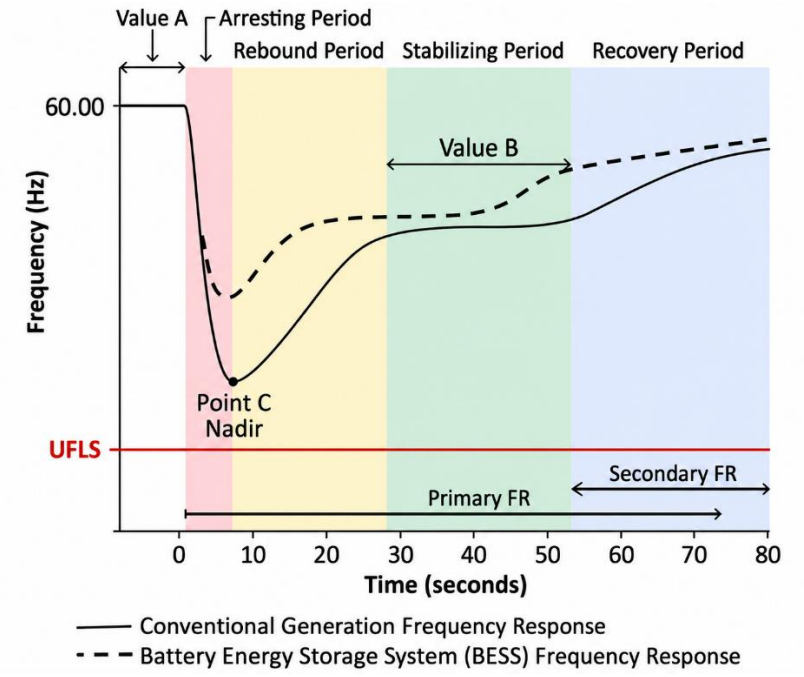


Figure 36: Frequency regulation form ESS[97]

The key metrics that characterise frequency performance are: RoCoF (Hz/s), determined by inertia and the size of the imbalance; nadir point (the lowest frequency reached), determined by inertia, FFR and the speed of primary response; settling frequency, determined by the aggregate drop of primary response; and the frequency response characteristic (FRC), expressed in MW/Hz, which represents the combined primary frequency response and frequency-sensitive load damping, as defined below:

$$FRC = \frac{\Delta P}{\Delta f_{settling}} \left[\frac{MW}{Hz}\right]$$

The Indian Electricity Grid Code (IEGC) 2023 specifies an operating frequency band of 49.90–50.05 Hz and requires primary response from eligible generators.[98] The reference contingency for frequency-response planning was initially specified as 4,500 MW. Under-frequency load shedding (UFLS) typically begins at 49.40 Hz.

The CERC's Ancillary Services Regulations, 2022, established the SRAS, procured by the system operator on an administered basis, and the TRAS, procured both administratively and through the power exchanges, which allow energy storage and demand response to provide ancillary services.[99] The CERC's September 2026 draft amendment to the IEGC proposes that standalone ESS of 10 MW and above connected at 33 kV and above must participate in primary frequency response with a droop setting in the range 0-10%, and that storage of 25 MW and above (excluding PSP) support automatic dispatch by load dispatch centres.[100] There is, however, no separately defined and remunerated *fast frequency response* product in India, whereas such products exist in Great Britain (*Dynamic Containment*, full delivery within 1 s), Australia (*Very Fast FCAS*, 1 s), ERCOT (*FFR*, full response within 15 cycles) and Ireland (*FFR* within 2 s under DS3), as further elaborated in Table 33.[101,102]

[97] North American Electric Reliability Corporation, State of Reliability 2025: Overview, NERC, Atlanta, GA, USA, 2025.

[98] Central Electricity Regulatory Commission, Central Electricity Regulatory Commission (CERC), Indian Electricity Grid Code) Regulations, MOP, 2023.

[99] Central Electricity Regulatory Commission, Central Electricity Regulatory Commission (Ancillary Services) Regulations, 2022.

[100] Central Electricity Regulatory Commission, Central Electricity Regulatory Commission (Indian Electricity Grid Code) (Second Amendment) Regulations, 2026 (Draft), Regulations (Central Electricity Authority (CEA), Ministry of Power, Govt. of India, 2026).

[101] National Grid Electricity System Operator (National Grid ESO), *Stability Market Design Innovation Project: Thought Piece*, Mar. 2022.

[102] Australian Energy Market Operator, 2024 Integrated System Plan (ISP) (Australian Energy Market Operator, 2024); Electric Reliability Council of Texas, 'NOGRR272: Advanced Grid Support Requirements for Inverter-Based ESRs', 2025.

Table 33: Frequency-response products: India compared with selected international systems

Product	India	Great Britain	Australia (NEM)	ERCOT / Ireland
Inertia / stability	Not procured separately; GFM advisory for new BESS (Jul 2026)	Stability Pathfinder / Stability Market	System-strength and inertia frameworks; GFM batteries	Ireland: Low Carbon Inertia Services; SNSP ≤ 75%
Fast frequency response	No distinct product	Dynamic Containment: full delivery ≤ 1 s	Very Fast FCAS: 1 s	ERCOT FFR: ≤ 15 cycles (0.25 s); Ireland FFR: 0.15–2 s
Primary response	Mandatory droop for generators; draft PFR for ESS ≥ 10 MW	Dynamic Moderation/Regulation	Primary frequency response mandatory; contingency FCAS (6 s, 60 s)	ERCOT Responsive Reserve; Ireland FCR/POR
Secondary	SRAS (AGC) – administered	Balancing Mechanism; quick reserve	Regulation FCAS	ERCOT Regulation
Tertiary	TRAS – administered and market-based	Slow reserve; balancing reserve	Delayed FCAS (5 min)	Non-spin; replacement reserves

.*Data Compiled from Multiple Sources*

4.3.2 Indian Experience: Khavda event of 13 May 2026

Case study: Largest generation loss in Indian Grid History[103]

Sequence. At about 14:02, a voltage dip, likely linked to a fault on the 400 kV Indore-Asoj line, was followed by low-frequency oscillations of about 0.458 Hz observed between 14:02 and 14:06. At 14:09, within about 16 seconds, the Khavda complex lost 8,963 MW of generation; 17 EHV lines tripped (eight at 765 kV and nine at 400 kV). The three pooling stations (KPS-1, KPS-2 and KPS-3) together hosted about 15.9 GW (14.8 GW RE and 1.1 GW BESS).

Frequency impact. All-India frequency fell by 0.56 Hz, from 49.953 Hz to 49.398 Hz. UFLS operated at 49.40 Hz but shed only about 6,000 MW against a requirement of about 12,000 MW. Most pumped-storage plants did not provide the expected automatic load relief.

Causes identified. Low SCR at the pooling stations (2.58, 4.41 and 4.65 against a CEA minimum of 5); three successive LVRT events; RE plants continuing to inject reactive power after the voltage dip cleared, which likely caused overvoltage and the tripping of plants and evacuation lines.

Actions recommended. Grid-forming inverters for new BESS above 50 MW (and a share of GFM capacity in new RE plants); expedited STATCOM commissioning at Khavda; synchronous condensers; uniform SCR computation; inverter-level data at 1 ms resolution from RE developers.

Relevance for storage. The event shows that (i) fast frequency response must be sized for common-mode CBR losses of up to ~9 GW, not only for the 4,500 MW reference contingency; (ii) reactive-current behaviour during and immediately after faults is as important as active-power response; (iii) BESS in weak grids should be grid-forming; and (iv) PSP pumping-load relief must be specified and tested.

The Khavda event was the most severe of a series. The CERC Chairperson reported 68 major renewable-related grid disturbances between January 2022 and June 2025, with generation losses of 1–7 GW per event, concentrated in Rajasthan and Gujarat and associated with non-compliance with LVRT and HVRT requirements[104]. In recent years, Grid-India also flagged severe oscillation events during high RE generation hours affecting the Bhadla-Bikaner-Fatehgarh complex of Rajasthan.

Storage mapping: FFR and synthetic inertia from GFM BESS; primary response with droop; SRAS; PSP pump-tripping schemes for load relief.

Critical attributes: Response time (< 200–500 ms for FFR), power headroom reserved in both directions, energy reserve for 10–30 minutes of sustained response, and correct behaviour during low-voltage conditions.

4.4. Voltage stability and dynamic voltage control

4.4.1 Steady-state and Dynamic Voltage Challenges

Voltage challenges in CBR-dominated grids emerge across multiple timescales, from fast transient phenomena to slower, system-wide voltage dynamics:

- **Steady-state overvoltage at light load:** At midday, when RE output is high and long EHV lines are lightly loaded, line charging leads to overvoltage. During such instances operators switch shunt reactors and, where necessary, open lines. In RE complexes, overvoltage is exacerbated when RE plants operate at unity or fixed power factor rather than in voltage-control mode.

[103] Western Regional Power Committee, Report of the Committee on Grid Disturbance at Khavda Pooling Station occurred on 13.05.2026, WRPC/Prot/GD/2026/2973-298/, 5 Oct 2026.

[104] Grid Controller of India Limited (GRID-INDIA), "Monthly Grid Disturbance and Grid Event Reports," Regional Load Despatch Centres (RLDCs), Ministry of Power, Government of India, New Delhi, India.

- **Dynamic voltage recovery after faults:** During a fault the dip in the bus voltages are observed. Post fault clearance, bus voltages must recover quickly to it's nominal operating range. CBRs must ride through the voltage dip (low-voltage ride-through, LVRT), inject reactive current, and restore active power promptly afterwards. Inadequate or poorly tuned responses delay recovery. In systems with large induction-motor loads, slow recovery can cause fault-induced delayed voltage recovery as motors stall, which is a growing concern in Indian cities with rapidly increasing AC load.
- **Post-fault overvoltage:** If CBRs continue injecting reactive current after the fault is cleared, or if their active power recovers slowly while reactive injection persists, voltages overshoot, and plants trip on high-voltage protection (HVRT) limits. This mechanism was identified during events in Khavda and Rajasthan and was central to the Iberian blackout of 28 April 2025, in which an overvoltage cascade disconnected about 2.5 GW within 78 seconds.[105]
- **Reactive-current priority:** During faults, grid codes typically require CBRs to prioritise reactive current proportional to the voltage deviation ($\Delta Iq = K\Delta V$, with K typically ranging between 2-6 per unit), limiting active current to stay within the converter current rating. The settings of K, the dead band, and the post-fault ramp-back of active power have a first-order effect on system stability.

The CEA Technical Standards for Connectivity require wind and solar plants to remain connected when the voltage at the interconnection point falls to 0.15 pu for up to 300 ms and specify reactive power capability and HVRT requirements.[106] During the voltage dip, reactive-power support receives priority, while active power must recover to at least 90% of its pre-fault value within one second after voltage restoration. Compliance and performance verification, rather than the requirements themselves, have been the main weakness with several RE generators failing to comply with it during operational stage. The 2026 draft for the grid connectivity standard revises these provisions for the next generation of plants.[107]

[105] ICS Investigation Expert Panel, Grid Incident in Spain and Portugal on 28 April 2025, Final Report (European Network of Transmission System Operators for Electricity (ENTSO-E), 2026.

[106] Central Electricity Authority, Central Electricity Authority (Technical Standards for Connectivity to the Grid) (Amendment) Regulations, 2019.

[107] Central Electricity Authority, 'Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026', Draft Regulations, Central Electricity Authority, Ministry of Power, Government of India, July 2026.

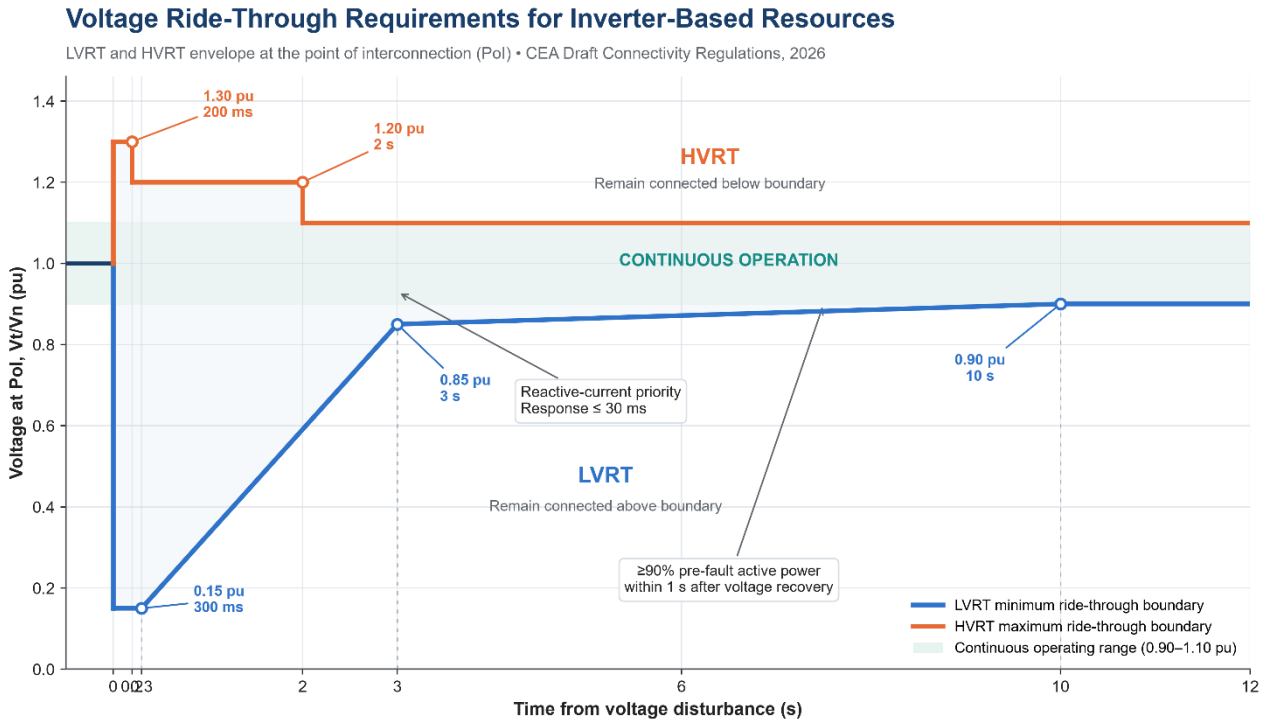


Figure 37: Low- and high-voltage ride-through envelope for CBRs, and the region of reactive-current injection as per the CEA Technical Standards for Connectivity to the Grid

(Source: This figure has been plotted using data sources from CEA connectivity regulations and the identified 2026 draft)

4.4.2 Voltage-control coordination

Voltage control in RE complexes requires coordination among several layers: the plant-level controller of each CBR plant to control voltage, reactive power, or power factor mode at POI, the pooling-station devices like STATCOMs, SVCs, shunt reactors, capacitor banks, synchronous condensers, and transformer tap changers, and the regional control centre. The lesson learnt from the Iberian blackout, which states that plants in fixed power-factor mode amplify voltage swings rather than damping them, argues for requiring voltage-control mode with coordinated droop as the default for large CBR plants and storage in India.[108] Energy storage has a particular advantage here: a BESS PCS can provide reactive power at without substantial battery-energy discharge, including during standby operation, subject to converter MVA limits, auxiliary supply, DC-link conditions and control settings.

4.4.3 Distribution-level voltage issues

At the distribution level, rooftop solar and feeder-level solar cause voltage rise and reverse power flow, particularly on long rural feeders with high resistance-to-reactance (R/X) ratios. The approximate voltage, ΔV, change along a feeder is given by below equation:

$$\Delta V \approx {(P \cdot R + Q \cdot X)}/{V}$$

On overhead LV and 11 kV feeders, R is comparable to or larger than X, so active-power injection (P) has a large effect on voltage and reactive-power control (Q) is relatively ineffective. This is why active-power control by energy storage is often more effective than inverter Volt-VAR control on weak rural feeders. Reverse flows also increase on-load tap-changer (OLTC) operations, stress distribution transformers, and complicate protection. DISCOMs have responded by limiting new rooftop connections or imposing export limits; distribution-level storage and smart-inverter functions (Volt-VAR, Volt-Watt) can instead raise hosting capacity.

[108] ICS Investigation Expert Expert Panel on the Grid Incident on 28 April 2025, Grid Incident in Spain and Portugal on 28 April 2025: ICS Investigation Expert Panel Final Report. European Network of Transmission System Operators for Electricity (ENTSO-E), Mar. 20, 2026 Panel, "Grid Incident in Spain and Portugal on 28 April 2025.

Storage mapping: Dynamic reactive current from BESS PCS; GFM voltage-source behaviour; charging to absorb midday surplus on feeders; coordinated voltage control.

Critical attributes: MVA headroom, reactive-current response time (< 30–60 ms), control mode, and coordination with other voltage-control devices.

4.5. Converter-driven Stability & System Strength

4.5.1 Grid-following inverters and their limits

Almost all CBRs in India today are grid-following (GFL), since they measure the grid voltage angle with a phase-locked loop (PLL) and inject a controlled current in synchronism with it. GFL control works well in strong grids but has inherent limitations in weak grids.[109]

- **PLL instability:** Under weak-grid conditions (low SCR), the inverter's injected current significantly influences the voltage at the point of connection, potentially destabilizing the PLL and causing loss of synchronization. The stability threshold depends on the PLL bandwidth, converter control parameters, and grid impedance.
- **Control interactions:** Slow interactions between PLLs and outer power/voltage controls of multiple nearby plants, and fast interactions between current controllers and network resonances (hundreds of Hz to kHz).
- **Sub-synchronous and super-synchronous oscillations**: These oscillations can arise from interactions between inverter control systems and grid impedance, particularly in weak grids and series-compensated networks. Such oscillations have been widely reported internationally in wind farms and weak-grid PV clusters, including observations in India's Rajasthan renewable energy complexes[110].
- **Fault ride-through failures**: During deep faults, the PLL may lose track of the voltage angle; after faults, current-limited controllers may recover poorly, causing repeated dips or trips. Plant-controller coordination, protection settings and accurate simulation models are therefore important.
- **Absence of inherent inertia and limited fault current**: GFL inverters provide no inertia and typically only 1.0-1.2 pu fault current. Their response depends on control settings and short-term current limits.

4.5.2 Grid-forming converters

Grid-forming (GFM) converters behave as controlled voltage sources behind an impedance: they set their own internal voltage magnitude and phase angle and adjust them in response to power imbalances, much as a synchronous machine does.[111] As a result, GFM converters provide an instantaneous response to changes in grid voltage and angle (including inertia-like behaviour), can operate stably in very weak grids and islands, can black-start networks and help damp oscillations. Table 34 compares the two technologies, and Figure 38 shows their simplified control structures.

Table 34: Grid-following versus grid-forming converters

Attribute	Grid-following (GFL)	Grid-forming (GFM)
Electrical behaviour	Controlled current-source operation, typically using a PLL to estimate the grid-voltage phase angle	Controlled voltage source behind an impedance; sets its own voltage angle and magnitude
Synchronisation	PLL	Internal voltage-angle control; PLL may be

[109] Xiongfei Wang et al., 'Grid-Synchronization Stability of Converter-Based Resources—An Overview', IEEE Open Journal of Industry Applications 1 (2020): 115–34, https://doi.org/10.1109/OJIA.2020.3020392.

[110] Aleksandar Boričić et al., 'System Strength: Classification, Evaluation Methods, and Emerging Challenges in IBR-Dominated Grids', 2022 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), 2022, 185–89,.

[111] Wang et al., 'Grid-Synchronization Stability of Converter-Based Resources—An Overview'; Boričić et al., 'System Strength: Classification, Evaluation Methods, and Emerging Challenges in IBR-Dominated Grids'.

Attribute	Grid-following (GFL)	Grid-forming (GFM)
		used for monitoring or synchronisation during transitions
Response to grid disturbance	After measurement and control delays (tens of ms)	Instantaneous (sub-cycle) inherent response to voltage/angle changes
Inertia	Non-inherent; can provide FFR after detection of frequency or RoCoF change	Can provide inertia-like frequency response depending on the implemented GFM control strategy, subject to available power headroom, energy, and converter limits.
Weak-grid performance	Degrades below SCR ≈ 2–3; oscillation risk	Stable at very low SCR (CEA advisory requires stable operation at SCR ≤ 2)
Fault current	~1.0–1.2 pu, controlled	Voltage-source response up to current limit (e.g., 1.5 pu for 200 ms per CEA advisory, if rated)
Islanding and black start	Cannot form an island without a voltage reference	Can form and sustain islands; black-start capable
Oscillation damping	Can create interactions	Can provide damping (e.g., 0.1–20 Hz range in CEA advisory)
Design implications	Standard	Requires current and energy headroom, advanced current limiting, EMT-validated models
BESS Chemistry dependence	None (control property)	None (PCS/control property, constrained by DC-side energy and converter rating)

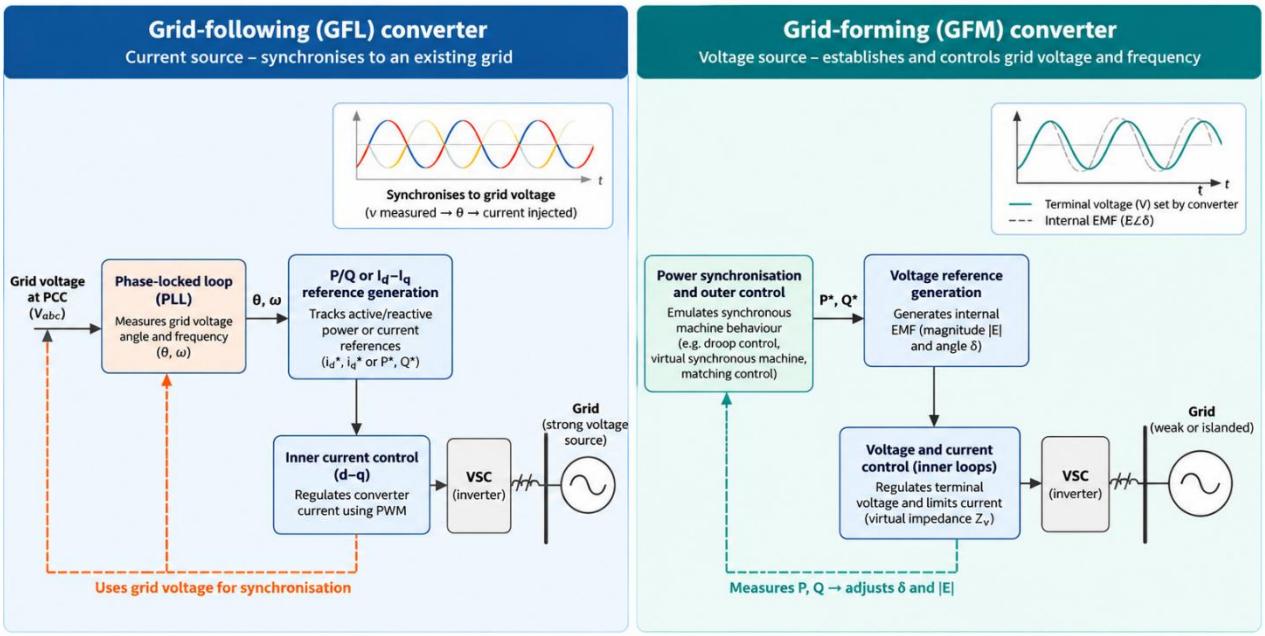


Figure 38: Simplified control structure for grid-following and grid-forming converters

(Source: This figure has been adapted from R.Rosso et. al)

4.5.3 Solutions to address low system strength

In literature and field practice, several complementary measures are adopted to address low system strength including transmission reinforcement; synchronous condensers by providing inertia and high fault current of 5–7 p.u.; STATCOMs for fast reactive power, but conventional GFL STATCOMs do not add system strength in the same way, GFM STATCOMs with small energy buffers; GFM BESS acting as voltage-source behaviour, synthetic inertia, damping and black start; GFM retrofits or partial GFM in RE plants (the draft CEA regulations propose at least 15% GFM inverters in new solar and wind plants from July 2027)[112]; and PSP units in condenser mode. The optimal combination is location-specific and must be determined by EMT studies with validated models.

Storage mapping: GFM BESS at the pooling stations; hybrid GFM BESS + synchronous condenser (Section 13.5).

Critical attributes: GFM control performance (Section 13.3), short-term overload capability, DC energy reserve, validated RMS/EMT models.

4.6. Network congestion

4.6.1 Types of Congestion

Network congestion must be analysed at three levels, since the appropriate response differs based on the operating criteria applied:

1. **Local RE evacuation**: The pooling station transformers, radial lines or first substations cannot carry the full output of connected RE during certain operating conditions. Rajasthan's experience in 2025 (about 23 GW connected against about 18.35 GW of effective evacuation capability, with plants operating under Temporary General Network Access and near-total curtailment of some plants at midday even after the 765 kV Khetri-Narela line was commissioned) is the clearest example.[113] Local congestion is often time-limited: it may occur

[112] Central Electricity Authority, 'Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026'.

[113] Vibhuti Garg and Prabhakar Sharma, 'Green Power Transmission: The Invisible Barrier in India's Clean Energy Growth', in Institute for Energy Economics and Financial Analysis (IEEFA), 2025.

during high-RE periods and can be relieved through network augmentation, operational measures or appropriately located storage.

2. **Inter-state and inter-regional transfer**: Power transfers between states and regions are constrained by thermal limits, voltage and stability requirements, and applicable security criteria. India's inter-regional transfer capacity was about 120 GW in December 2025 and is planned to rise to 143 GW by 2027 and 168 GW by 2032. 25 ISTS projects have been delayed due to right-of-way issues.[114] The National Electricity Plan (Volume II: Transmission) and the CEA's plan to integrate over 500 GW of RE by 2030 set out the required corridors.[115] The CERC has proposed dynamic congestion charges of ₹3–10/kWh linked to deviation-settlement rates.[116]
3. **Distribution constraints**: Distribution transformers and feeders in systems with a high penetration of rooftop solar may get overloaded by reverse power flow at midday or by evening peaks, which need to be considered during operational planning and dispatch. The effectiveness of feeder-level storage depends on its location relative to the constrained network element.

4.6.2 Storage Deferral versus Network Reinforcement

Energy storage can relieve congestion by charging on the export side of a constraint during periods of high RE generation and discharging later when sufficient evacuation capacity is available, or by discharging on the import side during peak loading.

It can also act as a virtual transmission resource when coordinated storage at suitable locations modifies power transfers and provides contingency support. Such arrangements require operator-approved control schemes and cannot be assumed to increase the physical transfer capacity of a corridor. The choice between energy storage and reinforcement depends on the characteristics summarised in Table 35.

Table 35: Storage for congestion relief versus network reinforcement: decision criteria

Criterion	Favourable Grounds for ESS	Reinforcement requirement
Duration and frequency of congestion	Congestion lasts a few hours per day on a limited number of days	Congestion is persistent, many hours per day, growing
Energy trapped per congestion event	Small relative to storage MWh	Large (would require very large storage)
Load/RE growth rate	Slow or uncertain growth; bridging is needed until a line is built	Rapid, certain growth
Lead time	Line lead time is long (3-4+ years; RoW risks), and storage can be built in 6–18 months	The line can be built quickly
Additional value streams	Storage can also earn arbitrage, reserves, and voltage support	Line provides decades of low-cost bulk transfer, reliability, and market integration

[114] Ministry of Power, Government of India, "Strengthening Transmission Infrastructure for Integration of Renewable Energy," Press Information Bureau (PIB), New Delhi, India, Mar. 23, 2026.

[115] Central Electricity Authority, Transmission System for Integration of over 500 GW RE Capacity by 2030, Transmission Planning Report (Central Electricity Authority, Ministry of Power, Government of India, 2022); Central Electricity Authority, National Electricity Plan, Volume I: Generation.

[116] Central Electricity Regulatory Commission, Rate of Congestion Charge in Real-Time Operation in Inter-State Transmission of Electricity, Order Petition No. 1/SM/2026, 2026.

Relocation option	Modular BESS can be relocated after reinforcement	Not applicable
Security	Storage-based remedial action (virtual line) accepted by the operator	Operator requires physical N-1 capacity

Worked Example: Pooling-station BESS versus Grid reinforcement

A pooling station has 3,000 MW of solar connected, but 2,400 MW of evacuation capability for 18 months until a new line is commissioned. On a clear day, solar output exceeds 2,400 MW for about 5 hours with a peak excess of about 500 MW; the trapped energy is about 1,500 MWh per day (≈300 days a year).

- **Without storage:** ≈450 GWh/yr curtailed. At ₹2.5-3.0/kWh, ≈₹110–135 crore/yr of foregone RE revenue (and higher system cost if replaced by thermal generation).
- **With a 500 MW / 2,000 MWh BESS:** Almost all trapped energy is shifted to the evening (≈1,500 MWh/day × 0.86 RTE ≈ 1,290 MWh/day discharged), where it is worth more. After the line is commissioned, BESS continues to provide evening-peak supply, reserves and voltage support.
- **Conclusion:** ESS can mitigate constraints during the interim period while retaining long-term system value after transmission expansion. The appropriate strategy is therefore "storage and transmission," with storage sized according to its enduring system role.

Storage mapping: Congestion relief; network deferral; virtual transmission (with remedial action schemes).

Critical attributes: Location, MWh relative to trapped energy, response speed in contingency-based schemes, and the possibility of device relocation.

4.7. Protection in converter-dominated networks

Protection systems were traditionally designed for networks in which faults are fed by synchronous machines that deliver large, predictable currents (typically 5–7 times rated current, with well-defined sequence components). The rapid growth of CBRs has led to a fundamental change in these assumptions as converter fault-current magnitude, phase angle and sequence components depend on control settings and current limits. India's protection framework requires these characteristics to be considered during relay coordination and periodic protection reviews. Table 36 summarises the principal challenges and mitigation options.

- **Limited fault current and current limiting:** Converters must protect their semiconductor circuits, so fault current is limited to about 1.0-1.2 pu for GFL designs and typically 1.2–2 pu for GFM designs, depending on the converter's short-term overload rating (the CEA advisory of July 2026 requires at least 1.5 pu for 200 ms from GFM BESS).[117] Overcurrent relays and fuses may not operate or may operate slowly, especially in parts of the network fed predominantly by CBRs.
- **Sequence-current behaviour:** Many protection functions, such as directional elements, fault-type selection, and some distance-protection schemes, rely on negative-sequence current. Traditional GFL controls suppress

[117] Central Electricity Authority, "Advisory for implementation of 100% Grid Forming Invertors (GFMs) in all upcoming BESS projects," Ministry of Power, Government of India, New Delhi, India, Jul. 2026

negative-sequence current; IEEE 2800-2022 now requires CBRs to inject negative-sequence current during unbalanced faults in a specified way.[118] India's requirements should be harmonised accordingly.

- **Distance protection:** CBR-controlled fault currents with unusual phase angles, combined with fault resistance and limited magnitude, can cause distance relays to mis-measure impedance (under- or over-reach) or misclassify fault types. Power-swing blocking logic may also mis-operate during converter-driven oscillations.
- **Directional protection:** Negative-sequence-polarised directional elements may be unreliable when CBR negative-sequence contributions are small or controlled. Alternative polarisation methods or communication-assisted schemes may be required.
- **Coordination:** Fault levels vary widely between high-RE midday and low-RE night conditions, complicating relay grading. Adaptive settings or multiple setting groups may be needed.
- **Island detection and anti-islanding:** Distributed CBRs must detect unintentional islands (passive RoCoF/vector-shift methods or active methods). As system RoCoF rises during large events, RoCoF-based anti-islanding relays risk tripping large amounts of distributed generation unnecessarily, a lesson learnt from the GB disturbance event of 9 August 2019.[119]
- **DC faults in BESS:** BESS operate at up to 1,500 V DC and can experience very high prospective short-circuit currents from battery racks. DC arcs do not self-extinguish at current zeros, so DC fuses, DC breakers, insulation-monitoring devices and arc-flash studies are essential. Ground faults on floating DC systems must be detected before a second fault creates a short circuit.
- **GFL versus GFM differences:** GFM converters behave more like voltage sources during faults before reaching current limits, which can improve protection performance, but their current-limiting strategy may employ virtual impedance, current saturation or transition to current-control operation. This strategy determines the magnitude, angle, and sequence content of the fault current and must be modelled in protection studies. GFM capability alone does not guarantee reliable operation of conventional overcurrent or distance protection.

Table 36: Protection challenges with high CBR penetration and mitigation options

Challenge	Effect	Mitigation (including storage role)
Low fault current	Overcurrent relays/fuses do not operate or are slow	Synchronous condensers; GFM BESS with overload rating; differential and communication-assisted protection; adaptive settings
Non-standard fault-current angle and sequence content	Distance relays mismeasure; directional elements maloperate	IEEE 2800-style negative-sequence requirements; relay algorithms tested with CBR EMT models
Varying fault levels	Coordination difficult between high- and low-RE conditions	Adaptive/setting-group protection; wide-area protection
Power swings and oscillations	Power-swing blocking/out-of-step mis-operation	Damping (GFM, POD), updated swing-detection logic
Anti-islanding and RoCoF relays	Nuisance tripping of DERs during system events	Harmonised RoCoF withstand (e.g., ≥1–2 Hz/s) and ride-through for DERs
DC faults in BESS	High DC fault currents; arc flash; fire initiation	DC fuses/breakers, IMDs, arc-flash studies, rack-level disconnects

[118] 'IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems', IEEE Std 2800-2022, 2022, 1–180.

[119] Office of Gas and Electricity Markets (Ofgem), "9 August 2019 Power Outage Report, Investigation Report", Office of Gas and Electricity Markets, 2020.

Transformer inrush during energisation	Nuisance trips; voltage dips	Soft energisation by GFM BESS; point-on-wave switching

Storage mapping: Fault-current contribution from GFM BESS rated for short-term overload; soft energisation; support for protection schemes through fast, predictable behaviour.

Critical attributes: Overload rating (p.u. and duration), current-limiting strategy, negative-sequence behaviour, validated EMT models shared with protection engineers.

4.8. Power quality issues

Increasing penetration of CBRs requires greater attention to harmonic distortion, resonance, voltage fluctuations and unbalance. These issues depend on converter design, network impedance and the interaction of multiple connected devices.

- **Harmonics**: Characteristic and non-characteristic harmonics from converter switching and control, equiring compliance with applicable harmonic limits at the point of common coupling (PCC). The CEA connectivity regulations reference IEEE 519-2014, as amended from time to time, for specified requirements. IEEE 519-2022 is the current edition [120].
- **Interharmonics and supraharmonics**: Components at non-integer multiples of fundamental frequency and higher-frequency components associated with converter switching and control interactions can interfere with metering, power-line communication and sensitive equipment. Their significance depends on the equipment and network characteristics.
- **Resonance**: Interaction of converter output filters and cable/line capacitance with network inductance can create parallel or series resonances that amplify harmonics; large collector cable networks in solar parks and BESS plants are susceptible. Harmonic impedance studies are therefore important when multiple converters share a pooling station.
- **Flicker and rapid voltage changes**: From fast PV fluctuations under passing clouds, particularly on weak distribution feeders. Appropriately controlled BESS may reduce these fluctuations, subject to available power and energy capacity.
- **Converter switching interactions**: Interactions among multiple converters and network impedance, potentially leading to harmonic amplification, resonance, and control instability, particularly when converters have similar switching frequencies or overlapping control bandwidths.
- **Voltage unbalance**: From uneven single-phase rooftop PV connections on LV networks. Compensation requires suitable phase-specific converter controls and current capacity.

Different power quality issues caused by increasing CBRs and it's mitigation in summarised in Table 43:

Table 37: Power-quality issues, causes and mitigation

Issue	Main causes	Standard / limit	Mitigation (including storage)
Harmonics	PWM switching, control, and non-linear loads	IEEE 519-2022; IEC 61000-3-6	Filter design; harmonic studies; BESS PCS as active filter (where rated)

[120] 'IEEE Standard for Harmonic Control in Electric Power Systems', IEEE Std 519-2022 (Revision of IEEE Std 519-2014), 2022, 1–31, https://doi.org/10.1109/IEEESTD.2022.9848440; Central Electricity Authority, Central Electricity Authority (Technical Standards for Connectivity to the Grid) (Amendment) Regulations, 2019.

Interharmonics / supraharmonics	Control interactions; high-frequency switching	IEC 61000-2-2/-4-7 guidance	Control tuning; EMI filters; measurement campaigns
Resonance	Cable capacitance + network inductance + converter filters	Plant-specific studies	Frequency scans; damping resistors; active damping in PCS
Flicker	Cloud-driven PV fluctuations; weak feeders	IEC 61000-3-7	BESS smoothing; ramp-rate limits
Unbalance	Single-phase DERs	Grid code limits (typically ≤ 2–3%)	Phase balancing; three-phase BESS with unbalance compensation

4.9. Adequacy and Resilience

4.9.1 Prolonged low-RE periods and Non-solar Adequacy

As RE share grows in the country, resource adequacy must account for both peak demand and high net-load periods after sunset. Prolonged periods of low solar or wind generation can also create energy-adequacy challenges extending over several days. identify a Loss of Load Probability (LOLP) of 0.2% and Normalized Energy Not Served (NENS) of 0.05% as the reliability benchmarks adopted by CEA for the National Electricity Plan. The guidelines also provide for capacity-credit assessment of energy-limited resources, including storage.[121]

Energy storage adequacy assessment should consider its available discharge duration, charging opportunities and contribution during periods of system stress. The Ministry of Power guidelines recognise Effective Load Carrying Capability (ELCC) as a capacity-credit assessment method, with implementation dependent on data and modelling capabilities. Multi-year weather and demand scenarios are also needed to evaluate prolonged low-RE periods and determine the required storage power and usable energy.

4.9.2 Extreme weather, transmission outages and network islanding

India faces a wide range of climate hazards, including extreme heat, cyclones on both coasts, floods, landslides in the Himalaya and Western Ghats, and dust storms. These events can derate or damage generation, transmission and storage assets, disconnect RE complexes from load centres, and create islands. Heatwaves combine high demand with the derating of thermal plants, transmission lines, transformers and converters. For BESS, high ambient temperatures, dust exposure and inadequate cooling can affect available power, efficiency and equipment reliability. Flooding and cyclonic conditions introduce additional risks to site accessibility, electrical insulation, auxiliary supplies and communication systems.

Resilience-oriented energy storage planning must therefore consider location-specific hazards, thermal derating, equipment protection and the availability of stored energy during extended outages. Storage intended to support critical loads must also have suitable electrical isolation, local controls and independent auxiliary supplies.

4.9.3 Restoration and Black Start

India's restoration plans rely mainly on hydro and gas units with black-start capability. The Northern and Eastern grid failures of 30-31 July 2012, which affected more than 600 million people, remain the reference case for restoration planning. As the synchronous generators share falls, black-start resources become scarcer and more distant from RE-rich areas, and restoration paths must energise networks with high CBR content, long lines requiring with large charging currents and transformers requiring high inrush currents.

[121] Ministry of Power, "Guidelines for Resource Adequacy Planning Framework for India," Guidelines F. No. 09/01/2021-RCM, 2023).

The IEGC 2023 requires annual review of restoration procedures and mock trials covering applicable black-start and grid-forming capabilities. Regulation 34 also requires restoration studies to consider the cranking path, island stability, line and transformer charging, reduced fault levels and protection settings.

GFM BESS can provide black-start and island-forming capability close to load centres and RE complexes, provided that sufficient SOC is reserved and that energisation, synchronisation and load pick-up are designed and tested. The CEA advisory of July 2026 requires BESS to have a black-start capability of 50 MW or more.[122]

Storage mapping: Long-duration and multi-day storage; reserved SOC for resilience; GFM black start and island formation; backup for critical loads.

Critical attributes: Duration and energy, reserved SOC, GFM capability, equipment strengthening and reinforcement to survive extreme heat, flooding and cyclones.

4.10. Major Grid Events in RE Dominated Power System and Role of Energy Storage

Grid disturbances in India and other power systems highlight the importance of fault ride-through, voltage control, coordinated protection and validated inverter performance. Table 38 consolidates the Indian and international events cited in this report, along with key takeaways applicable to ESS.

Table 38: Selected grid events and role of energy storage

Event	Phenomenon	Impact	Possible Root causes	Role of Energy storage
Khavda, Gujarat (13 May 2026)	RE loss after voltage dip and oscillation	8,963 MW lost; Δf −0.56 Hz; UFLS short by ~6 GW	Low SCR; LVRT events; post-fault reactive injection; overvoltage; system protection schemes (preliminary analysis)	GFM BESS; size FFR for common-mode CBR loss; test PSP load relief
Rajasthan RE complex (May 2026)	Severe oscillation in 3.16 GW complex	Operator restrictions	Converter-driven interaction in weak grid; missing PMU data (6.7 GW) (preliminary analysis)	Damping by GFM; data and model requirements
68 RE disturbances (Jan 2022–Jun 2025)	Repeated RE tripping	1–7 GW per event	LVRT/HVRT non-compliance	Compliance testing and monitoring for all CBRs, including BESS
Rajasthan curtailment (2025)	Evacuation congestion, T-GNA restrictions	Up to 50–55% curtailment of some plants at peak hours	Transmission lag; low SCR; 400 kV bottlenecks	Pooling-station BESS as a bridge and long-term asset
Tamil Nadu curtailment litigation (2018–22)	Curtailment disputes	Revenue loss; regulatory proceedings	Opaque reasons; must-run vs PPA terms	Reason-coded curtailment data; storage reduces disputes

[122] Central Electricity Authority, "Advisory for implementation of 100% Grid Forming Invertors (GFMs) in all upcoming BESS projects," Ministry of Power, Government of India, New Delhi, India, Jul. 2026.

Northern/Eastern grid failure (30–31 Jul 2012)	Cascading blackout	>600 million people affected	Overloaded inter-regional corridors; inadequate defence plans	Black-start and restoration resources near load centres
Iberian blackout (28 Apr 2025)	Overvoltage cascade	Spain and Portugal blacked out	Insufficient dynamic voltage control; fixed-PF operation; oscillations	Voltage-control mode and dynamic reactive support from CBRs and BESS
GB event (9 Aug 2019)	Near-simultaneous loss of wind farm and gas plant, plus DER trips	~1.1 million customers disconnected	Offshore wind control interaction; RoCoF/vector-shift DER trips	FFR procurement; DER ride-through; RoCoF standards
South Australia (28 Sep 2016)	Wind farm tripping after multiple faults	State-wide blackout	Protection settings limiting repeated ride-through	Ride-through of multiple faults; GFM batteries later deployed
Odessa, Texas (2021, 2022)	Large-scale CBR tripping for remote faults	~1.1–2.5 GW lost	Inverter protection and control settings	Plant-level performance validation (NERC)

Data Compiled from Multiple Sources

4.11. Summary: Mapping Challenges to ESS Applications

Grid-integration challenges impose different requirements on ESS power, usable energy, response speed, converter control and location. Fast electrical support, energy shifting and long-duration adequacy are distinct services. ESS selection and sizing must therefore be based on the required service, operating conditions and validated system performance. Table 39 summarises the characteristics required form ESS for corresponding grid integration challenges.

Table 39: Mapping of ESS Characteristics to Grid Challenges and Applications

Challenge	Required storage service	Response time	Duration / energy	GFM needed?	Best-suited options
Evening ramp and net peak	Energy shifting, peak supply	Minutes	4-8 h	No (desirable)	4 h+ BESS, PSP
Midday over-generation / curtailment	Charging sink	Minutes	2-6 h	No	BESS, PSP (variable-speed preferred), flexible loads
Forecast uncertainty	Reserves (SRAS/TRAS)	Seconds–minutes	0.5-2 h	No	BESS, PSP, hydro
Large contingency / low inertia	FFR, synthetic inertia	< 0.5 s	10-30 min	Yes (for inertia)	GFM BESS, flywheel hybrid, synchronous condensers

Dynamic voltage / post-fault overvoltage	Dynamic reactive current	< 60 ms	Minimal	Preferred	BESS PCS (MVA headroom), STATCOM, sync condenser
Weak grid / oscillations	Voltage-source behaviour, damping	Sub-cycle	Minutes	Yes	GFM BESS, GFM STATCOM, synchronous condenser
Local congestion	Congestion relief, virtual line	Seconds (RAS)–hours	2-6 h	Preferred	Pooling-station BESS
Distribution voltage rise	Active-power absorption, Volt-VAR	Seconds	2-4 h	Optional	DT/feeder BESS
Low fault current	Short-term overcurrent	Sub-cycle	Seconds	Yes	GFM BESS with overload rating; synchronous condensers
Prolonged low-RE periods	Multi-day energy	Minutes	24-100 h+	No	PSP (large reservoirs), LDES, hydrogen
Black start / islanding	Grid formation, energisation	Sub-cycle	1-4 h reserved	Yes	GFM BESS, PSP, hydro

Chapter 4: Key Takeaways

- Energy balancing and congestion relief require appropriate storage duration, location, charging opportunities and coordinated dispatch. Storage complements thermal flexibility and network reinforcement. Frequency and voltage security require fast, reliable active- and reactive-power response. Large RE disturbances highlight the importance of coordinated controls, fault ride-through and reserve adequacy. Grid-forming BESS, synchronous condensers and transmission reinforcement offer complementary solutions for weak-grid conditions. Their selection requires validated dynamic and electromagnetic transient studies.
- Protection schemes must account for converter-limited fault currents, control-dependent fault behaviour and changing network conditions. Compliance testing and protection coordination are essential. Non-solar and prolonged low-RE periods require probabilistic adequacy assessment, while resilience and restoration applications depend on available stored energy, equipment design and verified black-start capability.

Chapter 5.

Energy Storage Applications and Grid Integration



Energy storage has diverse applications across the different levels of the power system such as generation, transmission, distribution, and end-use, making it a key enabler of flexibility, reliability, and RE integration. Energy storage supports grid stability and effective network functioning at the transmission level. It offers auxiliary services such voltage control, fast frequency response (FFR), VAR support, and frequency regulation. It also improves power factor correction, voltage regulation, and reliability at the distribution level, especially in networks with high rooftop solar penetration.

In India's power system, energy storage applications extend from bulk energy shifting and ancillary services to local voltage regulation, congestion relief, renewable firming and critical-load supply. The value of each application depends on the electrical location, power and usable energy capacity, response capability, operating constraints and required service duration. Indian BESS and pumped storage projects demonstrate several of these applications, while others require site-specific validation and appropriate regulatory arrangements.

5.1. Energy Storage Applications at the Transmission System Level

Transmission-level energy storage refers to the deployment of large-scale energy storage systems at transmission substations, generating stations, renewable-energy pooling stations, or other strategically selected nodes of the high-voltage network. Such systems can enhance system security, operational flexibility, and utilization of existing transmission assets by rapidly modulating active and, where converter capability permits, reactive power exchange with the grid. Their role is becoming increasingly important with the growing penetration of variable renewable energy (VRE) and CBRs, which can increase the variability of power transfers, alter system dynamic characteristics, and reduce the amount of synchronously connected generation available to provide conventional frequency and voltage support[123].

In India, the suitability of transmission-connected energy storage depends on the identified grid constraint and the service required. Energy balancing, frequency response, voltage support and congestion management impose different requirements on storage capacity, converter capability, location and dispatch.

5.1.1 Ancillary Services

One of the most important applications of transmission-connected energy storage is the provision of frequency-control and other ancillary services. ESS are particularly suitable for these applications as their active-power output can be varied rapidly and accurately over a wide operating range.

Depending on the applicable grid code, market structure, and control capability, ESS can provide services such as fast frequency response (FFR), primary frequency response, secondary frequency regulation, spinning or non-spinning reserve, contingency support, and ramp-rate control. Following a generation outage or sudden load increase, a BESS can rapidly inject active power to reduce the rate of frequency decline and assist in arresting the frequency deviation. Conversely, during periods of excess generation, the BESS can consume active power and support restoration of the generation-load balance.

The effectiveness of storage for frequency regulation is particularly relevant in systems with high penetration of converter-interfaced renewable generation, where conventional synchronous generation, and consequently naturally available rotational inertia and governor response, may be reduced. Advanced converter controls can further enable BESS to emulate inertial response or provide grid-forming frequency support under low-inertia operating conditions.

Indian operational evidence is available from GRID-INDIA's AGC pilots. In May 2025, the 20 MW/40 MWh Kilokari-1 BESS in Delhi successfully followed charging and discharging commands during closed-loop AGC testing. GRID-INDIA also conducted AGC tests on two 250 MW units of Tehri PSP in September 2025. The tests demonstrated controllable response but identified a limited regulation range in pumping mode at Tehri[124].

[123] R. R. Trivedi and Z. H. Rather, *Global Energy Storage Systems: A Critical Technical Review*. Mumbai, India: Indian Institute of Technology Bombay and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) India, Aug. 2026.

[124] Ministry of Power, Government of India, Annual Report 2025–26, New Delhi, India, Apr. 2026.

These demonstrations establish the technical feasibility of storage-based secondary frequency control in India. However, sustained ancillary-service delivery requires adequate energy reserves, available control range and compliance with dispatch instructions. The Kilokari pilot also identified operational restrictions associated with charging and discharging windows and cooling requirements. Routine participation and compensation remain subject to the applicable ancillary-service framework.

5.1.2 Voltage Regulation and Reactive Power Support

Converter-interfaced ESS can also contribute to transmission-system voltage control by regulating reactive-power exchange at the point of interconnection. Within the apparent-power and current limits of the power conversion system, the converter can inject or absorb reactive power to support local bus voltage and improve the voltage profile of the surrounding network. Such functionality enables ESS to provide Volt/VAR regulation, dynamic reactive-power support, and power-factor control. Unlike the active-power component of storage operation, reactive-power support does not necessarily require significant energy exchange with the battery and may therefore be available even when the battery's state of charge limits sustained active-power operation, subject to converter loading and control priorities and the availability of the DC-link and auxiliary power systems. During network disturbances, fast reactive-current injection can also assist voltage recovery. Consequently, appropriately designed ESS installations can complement conventional voltage-control resources such as synchronous condensers, shunt capacitors, reactors, static VAR compensators, STATCOMs, and E-STATCOMs.

In India, reactive-power support is particularly relevant at renewable-energy pooling stations and transmission nodes experiencing significant voltage variations. The Indian Electricity Grid Code, 2023, provides for voltage and reactive-power control through generator capability and instructions from the concerned load despatch centres. BESS can contribute to these requirements where suitable converter capacity, controls and verified dynamic performance are available.

Pumped storage can also provide reactive-power support through suitable generating or condenser operating modes. At the 1,000 MW Tehri Pumped Storage Plant in Uttarakhand, the first 250 MW variable-speed unit was synchronised with the grid in pump-condenser mode on 23 April 2025. THDC reported consumption of approximately 4 MW and 13.6 MVAr for about 10 minutes during the test. This demonstrates reactive-power exchange capability in pump-condenser mode, although the reported test does not establish sustained voltage-regulation performance during normal commercial operation[125].

For transmission-connected ESS, the required reactive-power rating and operating mode should therefore be determined through site-specific network studies. The available capability must be validated at the point of interconnection, considering active-power dispatch, converter MVA limits, voltage operating range and grid-code requirements.

5.1.3 Power-System Stability and Dynamic Support

Beyond conventional frequency and voltage regulation, transmission-connected ESS can contribute to the dynamic stability of the power system. The fast controllability of power-electronic converters allows supplementary control signals to be incorporated into ESS controllers for applications such as power and voltage oscillation damping and transient support. Grid-forming BESS can provide additional capabilities by establishing voltage and frequency references rather than solely following an externally imposed grid waveform. Such functionality can become important in weak-grid or low-inertia conditions and may support system operation where the proportion of inverter-based generation is high[126].

Depending on the converter design, protection architecture, and applicable grid-code requirements, transmission-connected BESS may also contribute to fault ride-through, post-disturbance voltage recovery, system restoration, and black-start operation. However, these capabilities are not inherent to every BESS. Their

[125] THDC India Limited, “THDCIL Landmark Achievement with Synchronization of 1st Unit of India's First 1000 MW Variable Speed Pumped Storage Plant in Pump Condenser Mode,” Apr. 24, 2025.

[126] Z. Chunyang, et al. "Grid-connected battery energy storage system: a review on application and integration." Renewable and Sustainable Energy Reviews, 2022.

provision requires suitable converter controls, current-limiting capability, operating headroom and validated dynamic performance. Site-specific RMS and electromagnetic transient studies are necessary to assess interactions with other CBRs and transmission-network controls.

5.1.4 Transmission Congestion Management

Transmission-level storage can also improve the utilization of transmission infrastructure through congestion management. When a transmission corridor becomes constrained, energy storage located on the receiving or sending side of the constraint can modify the pattern of power flows by charging on the generation side of an export-constrained corridor to reduce power injection or discharging on the load side of an import-constrained corridor to reduce power transfers during peak demand. The stored energy can be discharged or replenished when transmission capacity becomes available. This can reduce line and transformer loading, alleviate network bottlenecks, decrease renewable-energy curtailment, and improve the utilization of existing transmission assets.

In India, this application is particularly relevant to RE-rich regions facing transmission evacuation constraints. CEA's December 2025 National Committee on Transmission meeting recorded that transmission schemes for evacuating approximately 62 GW of prospective renewable capacity in Rajasthan had not been finalised[127]. Co-location of storage with RE generation was also advocated to improve transmission utilisation. BESS installed at suitable RE-energy pooling stations could consume generation during constrained export periods and discharge when transmission headroom becomes available. However, the effectiveness of this approach depends on the location, duration and frequency of congestion, available energy capacity and downstream network conditions.

A related application is transmission investment deferral. Conventional transmission reinforcement, such as construction of new lines, substations, transformers, or reconductoring of existing corridors, is generally planned to accommodate peak or contingency-driven loading conditions that may occur only during limited periods of the year. Strategically located storage can reduce these peak network stresses by shifting energy across time and providing localized capacity during critical operating periods. Where the constraint is sufficiently intermittent and the required storage duration is technically and economically feasible, storage can defer or reduce the scale of conventional transmission augmentation and may offer a faster-to-deploy alternative to network expansion subject to network security, reliability and cost-benefit assessments. Energy storage cannot replace transmission reinforcement where sustained power transfers exceed network capability, or the available storage duration is insufficient.

5.1.5 Renewable Energy Integration and Curtailment Reduction

Storage installed at or near RE pooling substations can consume surplus generation that would otherwise be curtailed when sufficient charging capacity is available, and the storage connection is not restricted by the same network constraint. The stored energy can subsequently be discharged during periods of lower renewable output, higher demand or greater transmission availability. This can improve the utilization of both renewable-generation assets and associated transmission infrastructure.

An operational Indian example is SECI's 100 MW solar PV project integrated with a 40 MW/120 MWh BESS at Rajnandgaon, Chhattisgarh, commissioned in February 2024. The system stores solar energy during generation hours and supplies electricity during non-solar peak periods to meet demand in Chhattisgarh. The project is connected to the 220/132 kV Thelkadih substation through a 132 kV transmission line[128]. It demonstrates the practical integration of solar generation with storage for evening peak supply, although the publicly reported project information does not quantify avoided renewable curtailment.

BESS can additionally provide renewable ramp-rate control, short-term output smoothing, and firming of aggregated renewable generation. These functions reduce rapid variations in power injected into the

[127] Central Electricity Authority, “Minutes of the 36th Meeting of the National Committee on Transmission, meeting held Dec. 30, 2025”, 2025.

[128] Ministry of New and Renewable Energy, “SECI Unveils India's Largest Solar-Battery Project, Pioneering Renewable Energy Innovation in Chhattisgarh,” Press Information Bureau, Government of India, Feb. 24, 2024.

transmission network and can improve the controllability of large renewable-energy complexes. Their effectiveness depends on the available charging and discharging headroom, energy capacity, plant-level controls and operating schedules. In India, storage located at renewable-energy pooling stations can support compliance with scheduled power injection and reduce short-duration output variations. However, curtailment reduction requires that the otherwise curtailed energy can physically reach the storage system and be discharged subsequently without violating network constraints.

GW-scale storage for Round The Clock power

Energy storage supports Round-the-Clock (RTC) and Firm and Dispatchable Renewable Energy (FDRE) supply by shifting renewable generation to periods when the contracted demand cannot be met directly. RTC power refers to the continuous supply of electricity, typically defined as availability for 24 hours a day or for predefined time blocks with high reliability. As solar and wind generation are inherently intermittent and time-dependent, large-scale (GW-level) energy storage is essential to bridge temporal gaps between generation and demand and to ensure firm power delivery.

PSP, BESS, and emerging long-duration storage technologies, enable the aggregation and firming of renewable energy over multiple hours or days. These systems store surplus energy generated during periods of high renewable output such as midday solar or high wind conditions and discharge it during low-generation periods, including night-time hours, the evening peak, or prolonged low renewable availability. By doing so, storage smooths variability, reduces curtailment, and enables renewable generators to meet contractual RTC power obligations. Every stage of the power value chain benefits from RTC power. The required storage capacity depends on the renewable generation profile, supply obligations, forecast uncertainty and permissible shortfalls. Figure 39shows the benefits of RTC power for different power sectors.

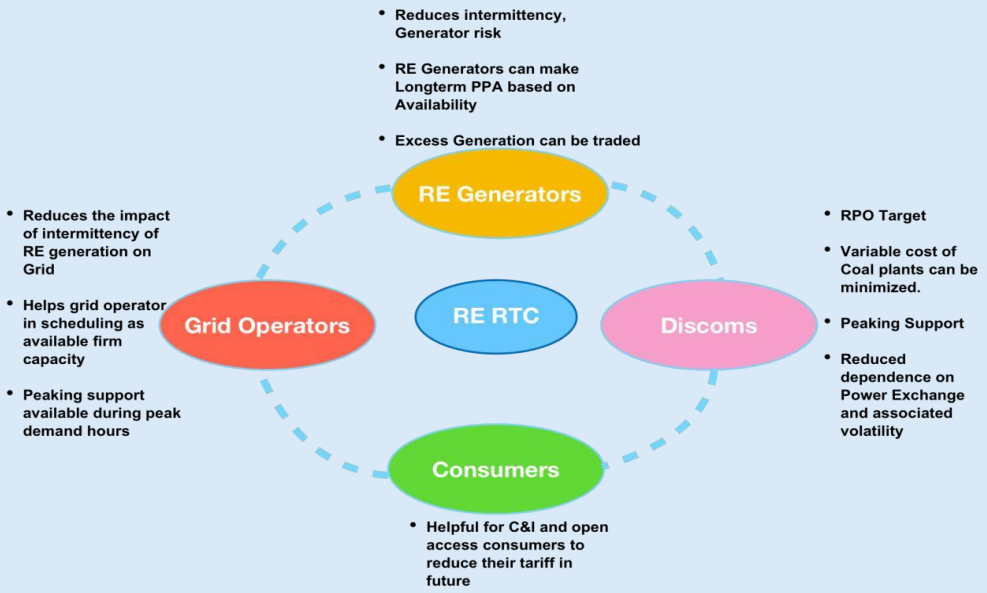


Figure 39: Advantages of RTC power for different sectors[129]

For Indian RTC and FDRE procurement, storage sizing must be aligned with the specified hourly demand profile, seasonal renewable availability and charging opportunities. BESS is suitable for short-duration balancing and peak supply, while PSP can provide bulk energy shifting over longer periods. Storage alone

cannot guarantee uninterrupted supply during prolonged renewable-generation deficits without sufficient energy availability or complementary resources. [129].

5.2. Applications of Energy Storage at the Distribution Level (11 kV / 33 kV)

Distribution-connected energy storage refers to energy storage systems deployed at distribution substations, 33/11 kV substations, 11 kV feeders, distribution-transformer locations, renewable-energy interconnection points, or other strategically selected nodes within the distribution network. Unlike bulk storage connected at the transmission level, distribution-connected storage is electrically located closer to the loads and distributed energy resources (DERs) responsible for many local network constraints. It can therefore directly influence feeder active- and reactive-power flows, transformer loading, voltage profiles, reverse power flow, and the utilization of existing distribution assets[130].

Indian distribution networks commonly include 33/11 kV substations, 11 kV feeders and low-voltage distribution systems, with configurations varying across utilities. However, long feeder lengths, relatively high feeder impedances, heavily loaded network elements, ageing infrastructure, and limited deployment of continuously controllable voltage-regulation equipment can contribute to voltage deviations, technical losses, equipment overloading, and reduced quality of supply[131]. The CEA specifically identifies energy storage as an emerging distribution-system technology for renewable-energy integration, peak-load management, voltage and frequency support, electric mobility, improved reliability, and deferral of transmission and distribution investment

The technical value of a distribution-connected BESS arises from its ability to independently schedule charging and discharging while using its power electronic converter to control both active power (P) and reactive power (Q). The simultaneous provision of these services is constrained by the converter current and apparent-power rating, as well as battery SoC, energy capacity, degradation limits, and network constraints[132]. Consequently, the location, rating, energy duration, converter capacity, and control strategy of the BESS strongly influence the services that can be provided to the distribution network.

India has operational distribution-connected BESS installations, including the 10 MW/10 MWh Rohini BESS and 20 MW/40 MWh Kilokari BESS in Delhi. These installations support the practical development of utility-scale storage for peak management, grid flexibility and supply reliability. However, the ability to relieve a particular feeder or transformer constraint depends on the electrical connection, dispatch schedule and available storage capacity.

5.2.1 Feeder Peak Shaving and Load Shifting

One of the principal distribution-level applications of energy storage is feeder and transformer peak-load reduction. The BESS can charge during periods of low network utilization or surplus renewable generation and discharge during periods of high demand. This reduces the maximum power transferred through upstream transformers and feeders and can improve the utilization factor of existing distribution infrastructure. Peak shaving is particularly valuable where network constraints are driven by relatively short-duration peaks. Examples include urban residential feeders with high evening demand, commercial areas with strong daytime peaks, agricultural feeders with concentrated pumping loads, and feeders supplying clusters of electric-

[129] Central Electricity Authority (CEA), "Techno-Economic Analysis of Renewable Energy Round-the-Clock (RE-RTC) Supply for Achieving India's 500 GW Non-Fossil Fuel Based Capacity Target by 2030," Ministry of Power, Government of India, 2024. Available:

[130] Central Electricity Authority, Electricity Distribution Network Planning Criteria, Ministry of Power, Government of India, 2023; published by CEA, Jan. 2024.

[131] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), "Analysis of Indian Electricity Distribution Systems for the Integration of High Shares of Rooftop PV," Aug. 2017.

[132] G. G. Farivar et al., "Grid-connected energy storage systems: State-of-the-art and emerging technologies," Proceedings of the IEEE, vol. 111, no. 4, pp. 397–420, Apr. 2023.

vehicle charging stations. The CEA's distribution planning criteria explicitly identify the possible use of BESS at distribution transformer level to reduce peak transformer loading[130].

An operational Indian example is Tata Power-DDL's 10 MW/10 MWh BESS installed at its Rohini substation in Delhi. Tata Power-DDL has reported charging its BESS installations during off-peak periods and discharging during peak demand conditions. This demonstrates the application of battery storage for distribution-level load shifting and peak management[133]. However, publicly reported information does not establish the actual reduction in peak feeder or transformer loading attributable to the Rohini installation.

Another example is the 20 MW/40 MWh standalone BESS commissioned at BSES Rajdhani's 33/11 kV Kilokari substation in Delhi in April 2025. The project is designed to support distribution-level peak demand management, renewable integration and grid stabilisation. Its nominal two-hour discharge capability can support concentrated demand peaks, subject to charging availability, dispatch schedules and operating constraints.

For Indian DISCOMs, feeder-level BESS sizing should be based on measured peak loading, the duration of network constraints, forecast demand growth and available charging periods. Storage placed downstream of an overloaded network element can reduce upstream loading during discharge. However, charging schedules must avoid creating new loading constraints, and the contribution to network capacity must be assessed under normal and contingency operating conditions.

5.2.2 Feeder Level Voltage Regulation and Reactive Power Support

Feeder-level voltage regulation refers to the control of voltage profiles along distribution feeders to ensure that customer voltages remain within statutory limits under varying load and generation conditions. Energy storage systems deployed at the feeder level, typically at 11 kV or near distribution transformers, can provide fast and localized voltage regulation when suitably located and configured. Using inverter-based control, BESS can inject or consume reactive power (VARs) independently of active power operation, enabling real-time voltage support at critical points along the feeder. During high rooftop solar generation and low load conditions, storage can consume reactive power to mitigate over-voltage, while during peak load periods it can supply reactive power to support low feeder voltages. The required reactive-power response depends on the feeder impedance, load and generation conditions.

In the Indian context, feeder-level voltage regulation is particularly relevant for long rural feeders, agricultural feeders, and urban networks with high rooftop solar adoption. Conventional voltage control devices such as on-load tap changers and capacitor banks operate through tap changes or switched compensation and may not respond to rapid voltage variations as flexibly as inverter-based controls[134]. Storage-based voltage regulation complements these devices by providing dynamic and continuous voltage control, potentially reducing unnecessary tap operations when coordinated with existing voltage-control equipment.

An Indian example is Tata Power-DDL's 10 MW/10 MWh BESS at Rohini, Delhi. The utility identifies Volt/VAR regulation and reactive-power management among the applications integrated with its Power System Control Centre, with provision for remote operation. This demonstrates the integration of voltage-support functions into a DISCOM-connected BESS control system. However, publicly available project information does not quantify reactive-power delivery or measured feeder-voltage improvement.

For Indian distribution networks, the effectiveness of BESS-based voltage regulation should be established through feeder load-flow studies and operating measurements. Converter reactive-power headroom, voltage sensitivity at the connection point and coordination with tap changers, capacitor banks and rooftop-PV inverters are important considerations.

[133] Tata Power Delhi Distribution Limited, “Tata Power Delhi Distribution Expects Peak Demand to Touch 2350 MW This Summer Season,” Mar. 2022.

[134] Central Electricity Authority, Electricity Distribution Network Planning Criteria, Government of India, 2023.

5.2.2.1. Mitigation of Voltage Rise and Reverse Power Flow

High penetration of rooftop PV and other distributed generation can result in periods during which local generation exceeds local consumption. Surplus power is then exported upstream through the distribution feeder, resulting in reverse power flow. Depending on the magnitude of export and feeder impedance, this can produce significant voltage rise toward the remote end of the feeder[135]. A BESS located electrically close to the distributed generation can charge during periods of excess generation. The reduction in net active-power export directly reduces reverse power flow and can substantially mitigate PV-induced voltage rise. Alam et al. demonstrated this principle using distributed storage to mitigate rooftop-PV impacts while retaining storage capacity for evening peak support[135]. Similar results have been reported using distributed BESS control for high-PV distribution networks.

In India, the 2019 *Energy Storage System Roadmap for India (2019–2032)* examined rooftop-PV integration across distribution feeders of six DISCOMs. The load-flow studies identified reverse power flow, voltage rise and other power-quality concerns associated with increasing rooftop-PV penetration. Complementing these findings, the Forum of Regulators examined the technical limits on rooftop-PV hosting capacity in Indian distribution networks, identifying feeder thermal constraints and overvoltage at the point of interconnection as key limiting factors.[136] Its analysis highlighted the importance of feeder-level assessments and appropriate network planning to accommodate increasing distributed solar generation. These findings are based on technical assessments and simulation studies rather than measured improvements following operational BESS deployment.

This distinction is important: active-power absorption through BESS charging directly addresses the excess generation causing reverse power flow, whereas reactive-power control principally modifies the voltage response to that flow. Therefore, coordinated (P-Q) control generally provides greater operational flexibility than using reactive-power absorption alone. For Indian feeders, the effectiveness of this application depends on the BESS location, available charging headroom, rooftop-PV generation profile and feeder impedance. Charging schedules must also preserve sufficient stored energy for subsequent peak-demand support where both services are required[137].

5.2.3 Distribution Congestion Management

Rapid growth in electricity demand, rooftop solar, electric mobility, and other DERs can create localized thermal constraints in distribution transformers, cables, overhead feeders, and substations. These constraints may occur even when substantial spare capacity remains elsewhere within the distribution system. A strategically placed BESS can modify the temporal pattern of power transfer through a constrained asset. Storage located downstream of a congested transformer or feeder can discharge during local peak demand and recharge when loading is lower. Similarly, storage located in a generation-dominated portion of the network can charge during periods of high DER export, reducing reverse loading of upstream equipment[132].

An Indian example is Tata Power-DDL's 150 kW/528 kWh Community Energy Storage System at Rani Bagh, Delhi, commissioned in March 2021. The installation was intended to manage peak loading of distribution transformers in a densely populated area where space for network augmentation was limited. Its operating strategy involves off-peak charging and peak-period discharge[138]. However, published utility information does not quantify the actual reduction in transformer loading.

A 2026 feeder-level in Visakhapatnam further examined this application. Simulations for a residential feeder reported that BESS integration reduced peak distribution-transformer loading from 160% to 131% under the

[135] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems," IEEE Transactions on Power Systems, vol. 28, no. 4, pp. 3874–3884, Nov. 2013, doi: 10.1109/TPWRS.2013.2259269

[136] Forum of Regulators, Report on Metering Regulation and Accounting Framework for Grid Connected Rooftop Solar PV in India. New Delhi, India: Forum of Regulators, 2019.

[137] India Smart Grid Forum, Energy Storage System Roadmap for India: 2019–2032, 2019, Chapters 3–4 and Annexure 2.

[138] Tata Power Delhi Distribution Limited, "Tata Power Delhi Distribution Collaborates with Nexcharge to Power Up India's First Grid Connected Community Energy Storage System," Mar. 27, 2021.

studied scenario. The results demonstrate potential congestion relief, although the reported peak loading remains above the nominal transformer rating.

For Indian DISCOMs, the effectiveness of congestion management depends on BESS location, the magnitude and duration of network overloading, available storage energy and charging schedules. The reduction in loading must be verified through feeder-level studies and operational measurements.

5.2.4 Distribution Network Upgrade Deferral

Congestion management can translate into longer-term distribution-investment deferral. Conventional reinforcement may involve installation of a larger distribution transformer, reconductoring a feeder, constructing an additional feeder, adding transformation capacity, or establishing a new substation. Where the network limitation occurs for a predictable and relatively limited number of hours, storage can reduce loading during those critical periods and postpone the year in which conventional reinforcement becomes necessary[132].

For Indian DISCOMs, the feasibility of network upgrade deferral should be assessed against projected feeder and transformer loading, the duration of peak constraints, BESS availability and future demand growth. Storage investment must be compared with conventional reinforcement costs while maintaining network reliability and required operating margins.

5.2.5 Enhancement of DER and Rooftop-PV Hosting Capacity

Distribution-network hosting capacity represents the amount of DER that can be connected without causing unacceptable violations of thermal, voltage, protection, or power-quality limits. In many radial feeders, voltage rise and reverse-flow constraints can limit additional rooftop-PV connection before the thermal capability of the conductor itself is reached. Storage can increase effective DER hosting capacity by absorbing excess generation, limiting feeder export, reducing voltage rise, and relieving transformer and feeder loading. Reactive power capability of the BESS converter provides an additional degree of freedom for regulating voltage[132].

This application is particularly relevant in India with increasing penetration of rooftop solar, feeder-level solarization, distributed renewable plants, and agricultural solar schemes. The 2019 Energy Storage System Roadmap for India assessed rooftop-PV hosting constraints using load-flow models of feeders from six Indian DISCOMs. The analysis showed that hosting limits depend on feeder loading, network configuration and voltage conditions[139]. More recently, APEPDCL modelled rooftop PV with BESS on distribution feeders in Visakhapatnam. The residential-feeder simulation showed elimination of reverse power flow and improved voltage conditions with BESS integration. These findings indicate the potential to accommodate additional distributed solar generation, although the increase in permissible PV capacity was not quantified.

Rather than curtailing RE generation or immediately reinforcing the network, strategically located storage can provide a controllable buffer between variable renewable generation and existing distribution infrastructure. However, storage cannot overcome protection, fault-level or persistent thermal constraints through charging alone. The achievable increase in hosting capacity must be established through feeder-specific studies considering BESS placement, charging availability, converter limits and network operating conditions.

5.3. Distribution-Level, Rural and Critical-Load Applications

In India, distribution-connected and local energy storage can address feeder peak loading, renewable-energy integration and supply reliability in rural, urban and island networks. The required storage configuration depends on local demand, network constraints, renewable generation and critical-load requirements. Existing Indian projects demonstrate several of these applications, while others remain prospective and require site-specific assessment.

[139] India Smart Grid Forum, “Energy Storage System Roadmap for India: 2019–2032,” 2019.

Table 40: Distribution, rural and critical-load storage applications

Application	Need	Storage configuration	Business model / enabler
Agricultural feeders (PM-KUSUM Component C)	Daytime solar supply to pumps; nighttime supply for other uses; feeder voltage	Substation-level BESS (1–10 MW, 2–4 h) with feeder solar plants	DISCOM-owned or RESCO; VGF/state support; tariff recovery
Urban distribution peak management	DT and feeder overloads at evening peak; space constraints	Compact 1–20 MW BESS at substations (e.g., Kilokari, Delhi)	Regulated DISCOM asset; deferral of network upgrades
Rooftop-PV-rich feeders	Reverse power flow; voltage rise	Community or DT-level BESS; Volt-Watt/Volt-VAR inverters	DISCOM asset or community storage; ToD tariffs
Remote and island systems	Diesel dependence (Andaman & Nicobar, Lakshadweep); resilience	Solar + BESS microgrids with GFM; diesel as backup	Government programmes; RESCO
Himalayan and border areas	Weak or no grid; extreme climate	Microgrids with GFM BESS; cold-climate batteries	Central schemes; defence and border infrastructure
Telecom towers	Diesel backup; grid outages	Li-ion replacing lead-acid; hybrid solar	Tower companies; opex savings
Healthcare and critical loads	Reliable supply for hospitals, cold chains, water pumping	BESS + solar; islanding capability	Public procurement; resilience funding
Commercial and industrial (C&I)	Demand charges; power quality; backup; green procurement	BTM BESS; open-access RE + storage	Tariff savings; ToD tariffs; green open access
EV charging hubs	Grid-connection limits; demand charges	BESS at charging stations	Charge-point operators; DISCOM tariffs

GIL Research

5.4. Behind-the-Meter Application of Energy Storage

Behind-the-Meter (BTM) energy storage refers to batteries or other storage systems installed on the consumer side of the electricity meter, typically at homes, commercial buildings, or industrial facilities. These systems operate primarily to serve the energy needs of the end-user, including renewable-energy self-consumption, peak-demand management, load shifting and backup supply. Aggregated grid-service participation is also technically possible, subject to metering, communication, dispatch and regulatory requirements.. When integrated with rooftop solar or captive renewable generation, BTM storage can shift surplus electricity to non-generation hours and maintain supply to selected loads during grid outages, provided suitable islanding and backup controls are installed.

In areas with time-variant tariffs, a BTM ESS can help users to reduce their billing costs by enabling them to store energy during low-price periods for use during high-price hours. The economic benefit depends on the

applicable retail tariff, demand charges, charging-energy cost, round-trip losses and battery degradation. The implementation of a PV plus BTM storage system is illustrated in Figure 40 [140].

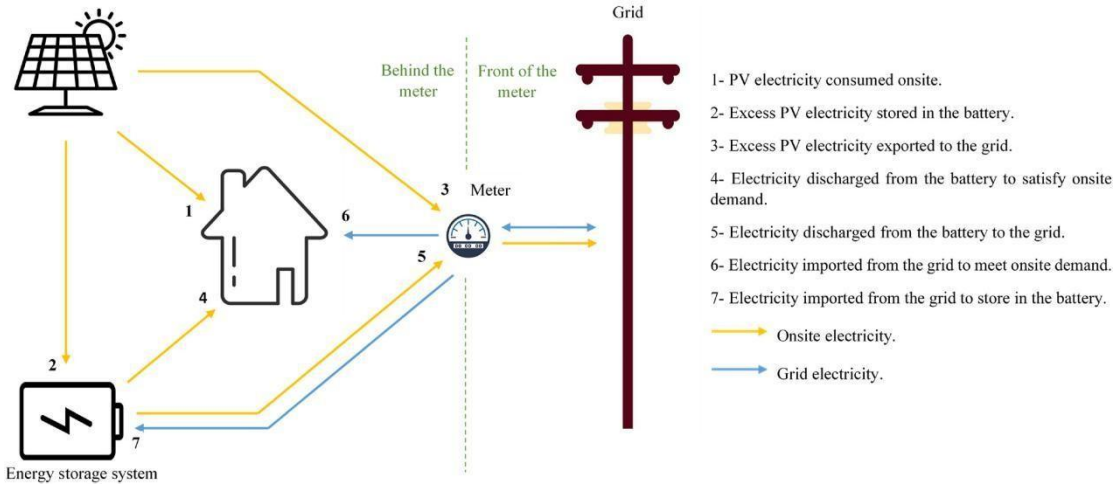


Figure 40: A schematic diagram of a behind-the-meter energy system[140].

An operational Indian example is UltraTech Cement's 7.5 MW behind-the-meter hybrid RE project at Sewagram Cement Works in Gujarat, commissioned in August 2025. The project integrates on-site solar, wind and battery storage to provide RTC RE for industrial operations. It demonstrates the application of storage for firming captive renewable supply and reducing dependence on conventional electricity sources[141]. However, the publicly reported 7.5 MW refers to the hybrid supply capacity, not the BESS rating, and the project's individual battery capacity and measured storage contribution are not disclosed.

In commercial and industrial facilities, BTM storage can be used for peak shaving, demand charge reduction, and load shifting, providing economic benefits while smoothing local power demand profiles. BTM systems also contribute to grid support when aggregated across multiple sites. Through smart energy management systems or virtual power plants, distributed BTM batteries can provide frequency regulation, demand response, and ancillary services to the grid, acting as a flexible and fast-responding resource. For Indian consumers, these benefits require appropriate storage sizing against measured demand profiles, tariff structures and reliability requirements. Grid-service participation through aggregation remains conditional on the applicable regulatory and technical eligibility framework.

5.4.1 PV local consumption

PV local consumption refers to the use of electricity generated by a rooftop or distributed solar PV system directly on-site, rather than exporting it to the grid. The goal is to maximize the fraction of solar energy consumed locally, reducing dependence on grid electricity and lowering electricity bills[142]. However, solar generation is often intermittent and may not align with local demand patterns. Therefore, energy storage is the key enabler for increasing PV self-consumption. For commercial and industrial facilities, storage-enabled PV self-consumption can also help reduce demand charges by offsetting peak loads with stored solar energy.

BTM BESS can store surplus daytime solar generation for use during evening or other non-solar hours, increasing on-site utilisation and reducing grid imports. Its economic value depends on the difference between

[140] Mostafa Rezaeimozafar, et al., "A review of behind-the-meter energy storage systems in smart grids," Renewable and Sustainable Energy Reviews, vol. 164, Art. no. 112573, 2022. DOI: 10.1016/j.rser.2022.112573

[141] Gentari, "Gentari Partners with UltraTech to Commission India's First-of-Its-Kind On-Site Hybrid RTC Renewable Energy Project," Aug. 18, 2025.

[142] Hyun Jin Julie Yu, "System contributions of residential battery systems: New perspectives on PV self-consumption," Energy Economics, vol. 96, Art. no. 105151, 2021. DOI: 10.1016/j.eneco.2021.105151

avoided electricity-purchase costs and export compensation, accounting for storage losses, capital costs and degradation.

In India, MERC's Demand Flexibility and Demand Side Management Consultation Committee considered a proposed programme in February 2025 to integrate rooftop solar with residential BESS. The programme envisaged 500 MWh of battery storage across approximately 70,000 rooftop-solar consumers, with coordinated charging and discharging to increase solar self-consumption and support peak-demand management[143]. These capacities represent programme objectives rather than commissioned installations.

5.4.2 Peak shaving and demand charge management

Peak shaving and demand charge management are two closely related applications of energy storage, particularly BTM aimed at reducing electricity costs by limiting peak electricity demand recorded at the consumer's meter. By smoothing demand, peak shaving not only reduces electricity bills but also relieves stress on local distribution networks and transformers.

Demand charge management targets charges that utilities levy based on billing demand, which may depend on measured maximum demand, contracted demand and other conditions specified in the applicable tariff. These demand charges can form a significant portion of commercial and industrial electricity bills. Energy storage can mitigate these costs by discharging during peak periods, effectively capping the facility's maximum demand and avoiding spikes that trigger higher fees. Storage can also be coordinated with on-site generation, such as rooftop PV, to further reduce peak demand and maximize cost savings.

In India, the economic relevance of this application is reflected in state-specific industrial and commercial tariffs. MERC's approved Tata Power-D tariff for FY 2026–27 specifies demand charges of ₹400/kVA/month for HT industrial consumers and ₹300/kVA/month for HT commercial consumers. The tariff also provides time-of-day incentives for shifting consumption towards lower-cost periods. BESS can therefore support both maximum-demand management and energy-cost optimisation, provided its discharge coincides with the relevant billing intervals[144].

However, reductions in measured peak demand do not always translate into proportional reductions in billed demand. Some Indian tariff schedules prescribe minimum billing demand linked to contract demand or previous billing periods. BESS sizing and financial assessment should therefore consider the measured demand profile, applicable billing conditions, discharge duration, charging costs, round-trip losses and battery degradation.

5.4.3 Commercial/industrial reliability needs

According to a recent industry report, the size of the Indian diesel backup generator market was approximately $1.5 billion in 2022, reflecting the high economic cost of power outages[145]. Therefore, in commercial and industrial sectors, BTM energy storage systems are increasingly deployed to meet stringent reliability requirements, ensuring continuity of critical operations during grid disturbances.

In India, BTM ESS can improve power-supply reliability for commercial and industrial consumers by supporting critical loads during grid interruptions and reducing dependence on diesel generators. The required storage capacity and configuration depend on critical-load demand, backup duration, permissible supply interruption and local grid reliability.

These systems provide backup power, mitigate voltage sags and short interruptions, and support seamless transition to islanded operation. In addition, BTM storage enhances power quality, reduces downtime costs,

[143] Maharashtra Electricity Regulatory Commission, Minutes of the First Demand Flexibility and Demand Side Management Consultation Committee Meeting, meeting held Feb. 21, 2025, minutes dated Apr. 3, 2025.

[144] Maharashtra Electricity Regulatory Commission, Press Note: Retail Electricity Tariff of the Tata Power Company Limited (TPC-D), Case No. 210 of 2024, order dated Mar. 28, 2025

[145] Akshaya Jha, et al., "Blackouts: The role of India's wholesale electricity market," NBER Working Paper, no. 29610, Dec. 2021.

and enables peak demand management, making it particularly valuable for industries with high sensitivity to supply interruptions such as manufacturing, data centers, and healthcare facilities.

An Indian example is ABB's industrial microgrid at its Vadodara manufacturing facility, commissioned in 2018 with a 500 kVA/1 MWh BESS integrated with rooftop solar. The system is designed to support islanded operation during grid outages until generators start or grid supply is restored. ABB's 2018 annual report also recorded reduced diesel-generator dependence through the use of stored solar energy during outages[146].

Another example is the 723 kWh BESS integrated with rooftop solar at Hi-Tech Blow Moulders in Bengaluru. The installation is intended to maintain production loads during grid interruptions and reduce diesel-generator operation[147]. These applications demonstrate the relevance of industrial BESS for supply continuity, although quantified reductions in downtime and verified transfer performance are not available from the cited project information.

5.5. Storage in Electric Mobility

The rapid electrification of transportation is creating an increasingly important interface between the mobility and electricity sectors. Electric vehicles (EVs) are fundamentally dependent on battery energy storage for propulsion, with the battery accounting for a substantial share of the vehicle's capital cost, weight, and operational characteristics. However, the role of energy storage in electric mobility extends beyond the energy requirements of individual vehicles. With increasing EV penetration, batteries in EVs are emerging as potential distributed energy resources capable of providing flexibility to the electricity grid, while stationary Battery Energy Storage Systems (BESS) are becoming relevant for managing the electrical demand associated with charging infrastructure.

5.5.1 EV batteries as Distributed Energy Resource

The utilization of EV batteries for electricity grid support can be broadly categorized into unidirectional smart charging and bidirectional charging.

Under unidirectional smart charging, commonly referred to as V1G, the charging power and timing of connected EVs are controlled to achieve specific operational objectives. These may include reducing peak demand, minimizing charging costs, avoiding distribution network congestion, and increasing the utilization of renewable electricity. Although V1G does not permit electricity export from the vehicle battery, it provides demand-side flexibility by modifying the charging profile. This can reduce the requirement for additional stationary storage in applications where EV charging demand can be shifted without affecting vehicle availability.

Vehicle-to-Grid (V2G), in contrast, enables bidirectional electricity exchange between an EV and the electricity network. A V2G-capable vehicle can charge its battery when electricity is available and discharge stored electricity when required by the grid. This enables EV batteries to provide several services associated with conventional BESS, including peak shaving, energy arbitrage, frequency regulation, and certain forms of network support. Reactive power compensation may also be provided by suitably designed bidirectional chargers, including under operating conditions where active battery discharge is not required.

An important distinction between stationary BESS and V2G is the availability of the storage asset. Stationary BESS is generally installed for an identified electrical application and can be operated according to its contracted availability requirements. EV batteries, however, are primarily intended to meet mobility requirements. Their availability for grid services is therefore conditional on vehicle connection status, battery state of charge, user preferences, and anticipated travel requirements.

5.5.1.1. Potential Aggregate Storage Capacity from EVs in India

[146] ABB Ltd., Microgrid for an Industrial Campus in India: Supporting Growth with Cost-effective Power Supply, Vadodara project factsheet, 2018, pp. 1–2.

[147] Orb Energy, “Solar with Battery Storage Keeps Production Running at Hitech Blow Moulders, Bengaluru,” project case study

The potential contribution of EV batteries to India's energy storage requirement was examined in the IIT Bombay policy brief *Implementation of Vehicle-to-Grid (V2G) in India*.

The study considered a projected stock of approximately 3.9 million electric four-wheelers and larger vehicles by 2030. Assuming an average battery capacity of 60 kWh and V2G participation by 10% of these vehicles, the corresponding aggregate battery capacity was estimated at approximately **23.4 GWh**, with maxim storage potential of 156 GWh provide 40% of the fleet is V2G capable with a mean battery capacity of around 100 kWh each as shown in Figure 41. This estimate illustrates the considerable theoretical storage resource represented by electric mobility, even at relatively modest V2G participation rates.

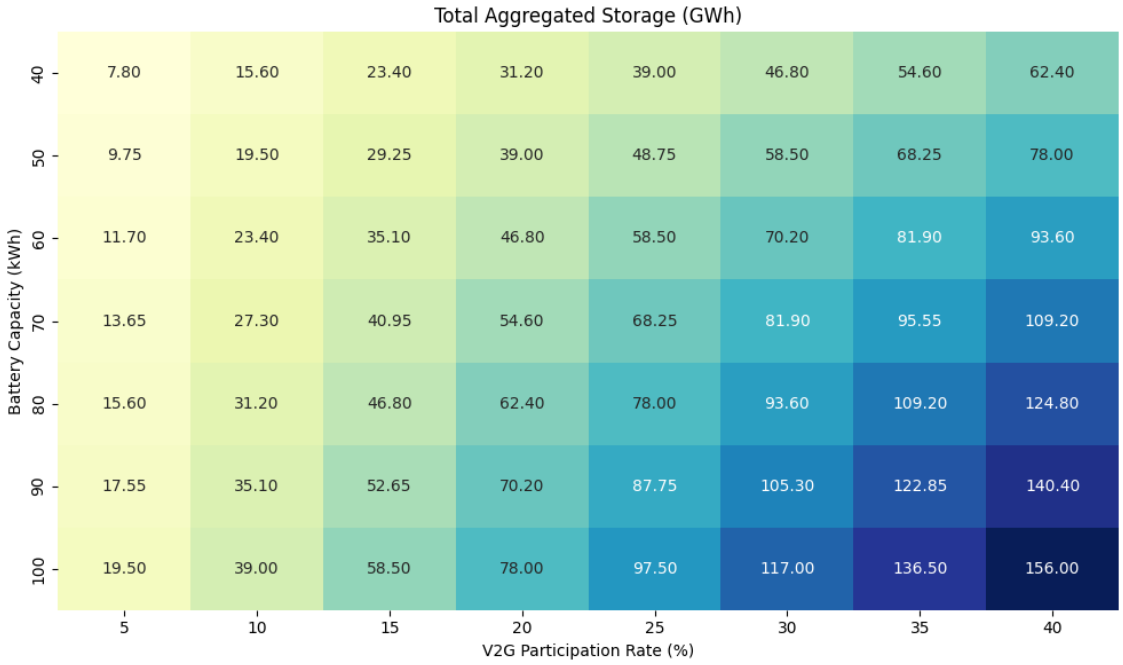


Figure 41: Total aggregated storage provided by V2G based on the average battery capacity and V2G participation rate[148]

Moreover, aggregate energy capacity alone does not establish the ability to provide grid services. The deliverable power would depend on the number of connected vehicles, the rated capacities of bidirectional chargers, network restrictions, and the coordination capability of the aggregation platform.

Nevertheless, the assessment demonstrates that EV batteries could constitute a meaningful supplementary storage resource in India. Unlike standalone BESS installations, the underlying battery investment is primarily justified by the transportation function of the vehicle. The additional expenditure required for V2G participation is therefore concentrated in bidirectional charging infrastructure, communication systems, control platforms, and market integration.

This distinction creates an opportunity for distributed storage aggregation, although the overall economic benefit must account for additional battery degradation, conversion losses, equipment costs, and compensation paid to vehicle owners.

Grid Services from Aggregated EV Batteries

The potential services provided through V2G can be broadly classified into energy management, distribution network support, and system-level ancillary services.

Energy management and peak shaving: Aggregated EV batteries can discharge during periods of high electricity demand and recharge during periods of lower demand or greater renewable availability. This may reduce peak imports, improve load factors, and lower the requirement for conventional peaking resources.

[148] Angshu Plavan Nath, Zakir Hussain Rather, Implementation of Vehicle-to-Grid (V2G) in India (Policy Brief), IIT Bombay, 2026

Distribution network support: Coordinated charging and discharging can help manage transformer loading, feeder congestion, and local voltage conditions. In distribution networks with substantial rooftop solar penetration, EV batteries may also help absorb surplus generation and mitigate reverse power flow.

Frequency regulation and ancillary services: Through suitable aggregation and control, EVs can modulate active power in response to grid frequency deviations. Their power-electronic interfaces provide rapid response capabilities, making them technically suitable for various frequency-support applications, subject to vehicle availability and applicable market rules.

Reactive power compensation: Appropriate EV charger converter configurations can supply or absorb reactive power to support local voltage management. Reactive power operation may be possible independently of significant energy exchange with the EV battery, thereby limiting additional battery cycling.

The IIT Bombay V2G policy brief reported results from a techno-economic assessment undertaken in collaboration with the Central Electricity Authority (CEA). For a small distribution system with 5.2 MVA capacity, the DISCOM can make annual savings of around INR 1 lakh, through reduction in reactive power penalties, INR 0.7 lakhs due to reduced losses. For a bulk industrial consumer of around 1 MVA, annual savings of INR 70 lakhs can be achieved through power factor correction.

For frequency-support applications involving an aggregation of 1,000 EVs, the study reported potential aggregator revenues ranging from approximately ₹90 lakh to ₹2.35 crore annually, with corresponding revenues for participating users ranging from ₹16,000 to ₹40,000 under the modelled assumptions.

5.5.2 Emissions from EV Charging and Role of BESS

These findings illustrate the potential economic value associated with grid-support services from EV charging infrastructure. However, these estimates are specific to the configurations, operating assumptions, and valuation mechanisms considered in the underlying analysis. They should not be interpreted as guaranteed or generally available revenues under existing electricity market arrangements.

The emissions assessment undertaken by IIT Bombay estimated that the 2023 Indian EV fleet resulted in approximately 2.84 million tonnes of CO_2 emissions annually from electricity consumption, compared with approximately 3.40 million tonnes for an equivalent fleet of internal combustion engine vehicles. This corresponded to an estimated reduction of approximately 0.56 million tonnes of CO_2, or 16.5%, under the electricity generation and charging assumptions considered. The diurnal variation of the emission profile of the national EV fleet for different seasons is shown in Figure 42. As can be observed the emissions across the seasons are highest at the midnight periods and lowest in the solar hours.

However, the benefits varied substantially across vehicle classes. Electric two-wheelers achieved an estimated average emissions reduction of approximately 27%, while three-wheelers achieved around 13.6% and light passenger vehicles approximately 23%. In contrast, heavy passenger vehicles were close to emissions parity with their conventional counterparts.

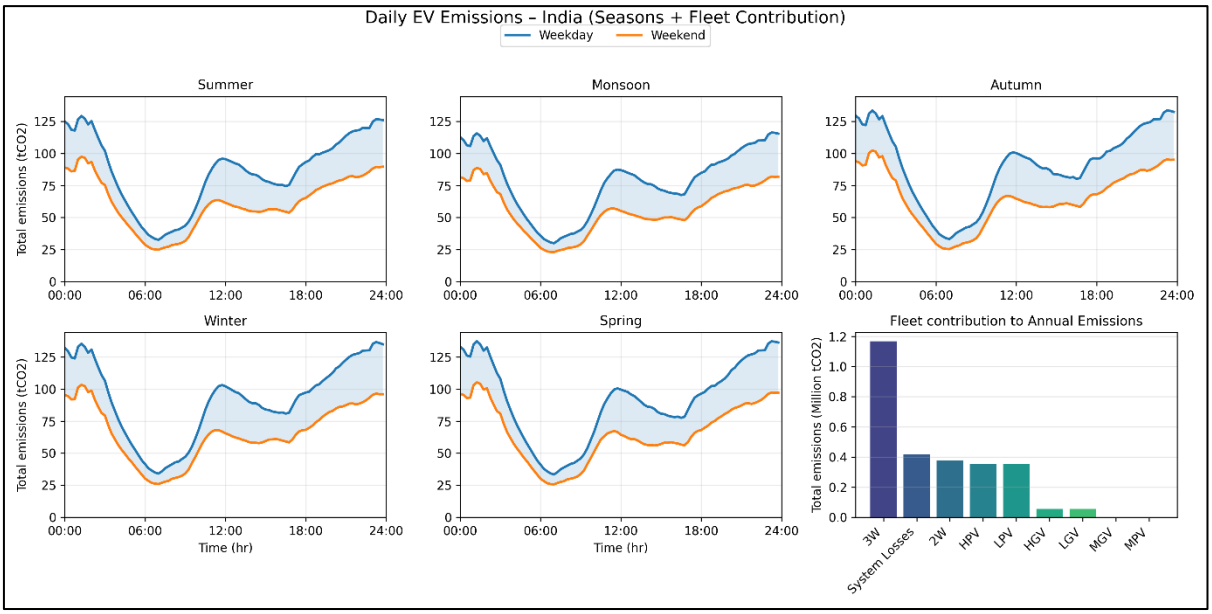


Figure 42: Diurnal variation of national EV related CO_2 emissions across five representative seasons (summer, monsoon, autumn, winter, and spring), showing weekday and weekend charging profiles, along with fleet wise contribution to total annual EV emissions.[149]

One contributing factor was the concentration of electric bus charging during evening and overnight periods, when the electricity generation mix can be relatively carbon-intensive.

These results highlight an important role for coordinated charging and energy storage. By shifting electricity consumption towards periods of higher renewable generation, smart charging can potentially improve the emissions performance of electric mobility without requiring changes to vehicle technology.

The study's 2030 assessment further indicated that charging during daytime periods could result in substantially lower marginal emissions compared with evening and nighttime charging in several Indian regions. The analysis reported reductions in marginal emissions intensity of approximately 40–60% for daytime charging relative to nighttime charging in many cases.

From the BESS perspective, these findings suggest two complementary applications.

- First, stationary batteries can store electricity during periods of relatively low marginal emissions and discharge during higher-emission periods, subject to round-trip efficiency and the generation response of the grid.
- Second, V2G-enabled vehicles can potentially provide similar flexibility by charging during renewable-rich periods and supplying electricity during subsequent high-demand periods.

Therefore, the environmental value of BESS in electric mobility depends not only on the quantity of electricity stored but also on the timing, location, and source of charging energy and the generation displaced during discharge.

5.6. Sector Coupling and Industrial Applications

Sector coupling refers to the strategic integration of the power sector with end-use sectors such as industry, transport, buildings, and heating/cooling to improve energy efficiency, flexibility, and decarbonization. Energy storage plays a central role in sector coupling by enabling electricity, especially from renewable sources to be

[149] Angshu Plavan Nath, Akhilesh Panwar, Zakir Rather, "Quantification and Comparison of Emissions due to Electric Vehicles", IIT Bombay, 2026.

stored and used across sectors and time, thereby aligning variable power generation with industrial and mobility energy demands.

In industrial applications, energy storage supports sector coupling by enabling electrification of processes traditionally dependent on fossil fuels, such as heating, cooling, and mechanical drive systems. Thermal energy storage is widely used in industries like cement, steel, chemicals, and food processing to store heat or cold generated using electricity during off-peak or high-renewable periods and utilize it during production cycles. Battery energy storage systems help industries manage peak demand, improve power quality, and ensure reliability, while also enabling participation in demand response and ancillary service markets.

Chapter 6.

ESS as Grid-Service Provider: Framework, Sizing, Stacking & GFM Capability



Energy storage deployment in India requires service-specific planning rather than procurement based solely on installed MW and MWh. Storage must be specified according to its intended grid service, response time, discharge duration, operating duty cycle, location and verifiable performance. The technical and economic value of storage also depends on its ability to provide multiple services without compromising contractual obligations, system security or equipment life. Grid-forming capabilities, converter ratings, energy headroom and validated dynamic performance are particularly important where storage is expected to support inverter-dominated networks.

6.1. Service-Oriented Framework

The central idea is that energy storage should be procured and evaluated as a service provider with measurable performance, not as a quantity of MW. *Figure 43* shows the logic chain, and Table 41 applies it to the principal grid integration issues.. The sizing of storage for each grid issue must therefore be undertaken separately, based on the magnitude, duration, response time, duty cycle, reliability requirement, and performance characteristics of the service to be delivered.

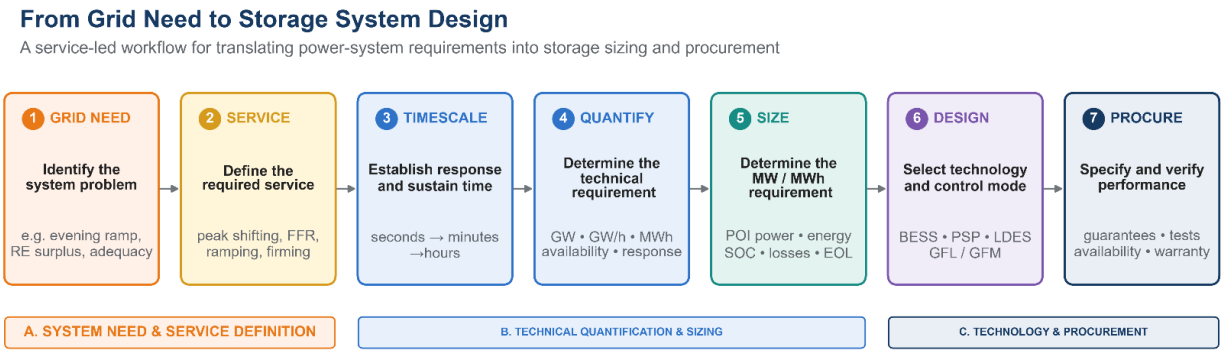


Figure 43: Service-oriented design chain: grid problem → required service → timescale → technical metric → MW/MWh requirement → technology and control mode → procurement and verification

Table 41: Service-oriented framework for storage in the Indian grid

Grid problem	Required service	Time-scale	Technical Metric	Suitable technology / control mode
Large CBR-loss contingency; low inertia	Synthetic inertia; FFR	0–10 s	RoCoF, nadir; delivery time < 0.5–1 s	GFM BESS; flywheel/supercapacitor hybrids; sync condensers
Frequency deviations	PFR; SRAS (AGC)	1 s–15 min	Droop (%), FRC (MW/Hz), mileage, accuracy	BESS (GFL or GFM), PSP, hydro
Forecast errors; unit outages	TRAS; contingency reserve	15 min–hours	Delivery within 15 min; sustain ≥ 1 h	BESS, PSP, hydro, gas
Steep evening ramps	Ramp support	Minutes–hours	GW/h; ramp adequacy margin	2–4 h BESS; PSP
Midday surplus and evening net peak	Energy shifting; peak capacity	Hours	Usable MWh in window; capacity credit	4–8 h BESS; PSP
Firm RE supply to DISCOMs	Firming and shaping (FDRE/RTC/peak supply)	Hours	Delivery profile compliance (e.g., ≥ 90–93%)	Co-located BESS; PSP; hybrid RE
RE evacuation congestion	Congestion relief; virtual line	Seconds–hours	Curtailment avoided (MWh); line loading	Pooling-station BESS with RAS
Voltage rise / post-fault overvoltage	Dynamic reactive support; voltage control	ms–minutes	Reactive current (pu), response < 60 ms	BESS PCS in voltage-control mode; STATCOM; GFM
Weak grid; oscillations	System strength; damping	Sub-cycle–seconds	Stable at SCR ≤ 2; damping 0.1–20 Hz	GFM BESS; sync condensers; GFM STATCOM
Blackout	Black start; island formation	Minutes–hours	Energisation success; load pick-up blocks	GFM BESS; PSP; hydro
Multi-day low-RE periods	Multi-day adequacy	Days	EUE in stress events	PSP (large reservoirs); LDES

Seasonal imbalance	Seasonal balancing	Weeks–months	Seasonal energy balance	Reservoir hydro; H_2/NH_3; demand flexibility

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6.2. Master Service-to-Technology Matrix

Table 42 compares the potential suitability of storage technologies for different grid services. The ratings are indicative and depend on plant configuration, discharge duration, converter capability, operating headroom and network conditions. A high rating indicates technical suitability under appropriate design conditions, not demonstrated service delivery or guaranteed regulatory eligibility. Site-specific studies, control verification and lifecycle assessment remain necessary before procurement.[150,151] presents the same information as a heat map.

Table 42: Suitability of storage technologies and control modes for grid services

(●●● high; ●● medium; ● limited; — unsuitable)

Service	Response needed	LFP BESS (GFL)	LFP BESS (GFM)	Na-ion / flow	PSP fixed speed	PSP variable speed	Flywheel / supercapacitor	LDES (Fe-air, CAES, LAES)	Hydrogen (P2H2P)	Thermal / flexible demand
Synthetic/ Synchronous inertia	Instantaneous	●	●●●	●●● (with GFM PCS)	●●● (synchronous)	●●	●●● (with GFM)	●● (synchronous turbines)	●	—
Fast frequency response	< 0.5-1 s	●●●	●●●	●●	●	●●	●●●	●	●	●● (fast DR)
Primary frequency response	Seconds	●●●	●●●	●●	●●	●●●	●●	●●	●	●●
Secondary (SRAS/AGC)	30 s-15 min	●●●	●●●	●●	●● (gen. only)	●●●	●	●●	●	●●

[150] Yashen Lin et al., Research Roadmap on Grid-Forming Inverters, Technical Report NREL/TP-5D00-73476 (National Renewable Energy Laboratory, 2020.

[151] Roberto Rosso et al., 'Grid-Forming Converters: Control Approaches, Grid-Synchronization, and Future Trends—A Review', IEEE Open Journal of Industry Applications 2 ,2021.

Tertiary (TRAS) / contingency reserve	15 min	●●●	●●●	●●●	●●●	●●●	—	●●	●	●●
Ramp control	Minutes	●●●	●●●	●●	●●	●●●	●	●	●	●●
Energy arbitrage / shifting	Minutes	●●●	●●●	●●●	●●●	●●●	—	●●	●	●●
Peak capacity (adequacy)	Minutes	●● (2 h) / ●●● (4 h+)	●●●	●●●	●●●	●●●	—	●●●	●●	●●
RE firming (FDRE/RTC)	Minutes	●●●	●●●	●●●	●●●	●●●	—	●●	●	●
Congestion relief / virtual line	Seconds–hours	●●●	●●●	●●	●● (siting)	●●	●	●	●	●●
Voltage / reactive support	< 60 ms	●●● (MVA)	●●●	●●	●●	●●●	●●	●●	●	—
System strength / weak-grid stability	Sub-cycle	●	●●●	●●● (with GFM PCS)	●●●	●●●	●●	●●	●	—
Oscillation damping	Sub-/Cycle(s)	●● (POD)	●●●	●●	●● (PSS)	●●●	●●	●●	●	—
Black start / islanding	Sub-cycle	—	●●●	●●● (with GFM PCS)	●●●	●●●	●	●●	●●	—
Resilience / critical-load backup	Seconds	●●	●●●	●●●	●●	●●	●	●●●	●●	●●
Multi-day adequacy	Hours	—	—	●	●● (large reservoirs)	●●	—	●●●	●●●	●
Seasonal balancing	Days	—	—	—	●	●	—	●	●●●	●● (seasonal TES)

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A few patterns become prominent from assessing ESS suitability for different services. First, GFM BESS is the most versatile single resource, rated high for nearly all services up to about eight hours, but it cannot provide multi-day or seasonal balancing. Second, variable-speed PSP is the most versatile synchronous resource, adding regulation in pumping mode to its inherent inertia, fault current, and long duration. Third, long-duration and seasonal needs require different technologies (large-reservoir PSP, LDES and hydrogen), which should be procured through separate instruments. Fourth, flexible demand and thermal storage can provide several services at low cost and should be included in technology-neutral procurement where feasible.

6.3. Illustrative Framework for ESS Sizing & Placement

ESS sizing and placement must jointly satisfy the required service, network constraints, operating conditions and lifecycle performance guarantees. A proposed BESS design must determine the MW at the point of interconnection (POI), the MWh available over the required dispatch window, the converter MVA rating and reactive capability, the DC nameplate energy, the thermal and auxiliary thresholds, the degradation reserve, the availability margin, and the augmentation. This section presents an illustrative approach to the sizing and placement of a grid-scale BESS suitable for Indian planning, tendering, and technical evaluation, which stakeholders can further adopt and strengthen based on use cases, constraints, and performance guidelines. The framework is not intended to prescribe an optimal national siting solution. Rather, it shows how network, adequacy, RE-integration, land, safety and economic considerations can be assessed together before detailed system studies and project-level optimisation.

6.3.1 Design basis: Sizing the service

The first design decision is to ascertain and size the service obligation at the contractual delivery point. The specification should state the POI, active-power obligation, energy/duration window, response time, duty cycle, charging opportunity, availability, reactive-power/PF requirement, ambient design conditions and contract life. This prevents ambiguity, such as the definition of a '250 MW / 1,000 MWh BESS', that may refer to DC nameplate energy or guaranteed AC energy at the POI, which are not the same.

6.3.2 Step-by-step sizing method

A brief ESS sizing methodology is presented to provide a systematic framework for translating system requirements into appropriate power and energy capacity.[152]

Step 1: Define the service, POI and operating envelope

Construct a time series of the quantity that the storage is intended to correct, such as net load, feeder loading, RE surplus, reserve requirement or market dispatch. Use time resolution appropriate to the service: dynamic/sub-second studies for stability; 1-5 min for ramps and reserves; 15 min for scheduling/adequacy; and chronological sub-hourly/hourly simulation for energy shifting. For stacked services, represent simultaneous commitments explicitly rather than adding standalone maxima.

Step 2: Determine rated active power at the POI

$$P_{POI,rated} \geq \max_t\,[P_{req}(t)] + P_{headroom}$$

$$P_{POI,rated} \geq \max\left(\Delta P_{ramp,\Delta t}\,, k_{share} \cdot \Delta P_{contingency}\right) + P_{headroom,other}$$

where $P_{POI,rated}$ is the required rated active power of the BESS at the POI (MW); $P_{req}(t)$ is the time-varying active-power requirement of the service; $P_{headroom}$ is the active-power margin reserved for additional or simultaneous services; $\Delta P_{ramp,\Delta t}$ is the required change in BESS output over the specified ramp interval Δt; $\Delta P_{contingency}$ is the system power imbalance associated with the design contingency (MW); and k_{share} is the fraction of that contingency assigned to the BESS (dimensionless). Headroom is a physical constraint. A BESS discharging at full output cannot simultaneously provide upward reserve unless power headroom and SOC are reserved.

[152] International Electrotechnical Commission, IEC 62933 Series: Electrical Energy Storage (EES) Systems—Performance, Planning, Sizing and Design, IEC Standards and Technical Reports (International Electrotechnical Commission, 2025).

Step 3: Size PCS active power and MVA

$$P_{PCS,nameplate} \geq \frac{P_{POI,rated}}{\eta_{AC} \cdot f_{derate}}$$

$$S_{PCS} \geq \frac{P_{PCS}}{PF_{min}}$$

$$Q_{available} = \sqrt{S_{PCS}^2 - P_{PCS}^2}$$

where S_{PCS} is the converter apparent-power rating (MVA); P_{PCS} is its required active-power output (MW); and PF_{min} is the minimum power factor at which the required P output must be delivered. $Q_{available}$ is the reactive-power capability available at the specified operating point (MVAr).

The final design is expected to use the OEM-provided P-Q capability and temperature/altitude derating curves. Grid-forming designs also require current-limit and transient-overload checks, which are often higher than their grid-following alternatives.

Step 4: Calculate usable AC energy at the POI

$$E_{POI} = \int P_{req(t)} dt$$

where E_{POI} is the usable AC energy that must be delivered at the POI (MWh), and $P_{req(t)}$ is the required BESS active-power trajectory (MW).

For an ESS with a rectangular 250 MW, 4-h obligation, E_{POI}= 1,000 MWh. For peak shaving, ramp following or FDRE schedules, integrate the actual profile, since nominal MW multiplied by duration can incorrectly size a non-rectangular obligation.

Step 5: Translate POI energy to required DC energy

$$E_{DC,usable} = \frac{E_{POI}}{[\eta_{disch} \cdot (1 - a_{disch})]}$$

$$E_{charge,POI} = \frac{E_{POI}}{\eta_{AC-AC,RTE}}$$

where $E_{DC,usable}$ is the usable energy required on the DC side of the BESS (MWh); η_{disch} is the one-way discharge-path efficiency from the DC system to the POI (pu); and a_{disch} is the fraction of discharge energy consumed by applicable auxiliary loads (p.u.). $E_{charge,POI}$ is the charging energy drawn at the POI (MWh), and $\eta_{AC-AC,RTE}$ is the AC-to-AC round-trip efficiency measured using consistent system boundaries (pu). One-way discharge efficiency must be used for discharge sizing, rather than RTE. η_{disch} must be ascertained from OEM-guaranteed PCS, transformer, collector and cable efficiencies at the relevant loading and temperature. The 2024 ATB by the National Laboratory of the Rockies (NLR, formerly NREL) uses 85% as a representative utility-scale Li-ion AC round-trip efficiency; actual guarantees vary with power, SOC, temperature, and auxiliaries.[153]

Step 6: Convert usable DC energy to the beginning of life (BOL) nameplate energy

$$E_{nameplate,BOL,predeg} = \frac{E_{DC,usable}}{\Delta SOC \cdot f_{temp,E}}$$

where $E_{nameplate,BOL,predeg}$ is the required BOL battery nameplate energy before degradation allowance (MWh); $\Delta SOC = SOC_{max} - SOC_{min}$ is the permitted operating SOC window (pu); and $E_{DC,usable}$ is the fraction of nominal energy available at the specified reference or design temperature (pu).

[153] National Laboratory of the Rockies, 'Annual Technology Baseline 2024b: Utility-Scale Battery Storage', National Laboratory of the Rockies (NLR), formerly the National Renewable Energy Laboratory (NREL), 2024.

The BMS SOC window, reference temperature and C-rate must match the warranty definition. A 90% SOC window may not be equivalent to a 90% warranted DoD under all operating conditions.

Step 7: Design for degradation, availability and end-of-life guarantee

$$E_{eff}(y) = \Sigma_j E_{add,j} \cdot SOH_j(y) \cdot A_E(y)$$

$$E_{eff}(y) \cdot \Delta SOC \cdot f_{temp}, E \cdot \eta_{disch} \cdot (1 - a_{disch}) \geq E_{POI,guaranteed}(y)$$

where $E_{eff}(y)$ is the effective battery energy available in year y (MWh); $E_{add,j}$ is the nameplate energy of the battery block or augmentation tranche j (MWh); $SOH_j(y)$ is the state-of-health or retained-capacity fraction of the tranche j in year y (pu); and $A_E(y)$ is the energy-availability factor in year y (pu). $E_{POI,guaranteed}(y)$ is the contractual usable AC energy that the BESS must be capable of delivering at the POI in year y. Capacity fade combines calendar and cycling degradation and depends on temperature, SOC, DoD, C-rate and throughput. The vendor retention warranty or a validated degradation model can be used. India's CEA Technical Standards for Construction of Electrical Plants and Electric Lines (Amendment) Regulations, 2026 require minimum BESS output retention of 90% after 5 years, 80% after 10 years and 70% after 15 years. Equipment procurement may demand stronger guarantees than this baseline.[154]

Step 8: Optimise augmentation instead of automatically overbuilding

$$\min NPV = C_0 + \sum_{y=1}^{Y} \frac{[C_{aug(y)} + C_{O\&M}(y) + C_{loss}(y) + C_{unavail}(y)]}{(1+r)^y}$$

where NPV is the net present value of lifecycle cost; C_0 is the initial installed capital cost; $C_{aug(y)}$ is augmentation expenditure in the year y; $C_{O\&M}(y)$ is the annual operation and maintenance cost; $C_{loss}(y)$ is the economic cost of conversion and auxiliary energy losses; $C_{unavail}(y)$ is the cost or contractual consequence of plant unavailability; r is the real discount rate; y is the operating year; and Y is the project evaluation horizon. The initial overbuild is to be compared with staged augmentation, PCS/collector limits, site space, warranty compatibility and maximum augmentation events. Staged augmentation can exploit future declines in cell costs but requires spare electrical and physical capacity. Few BESS approaches explicitly incorporate augmentation in fixed O&M to maintain rated capacity over a 15-year life.[153]

6.4. Stacked Services and SOC Headroom

$$-P_{ch,max} \leq P(t) \leq P_{disch,max}$$

$$SOC(t + \Delta t) = SOC(t) + \frac{\left[\eta_{ch} P_{ch(t)} - \frac{P_{dis(t)}}{\eta_{dis}}\right] \Delta t}{E_{nameplate}}$$

$$SOC_{min} + \frac{E_{up,res}}{E_{nameplate}} \leq SOC(t) \leq SOC_{max} - \frac{E_{down,res}}{E_{nameplate}}$$

A multi-service BESS should be co-optimised chronologically. For a symmetrical frequency response, both upward energy headroom (discharge capability) and downward headroom (charging capability) are required, so the operating SOC target may sit near the mid-window rather than at the level preferred for pure evening peak shifting.

6.4.1 Frequency response, FFR and synthetic inertia

$$E_{res,up} = P_{FFR} \cdot \frac{t_{sustain}}{\eta_{disch}}$$

For fast-frequency services, MW, current, and response speed usually dominate, while MWh is set by sustain time and recovery. A 100 MW response sustained for 15 minutes requires about 25 MWh at the POI, plus losses. Dynamic

[154] Central Electricity Authority, Central Electricity Authority (Technical Standards for Construction of Electrical Plants and Electric Lines) Amendment Regulations, 2026, Regulation (Ministry of Power, Government of India, 2026).

studies are still required to determine the MW response needed for RoCoF/nadir control. For GFM BESS, current limits and transient overload capability can be the limiting factors before energy capacity.

6.4.2 Resource Adequacy: Capacity Credit and ELCC

CEA's 2026 LT-NRAP examined continuous blocks in the top 10% of non-solar peak-demand periods and found that the maximum occurrence of consecutive peak blocks is typically six hours. It therefore assigns a six-hour BESS a capacity credit of 1.0; shorter durations are reduced proportionately, yielding about 0.67 for a four-hour BESS. For PSP, the maximum six-hour capacity credit is 0.95 after maintenance and auxiliary considerations.[155]

Effective Load Carrying Capability (ELCC) measures the firm capacity contribution of storage, i.e., how much additional peak load the power system can reliably serve after adding the storage resource while maintaining the same reliability criterion. It depends strongly on storage power, duration, dispatch, and system conditions. At higher storage penetration, probabilistic ELCC is preferable to a fixed-duration credit because scarcity can shift toward longer or multi-day events and the marginal capacity value of storage declines. The model should stimulate demand, VRE, thermal outages, hydro constraints, SOC, and charging availability in chronological order, and report LOLE/LOLP and expected energy not served.

6.4.3 Pumped-storage sizing

PSP sizing combines unit power (determined by head, flow, and machine selection) and reservoir volume (determined by the required storage duration). Several Indian PSP planning configurations target multi-hour generation, but actual discharge duration depends on usable reservoir storage, head variation, operating restrictions and project design, consistent with the CEA roadmap's assumption of six hours or more.[156] For variable-speed units, the pumping-power range must match the expected midday surplus profile; for fixed-speed units, the number and size of units determine the granularity with which the pumping load can follow solar output.

6.4.4 Probabilistic sizing for adequacy

For resource adequacy, storage must be sized probabilistically: the contribution of storage to reducing loss-of-load probability depends on the duration of net-peak events, the correlation of those events across days, and the availability of charging energy before each event. ELCC methods, which measure the additional load that can be served at the same reliability level when storage is added, capture these effects, including the declining marginal capacity value as storage penetration rises. The LT-NRAP's duration-based capacity credit rule (1.0 for 6 hours) is a reasonable simplification for current penetration levels, but it should be replaced by ELCC analysis in the 2030s.

6.5. Worked Example: 250 MW/1,000 MWh evening-peak BESS

Illustrative assumptions: 250 MW for four hours at the POI, one nominal full cycle/day, 15-year service life, 5–95% SOC window, 1.5% discharge auxiliaries, and the component efficiencies below. Values are transparent planning assumptions, not vendor guarantees.

Parameter	Assumption	Result
POI power	250 MW	Service requirement
POI energy	1,000 MWh	250×4 h
PCS / MV / HV / collection efficiency	98.2%/99.4%/99.6%/99.5%	Product = 96.73%
Discharge auxiliaries	1.5%	Site-dependent HVAC/controls

[155] Central Electricity Authority, Long Term National Resource Adequacy Plan (2026–27 to 2035–36).

[156] Central Electricity Authority, *Report on Roadmap to 100 GW of Hydro Pumped Storage Projects by 2035–36*.

Usable DC energy	—	1,000 / (0.9673×0.985) ≈ 1,050 MWh
SOC window	90%	5–95%
BOL nameplate before degradation	—	1,050/0.90 ≈ 1,167 MWh
CEA year-15 floor	70%	Minimum performance guarantee
No-augmentation BOL screen	—	1,167/0.70 ≈ 1,667 MWh

The 1,000-MWh contractual AC requirement corresponds to ≈1,050 MWh usable DC after one-way losses and auxiliaries, and about 1,167 MWh BOL nameplate after a 90% SOC window. If the same 1,000 MWh POI delivery must be guaranteed in year 15 with no augmentation and 70% retained capacity, the screening requirement is about 1,667 MWh. In practice, a developer should compare this heavy initial overbuild against cohort-based augmentation using the supplier degradation curve.

This example assumes no additional energy derating beyond the factors explicitly included and does not establish compliance with an equipment standard. The applicable degradation trajectory, availability guarantee, augmentation strategy and terminal-year deliverable energy require project-specific verification.

For the PCS, the illustrative downstream AC path (0.994×0.996×0.995≈0.985) yields about 254 MW at the inverter terminals. At PF 0.95, this is about 267 MVA before ambient derating. If only 90% of the standard-condition rating is available at the design ambient, the standard-condition PCS rating is about 297 MVA. Detailed design must replace these assumptions with the actual P-Q and derating curves.

6.5.1 A Multi-Criteria Siting Methodology for Energy Storage

A quantitative, multi-criteria siting methodology is presented that stakeholders can use to identify the placement and size of the ESS to deliver the greatest system value as shown in Figure 44. This framework recognises that the value of storage is strongly locational and service-specific, and that a BESS located in an RE pooling station in a weaker region of the grid provides very different services from one at a load-centre substation in the metropolitan cities.

The representative methodology has five primary steps:

1. **Define the service** for which sites are being ranked (e.g., curtailment reduction, evening-peak adequacy, system strength, congestion deferral, black start).
2. **Compute indicators** for each candidate node (substation or pooling station) from the data sources.
3. **Normalise** each indicator to a 0–1 scale across candidate nodes.
4. **Weight** indicators according to the service, as per preference, and compute a composite score.
5. **Screen** high-scoring nodes for land, water, safety and environmental constraints, then confirm with network studies (e.g. load flow, SCR/EMT, adequacy).

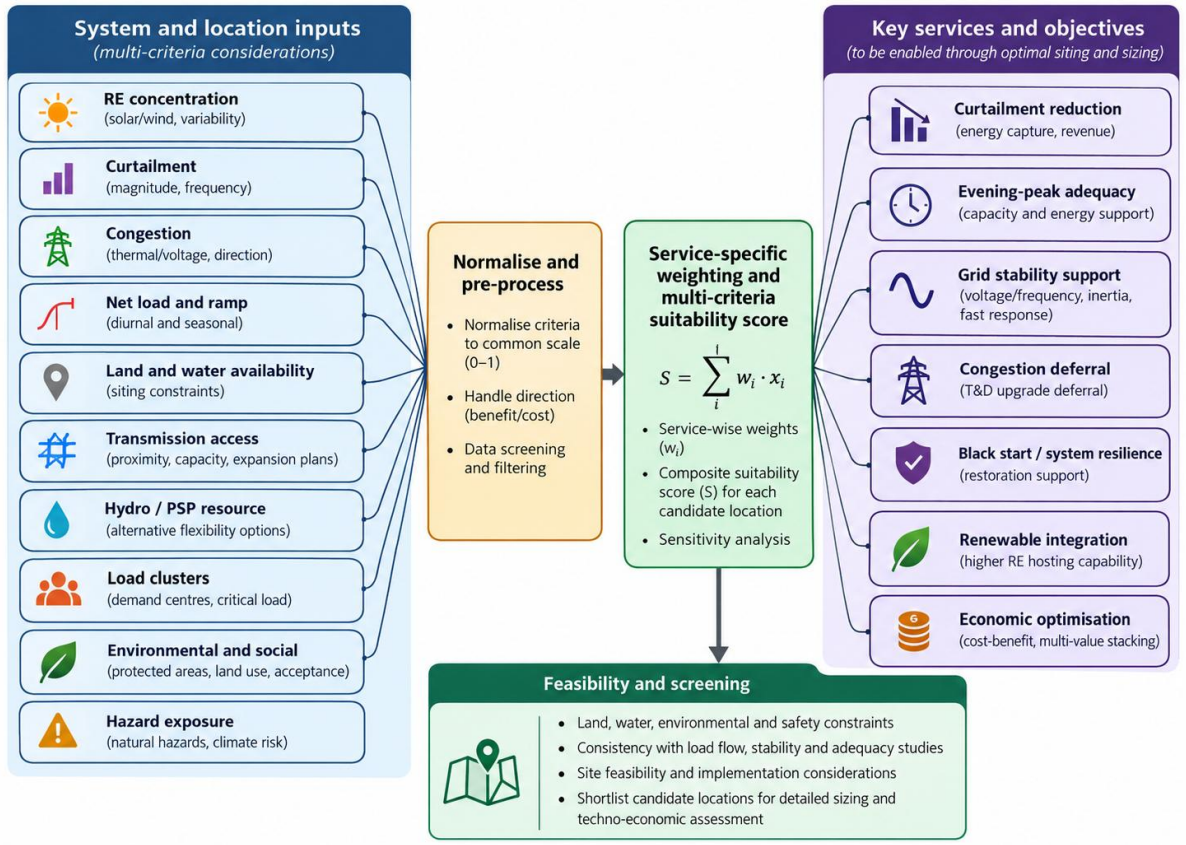


Figure 44: Illustrative multi-criteria siting methodology for storage: indicators, data sources, normalisation, service-specific weighting and priority-zone outputs

Table 43: Siting indicators, metrics and data sources

Indicator	Metric	Data source	Direction
RE concentration	GW of solar + wind within 50–100 km of node; RE/peak-load ratio of the state	MNRE, CTUIL connectivity data, SLDCs	Higher ⇒ higher need
Curtailment	MWh curtailed per year and % of hours with curtailment, by cause	RLDC/SLDC instructions; TRAS-down data	Higher ⇒ higher need
Congestion	Hours per year with line/ICT loading > 90%; T-GNA restrictions	CTUIL/STU studies; SCADA	Higher ⇒ higher need
System strength	SCR at POI; oscillation events; FRT incidents	Grid-India, CTUIL studies, PMU data	Lower SCR ⇒ higher need
Peak and ramp	State/zone evening ramp (GW); non-solar peak shortage events	SLDC data; EnergyMap/EAC-PM	Higher ⇒ higher need
Land and water	Available government/waste land; water for PSP	State land banks; CWC; CGWB	Enabler

Transmission access	Spare bays; available transformation capacity; planned lines	CTUIL/STU plans	Enabler
Hydro and PSP resources	Head, reservoirs, identified PSP sites	CEA PSP potential; CWC	Enabler (for PSP)
Load and industrial clusters	Industrial demand, data centres, hydrogen hubs, cities	DISCOMs; industry departments	Higher ⇒ higher value (adequacy, backup)
Hazard exposure	Heat, flood, cyclone, seismic zone	IMD, NDMA, BIS seismic zoning	Constraint / design driver

6.6. Revenue Stacking and Co-optimisation

6.6.1 Why stacking matters and why it is constrained

Most storage services individually do not justify the full cost of a BESS; combining several services, thereby 'stacking' them, improves utilisation and overall economics. However, services compete for the same three physical resources: energy (SOC), active-power headroom and converter apparent-power (MVA) headroom. An MW committed to upward reserve cannot simultaneously be used for evening discharge, and energy held in reserve for black start cannot be used for arbitrage. Further, the reactive power provided for voltage support reduces the active power available within the PCS rating. Table 44 shows the compatibility of common Indian storage services.

Table 44: Compatibility of storage services for stacking

(✓ compatible; ◐ compatible with headroom/SOC management; ✗ conflicting)

Service	Energy shifting	Peak capacity	FFR / PFR	SRAS	TRAS	Congestion relief	Voltage / reactive	Black start reserve
Energy shifting	—	◐	◐	◐	◐	◐	✓	✗
Peak capacity	◐	—	◐	◐	✗	◐	✓	◐
FFR / PFR	◐	◐	—	✓	◐	◐	◐	✓
SRAS	◐	◐	✓	—	◐	◐	◐	◐
TRAS	◐	✗	◐	◐	—	◐	✓	◐
Congestion relief	◐	◐	◐	◐	◐	—	✓	◐
Voltage / reactive	✓	✓	◐	◐	✓	✓	—	✓

Service	Energy shifting	Peak capacity	FFR / PFR	SRAS	TRAS	Congestion relief	Voltage / reactive	Black start reserve
Black start reserve	✗	◐	✓	◐	◐	◐	✓	—

Note: "◐" indicates that the combination is feasible if SOC bands and power/MVA headroom are explicitly reserved and co-optimised; "✗" indicates a fundamental conflict in the same time window, thereby making stacking infeasible.

6.6.2 Co-optimisation formulation

The standard way to resolve these conflicts is to co-optimise the storage schedule across energy and reserve services, with explicit headroom and SOC constraints. A compact formulation for a BESS participating in energy and reserve markets over time steps t of length Δt is:

$$\max \sum_t \left[\lambda_t^E \left(P_t^{dis} - P_t^{ch}\right)\Delta t + \lambda_t^{up} R_t^{up} + \lambda_t^{dn} R_t^{dn} - c_{deg}\left(P_t^{dis} + P_t^{ch}\right)\Delta t \right]$$

subject to the SOC dynamics, power and reserve headroom, energy sufficiency for and the converter apparent-power limit:

$$Et + 1 = Et(1 - \sigma\Delta t) + (\eta chPcht - Pdist/\eta dis)\Delta t$$

$$Pdist - Pcht + Rupt \leq Pmax, \quad Pcht - Pdist + Rdnt \leq Pmax$$

$$Et - Rupt\frac{\tau up}{\eta dis} \geq Emin + Ebs, \quad Et + Rdnt\,\tau dn\,\eta ch \leq Emax$$

$$(Pdist - Pcht \pm Rt)2 + Qt2 \leq Smax2$$

Here λ are prices, R reserve capacities, c_{deg} a degradation cost per MWh of throughput, σ self-discharge, τ the duration for which reserves must be sustainable, E_{bs} the energy reserved for black start or resilience, and Q_t the reactive power committed for voltage support. The degradation cost term makes the schedule *degradation-aware*, avoiding cycles whose marginal value is lower than the wear they cause. In practice, degradation cost depends nonlinearly on DoD, SOC, and temperature, and more sophisticated formulations use cycle-counting or piecewise-linear approximations of the model.[157]

6.6.3 Regulatory conditions for stacking in India

Indian ESS contracts differ in the degree of operational flexibility permitted. Some procurement structures dedicate storage capacity to contracted supply, while others permit additional use subject to priority and scheduling conditions. SECI's 2025 solar-plus-storage tender, for example, allows the ESS component to undertake specified additional off-peak applications while preserving the contracted supply obligations. Wider participation in multiple grid and market services requires suitable dispatch rights, metering, headroom declarations, settlement and prevention of duplicate remuneration. As the fleet grows, allowing stacking will reduce costs, but it requires clear rules:

i. *Priority*: which service prevails when conflicts arise;
ii. *No double payment*: the same MW or MWh should not be paid twice for the same period;
iii. *Measurement and verification*: separate metering and telemetry for each service;
iv. *SOC and headroom declarations*: the asset must declare, and the system operator must verify, the SOC and headroom reserved for each service; and
v. *Charging treatment*: charging energy should not be subject to double network charges or be treated as final consumption

[157] Bolun Xu et al., 'Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment', IEEE Transactions on Smart Grid 9, no. 2, 2018.

The CERC's 2026 draft IEGC provisions for standalone ESS are a first step towards this direction.[158] The connectivity and General Network Access regulations, and the deviation settlement regulations, will also need storage-specific provisions; for example, GNA quantum for charging and discharging, and deviation treatment for assets providing reserves, could be specified.[159]

6.7. Grid-forming Storage

Grid-forming (GFM) capability is determined primarily by converter control and the associated DC-source, protection and plant design. Battery chemistry alone does not establish GFM capability. The converter must maintain the required voltage-source behaviour within its current and DC-voltage limits, while the storage system must provide sufficient active-power and energy headroom for expected disturbances. GFM performance must therefore be specified and validated at the plant level rather than inferred from the PCS control label.GFM control approaches

GFM controls establish an internal voltage phasor whose angle and magnitude respond to measured power flows. The main families for grid-forming control technologies are:[160]

- **Droop control**, the simplest, in which frequency and voltage vary linearly with active and reactive power:

$$\omega = \omega_0 - m_p(P - P_0); \quad V = V_0 - n_q(Q - Q_0)$$

- **Virtual synchronous machine (VSM)** control, which emulates the swing equation of a synchronous machine with a virtual inertia constant H_v and damping D (Eq. (5.8)), providing explicit, tunable inertial response:

$$2 \cdot H_v \cdot \frac{d\omega}{dt} = Pref - P_e - D(\omega - \omega_0)$$

- **Synchronverters** and other machine-emulation variants.
- **Virtual oscillator control** (including dispatchable virtual oscillator control), which uses nonlinear oscillator dynamics for fast synchronisation.
- **Matching control** and other advanced schemes that tie the converter's angle to its DC-link dynamics.

GFM converters can provide an inertia-like power response through their internal control dynamics, while suitably configured GFL converters can deliver rapid frequency-responsive power. The contribution of either control mode to system RoCoF and frequency nadir depends on its response characteristics, power headroom, current limits and the surrounding power system. Current limiting, fault ride-through and phase-angle ride-through

Because a GFM converter behaves as a voltage source, a fault or phase jump in the grid would drive very large currents unless limited. Current-limiting strategies, such as virtual impedance, current-reference saturation with anti-windup, or temporary transition to current control, are essential and strongly affect behaviour during faults: fault-current magnitude, angle, negative-sequence content and post-fault recovery. The requirements, therefore, include: fault ride-through (LVRT/HVRT as for other CBRs, with voltage-source behaviour maintained as far as possible); phase-angle ride-through (the CEA advisory of July 2026 requires ride-through of phase jumps of up to ±60°)[161]; RoCoF withstand; short-term overcurrent capability (at least 1.5 p.u. for 200 ms in the CEA advisory); and resynchronisation after islanding or severe disturbances.

6.7.1 International and Indian requirements

Table 45 compares the July 2026 CEA advisory with international specifications. India's advisory is among the most ambitious internationally: it requires 100% GFM inverters for new BESS, black start and continuous AGC participation for BESS of 50 MW and above, stable operation at SCR ≤ 2, active/reactive response within 5 ms and full response

[158] Central Electricity Regulatory Commission, Draft Central Electricity Regulatory Commission (Indian Electricity Grid Code) (Second Amendment) Regulations, 2026.

[159] Central Electricity Regulatory Commission, Central Electricity Regulatory Commission (Connectivity and General Network Access to the Inter-State Transmission System) Regulations, 2022.

[160] R. Rosso, X. Wang, M. Liserre, X. Lu and S. Engelken, "Grid-Forming Converters: Control Approaches, Grid-Synchronization, and Future Trends—A Review," in *IEEE Open Journal of Industry Applications*, vol. 2, pp. 93-109, 2021.

[161] Central Electricity Authority, "Advisory for implementation of 100% Grid Forming Invertors (GFMs) in all upcoming BESS projects," Ministry of Power, Government of India, New Delhi, India, Jul. 2026.

within 30 ms, 1.5 pu overcurrent for 200 ms, ±60° phase-jump ride-through and oscillation damping in the 0.1–20 Hz range. The priority now is to convert these requirements into testable performance specifications, compliance procedures and validated models.

Table 45: Grid-forming requirements: India compared with international specifications

Requirement	India: CEA advisory (Jul 2026)	Australia: AEMO voluntary specification (2023)	GB: GC0137 (GBGF-I)	ERCOT: NOGRR 272 (2025)
Applicability	Applicable upcoming BESS projects ≥50 MW (100% GFM), subject to advisory exemptions.	Voluntary; used in ARENA-funded GFM batteries	Voluntary capability defined in the Grid Code; procured via stability services	New inverter-based ESRs (advanced grid support)
Voltage-source behaviour	Required	Core requirement	Core requirement	Required
Weak-grid operation	Stable at SCR ≤ 2	Stable in low-strength conditions	Stable operation defined	Required
Inertial response	Inertial response required	Inertia-like response specified	Inertia (H) capability declared	Inertial response required
Response time	Active/reactive within 5 ms; full within 30 ms	Near-instantaneous	Within first cycle	Near-instantaneous
Overcurrent / fault current	≥ 1.5 pu for 200 ms	Declared capability	Fault-current contribution defined	Specified
Phase-jump ride-through	±60°	Required	Required	Required
Oscillation damping	0.1–20 Hz	Damping required	Damping specified	Specified
Black start / islanding	Required ≥ 50 MW	Optional	Optional	—

Data Compiled from Multiple Sources

6.8. Black Start and Restoration with Storage

Deployment of GFM BESS for black start and restoration services requires careful consideration of the following steps:

1. **Self-start and grid formation:** The GFM BESS starts from its own auxiliary supply (UPS) and forms a voltage at its terminals, ramping voltage and frequency smoothly.
2. **Transformer energisation:** Energising a large power transformer can draw inrush currents of 5–10 times rated current for several cycles, with high harmonic and DC content. Soft energisation, such as ramping voltage from zero with the transformer connected, largely reduces inrush and is a major advantage of GFM converters over

synchronous black-start units. Where hard switching is unavoidable, point-on-wave-controlled switching or pre-insertion resistors reduce inrush current.

3. **Line energisation:** EHV lines draw capacitive charging current ($Q \approx V^2 \omega C$); a 400 kV line generates roughly 0.5–0.6 Mvar per km, so energising 150 km produces about 80–90 Mvar that must be absorbed by the GFM converter, shunt reactors or other devices to prevent overvoltage. The converter's reactive capability and the network's reactor switching sequence must be planned together.
4. **Load pick-up:** Loads are picked up in blocks sized to keep frequency and voltage dips within limits; the GFM converter's overload capability and headroom limit the block size.
5. **Synchronisation of other resources:** Synchronous generators (hydro, gas, and coal auxiliaries) are started and synchronised to the island; GFL CBRs can connect once a stable voltage is present.
6. **Resynchronisation:** The island is resynchronised with neighbouring islands or the main grid using synchro-check relays and frequency/angle matching by the GFM units.

The energy reserved for black start must cover the full sequence with a margin:

$$E_{bs} \geq \frac{\sum_k P_k t_k}{\eta_{dis}} + E_{aux} + E_{margin}$$

where P_k and t_k are the load and duration of each restoration step. For example, a 100 MW / 400 MWh GFM BESS supporting a restoration path that energises a 150 km 400 kV line and a 315 MVA transformer and picks up 60 MW of cranking and priority load for up to 90 minutes would need about 90 MWh plus auxiliaries and margin, about 25% of its capacity held in reserve. The CEA advisory requires black-start capability from BESS with a capacity of 50 MW or more.[162] Restoration plans prepared by RLDCs should identify which BESS are designated black-start resources, their reserved SOC, the associated payments and the test schedule.

6.8.1 Grid Forming Control Technology for Black Start

6.8.1.1. AC Side Grid Forming and Synchronization Control

The GFM converter controls its internal voltage magnitude and angle, enabling operation without an existing AC voltage reference. A virtual synchronous machine (VSM) active-power loop includes a temporary synchronization input. When connecting to an energized network, the controller measures the phase-angle mismatch at the point of common coupling (PCC) and adjusts its power reference to reduce the mismatch. The synchronization logic is given in equations below.

$$J\frac{d\omega}{dt} = \frac{1}{\omega_0}\left(P^* - P + S_{\text{sync}} P_{\text{sync}}\right) + D_p(\omega^* - \omega)$$

$$P_{\text{sync}}(s) = \frac{\Delta\delta_{g,\text{pcc}}}{2\pi}\left(k_{p,\text{sync}} + \frac{k_{i,\text{sync}}}{s}\right)$$

Here, J and D_p are the VSM inertia and damping parameters, P* and P are the commanded and measured active powers, and ω* and ω are the reference and converter angular frequencies. As shown in Figure 45, the switch Ssync equals 1 only during synchronization and 0 otherwise. The auxiliary signal Psync is generated by a PI regulator acting on the angle mismatch $\Delta\delta_{g,PCC}$. A secondary PI controller restores the steady-state frequency after load changes.

[162] Central Electricity Authority, "Advisory for implementation of 100% Grid Forming Invertors (GFMs) in all upcoming BESS projects," Ministry of Power, Government of India, New Delhi, India, Jul. 2026.

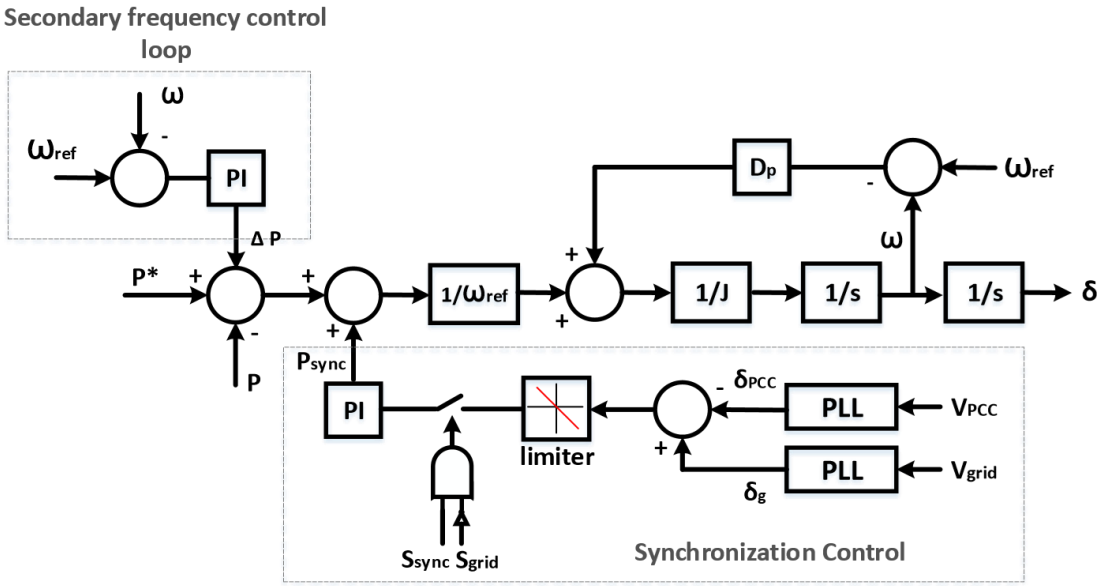


Figure 45: GFM active power control and transient synchronization logic

6.8.1.2. Voltage regulation and soft energization

The reactive power–voltage (Q–V) loop regulates the converter voltage magnitude. For network restoration, the fixed voltage reference is replaced by a time-varying ramp to increase terminal voltage gradually from zero to the nominal value, reducing the risk of transformer core saturation and high magnetizing inrush. The method depends on ramp time, transformer residual flux, saturation characteristics, and network impedance. The Q-V loop is shown in Figure 46 and is represented by below equations:

$$V = V_{\text{ref}} + k_q(Q^* - Q)$$

$$V_{\text{ref}}(t) = V_{\text{nom}} \frac{t}{T_{\text{ramp}}}, \quad 0 \le t \le T_{\text{ramp}}$$

$$V_{\text{ref}}(t) = V_{\text{nom}}, \quad t > T_{\text{ramp}}$$

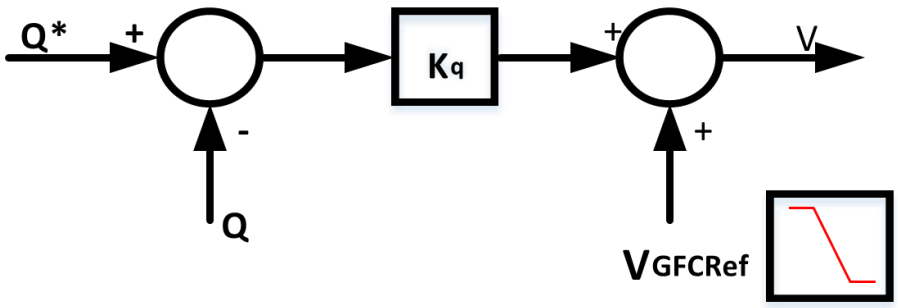


Figure 46: Modified Q–V loop with ramped voltage reference for soft energization

The output of the Q–V loop forms the voltage reference for cascaded d–q voltage and current controllers. The voltage controller uses PI controller with feedforward and cross-coupling compensation. The inner current controller tracks the resulting references and produces converter modulation commands.

6.8.1.3. Coordinated PV and battery DC-side control

The PV source is connected through a boost converter and can operate at maximum power point using a perturb-and-observe algorithm or at a de loaded operating point using PI control. The battery system is connected through a bidirectional buck–boost converter. Its outer PI loop regulates DC-link voltage, and the inner PI loop regulates battery current, as shown in Figure 47. This coordination allows the battery interface to draw or deliver the difference between PV power and AC-side requirements during restoration.

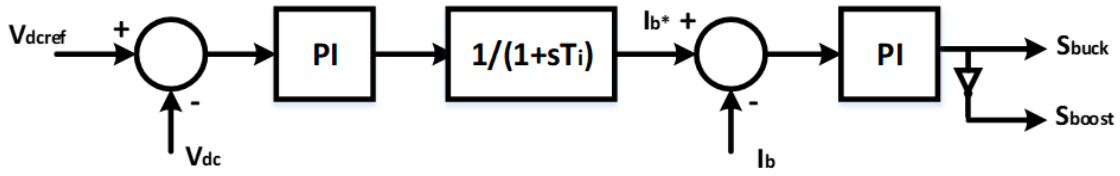


Figure 47:Cascaded battery-interface control for DC-link voltage and battery-current regulation

6.8.1.4. Power hardware-in-the-loop (PHIL) validation setup

A modified IEEE 9-bus network, shown in Figure 43, is simulated in a real-time digital simulator. The study includes two hybrid PV–BESS grid-forming resources: GFMI-1 simulated in the real-time simulation and GFMI-2 implemented using physical power electronic hardware. A synchronous generator remains available for synchronization near the end of the restoration sequence. For black-start studies, GFMI-1 and the synchronous generator are each stated to be rated at 100 MVA on the simulated network side.

A power amplifier reproduces the simulated network voltage at its output terminals. The measured current of the physical GFMI-2 is fed back to the real-time network through FPGA-based I/O, thereby closing the PHIL interface. An FPGA controller operates the PV-side DC–DC, battery-side DC–DC, and three-phase DC–AC power converters. This arrangement permits evaluation of a real converter interacting with the simulated transmission network during staged energization. The overall PHIL set-up is shown in Figure 48.

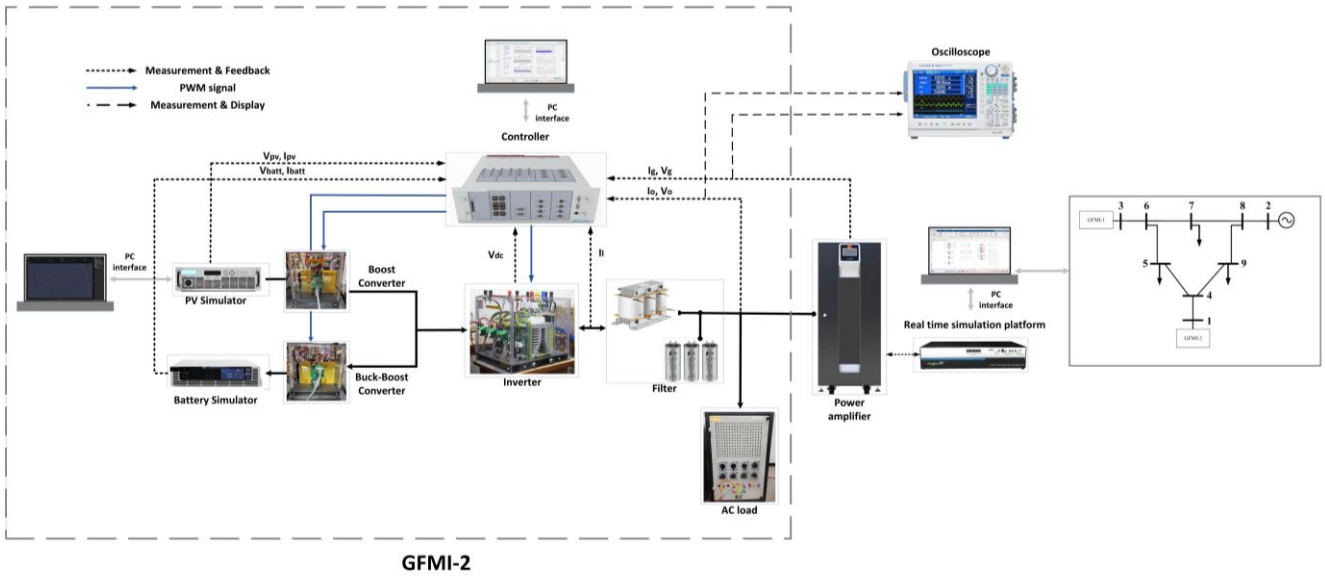


Figure 48: PHIL set-up with real-time network, power amplifier, PV and battery emulators, power converters, and FPGA-based control

6.8.1.5. Black-start test system and sequence

The test scenario begins with GFMI-1 energizing the isolated network and transformer T1. Additional loads are connected sequentially through circuit breakers CB-1 to CB-3. GFMI-2 first operates with an auxiliary load and is synchronized to the energized network through CB-4. The subsequent CB-5 and CB-6 operations add further load and an interconnecting transmission line. Finally, a synchronous generator is synchronized through CB-7, completing the demonstrated restoration process. A complete black-start sequence is given in Table 46.

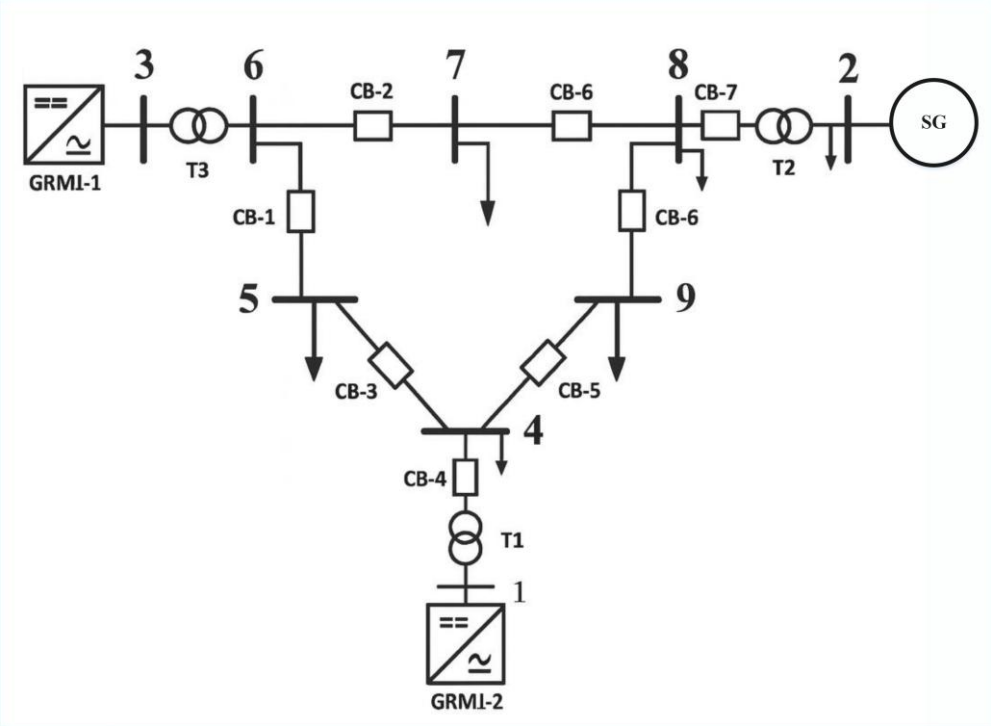


Figure 49: Modified IEEE 9-bus network and breaker locations used for the restoration sequence

Table 46: Black-start sequence

Event	Time (s)	Action / load connected
GFMI-1 started	10.0	Establishment of voltage and frequency
CB-1 closed	86.6	20 MW and 5 MVAr load
CB-2 closed	111.5	Additional 20 MW and 5 MVAr load
CB-3 closed	133.5	Additional 3 MW load
CB-4 closed	208.5	Synchronization of GFMI-2 to energized network
CB-5 closed	886.0	Additional 20 MW and 5 MVAr load
CB-6 closed	944.0	Line interconnection and additional 5 MW load
CB-7 closed	995.0	Synchronization of synchronous generator

Across the designated load-pickup operations, the scheduled increments total 68 MW and 15 MVAr (20 + 20 + 3 + 20 + 5 MW, with three 5 MVAr steps). These are network-model values used in the PHIL demonstration. The sequence evaluates network energization, load pickup, synchronization of another GFM resource, and eventual connection of a synchronous generator in one continuous restoration scenario.

6.8.1.6. Experimental observations and results

Power sharing during staged load pickup

Figure 44 shows the power response of the simulated GFMI-1. The plot shows successive increases in active power corresponding to the first three load pickups, followed by further increases when CB-5 and CB-6 are closed. The stepwise trajectory indicates that GFMI-1 supports the restoration path while it is the primary energized source. The corresponding physical GFMI-2 scaled response, shown in Figure 50, increases after the later switching operations, demonstrating that the synchronized hardware-controlled resource participates in meeting the additional simulated network demand.

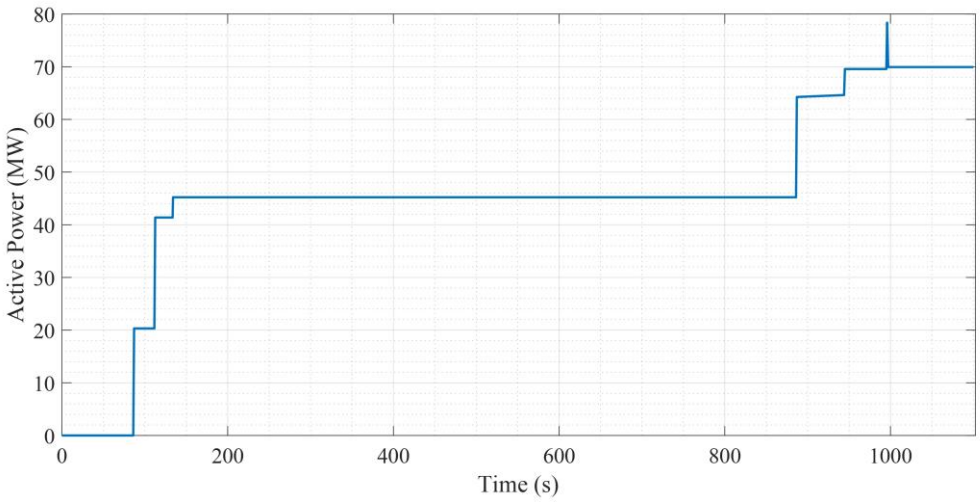


Figure 50: GFMI-1 active-power response during black start

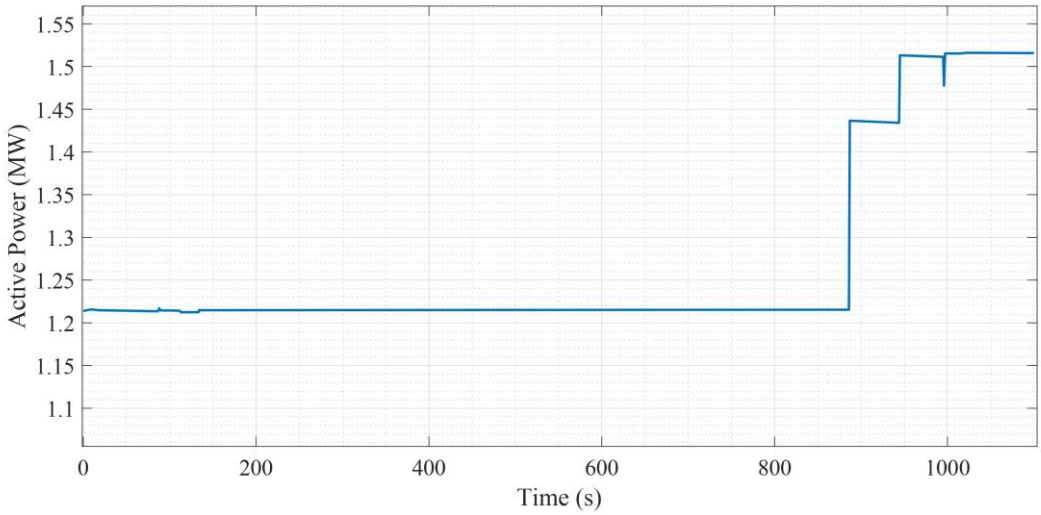


Figure 51: GFMI-2 active-power response during black start

6.8.1.7. System-frequency regulation

The frequency response remains close to the nominal 50 Hz throughout the reported black-start sequence, with small deviations at load pickup and breaker switching events. The paper attributes the recovery to secondary regulation embedded in the GFM control system. GFMI-2 is synchronized to the existing island at 208.5 s, and the synchronous generator is connected at 995 s. The results demonstrate smooth synchronization with minimal transients, attributed to the modifications in the voltage and synchronization control loops.

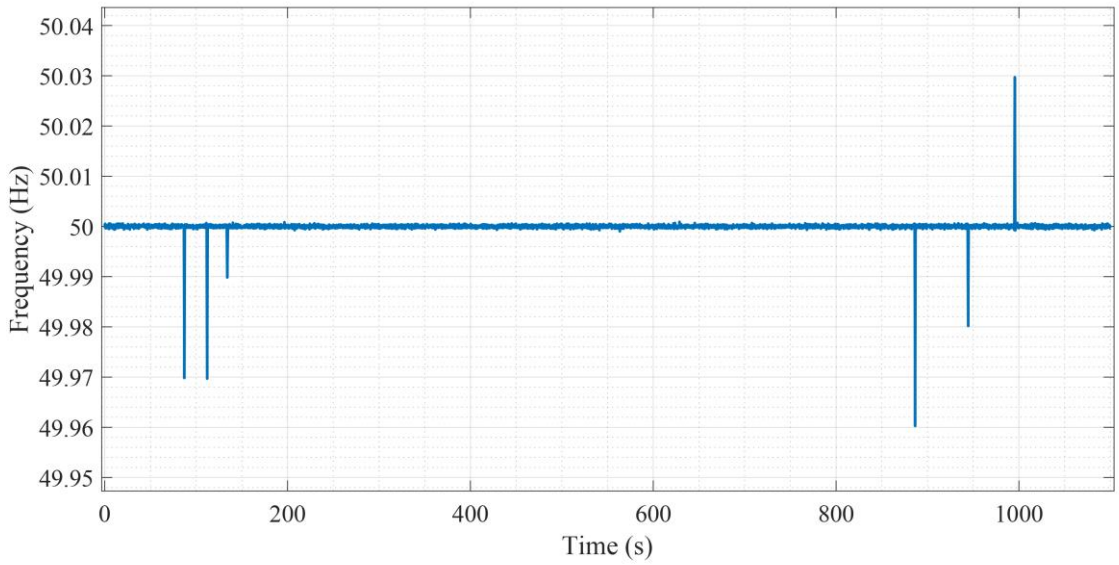


Figure 52:Network-frequency response over the black-start sequence

6.9. A Multi-Timescale Storage Architecture for India

Table 47 presents a layered flexibility architecture for India, with each layer addressing a distinct operational timescale using technologies best suited to the corresponding system need. The layers are complementary: a suitably designed BESS can provide sub-second stability services alongside multi-hour energy shifting, provided the PCS has the required control capability, including GFM functionality where applicable, and sufficient power, energy, and SOC headroom is maintained. Multi-day and seasonal balancing, however, require much larger energy inventories and are therefore better served by longer-duration storage and other complementary flexibility resources.

Table 47: Multi-timescale storage architecture: layers, technologies and indicative scale

ESS Services	Timescale / service	Technologies	Indicative scale by 2031-32
Stability	Sub-second: inertia, FFR, voltage, system strength, damping	GFM BESS (as a function of the fleet), sync condensers, PSP (condenser mode), flywheel/supercapacitor hybrids	GFM on all new BESS (≥ 40 GW); synchronous condensers at major RE complexes
Balancing	Seconds to 1 h: PFR, SRAS, TRAS, ramp control	BESS, variable-speed PSP, hydro	10–15 GW of reserve-capable storage

ESS Services	Timescale / service	Technologies	Indicative scale by 2031-32
Intraday shifting	2-6 h: evening peak, solar shifting, firming	LFP/Na-ion BESS, PSP	≈47 GW / 236 GWh BESS; ≈27 GW PSP (NEP)
Long / multi-day	10–100 h: multi-day adequacy, resilience	PSP with large reservoirs, flow, iron-air, CAES/LAES, thermal	Demonstrations; LDES procurement pilot (1–5 GWh)
Seasonal / sector-coupled	Weeks–months	Reservoir hydro, H_2/NH_3, seasonal TES, flexible electrolysers	Flexible electrolysers; hydro reservoir optimisation

Data Compiled from Multiple Sources

6.10. Storage Compared with Alternatives for Each Application

A comparison of energy storage with the alternatives for each principal application, indicating when storage is likely to be the preferred solution, is presented in Table 48. The comparison emphasises the fact that storage should compete on a level playing field with other flexibility resources in technology-neutral, attribute-based procurement.

Table 48: Storage versus alternative resources by application

Application	Storage option	Alternatives	Energy Storage Possible Preferences
Fast frequency response / inertia	GFM BESS, PSP	Synchronous condensers, retained synchronous units, GFM on RE, flywheels	Locations need both energy and stability services; fast deployment needed; low-inertia hours are frequent
Regulation (SRAS)	BESS, PSP	Hydro, gas, coal AGC	Performance-based payments reward speed/accuracy; thermal wear costs are high
Evening peak / net peak	BESS, PSP	Gas peaking plants, coal flexibility, demand response, imports	Net peak lasts 4-6 h; charging energy is cheap; gas is expensive or unavailable
Solar shifting / curtailment	BESS, variable-speed PSP	Coal flexibilisation to 40% MTL, flexible demand (electrolysers, pumping), exports	Surplus is daily and predictable; flexible demand is insufficient
Congestion relief	Pooling-station BESS	Transmission reinforcement, dynamic line rating, RAS	Congestion is hours-limited, or transmission is delayed; storage has long-term value after reinforcement

Application	Storage option	Alternatives	Energy Storage Possible Preferences
Voltage support	BESS PCS	STATCOM, SVC, synchronous condenser, RE plant reactive capability	BESS is already present; MVA oversizing is cheaper than a separate device
System strength	GFM BESS	Synchronous condensers, transmission, GFM STATCOM	Energy services are also needed at the location; condensers' inertia/fault-current benefits not critical
Black start	GFM BESS	Hydro, gas	Close to load centres; soft energisation valuable; hydro/gas remotely located
Multi-day adequacy	PSP, LDES	Retained thermal capacity, demand response, imports	Carbon constraints bind; LDES costs fall below thresholds (≈US$20/kWh energy cost)
Seasonal balancing	H_2/NH_3, reservoir hydro	Retained thermal, nuclear, and seasonal demand flexibility	Deep decarbonisation beyond 2040

Chapter 6: Key Takeaways

- Energy storage should be specified according to the required grid service, response time, usable energy, location, duty cycle and verified performance rather than installed MW/MWh alone.
- BESS and PSP offer complementary flexibility. Their suitability depends on service duration, network conditions, equipment configuration and lifecycle economics.
- ESS sizing must account for POI delivery guarantees, conversion losses, converter MVA, ambient derating, battery degradation, availability and augmentation.
- Revenue stacking can improve asset utilisation but requires explicit allocation of SOC, active-power and reactive-power headroom, along with compatible dispatch and payment arrangements.
- Grid-forming capability depends on converter control and associated system design. Its contribution to system stability must be validated through appropriate dynamic studies and testing.
- India's storage development requires a coordinated portfolio spanning fast stability support, intraday shifting, long-duration adequacy and complementary demand-side flexibility.

Chapter 7.

Status Quo of Energy Storage Deployment Landscape in India



This chapter reviews the current state of energy storage deployment in India. It begins with an overview of installed and pipeline capacity across technologies, and then takes each technology in turn: battery energy storage systems (BESS), pumped storage projects (PSP), hydrogen-based storage, and other forms of storage. For each, it covers the installed fleet, the project pipeline, procurement and notable projects, and the risks to delivery. Unless stated otherwise, data are as on 31 August 2026, the date of the latest CEA status reports; a few later developments, up to October 2026, are noted where relevant.

7.1. Energy Storage in India at a Glance

Table 55 summarises India's storage position as per the latest statistics.[163] PSP remains the largest installed storage resource, at 7,425.6 MW, of which about 5,986 MW can operate in pumping mode. Operational BESS capacity has grown to 3,027.85 MW / 9,080.20 MWh, and a further 53.8 GW / 167.6 GWh is under construction, awarded or at the tender stage. Against the NEP requirement for 2031-32 of 47.24 GW / 236.22 GWh of BESS and 26.69 GW / 175.18 GWh of PSP, the BESS pipeline already exceeds the power requirement and covers about three-quarters of the energy requirement, while PSP additions will need to accelerate to keep pace with the plan. The policy discussion has accordingly moved from whether to deploy storage to how to ensure that their performance is as specified, that they operate safely, and that they support the grid.

Table 49: India energy storage dashboard (as of 31 August 2026)

Indicator	Value	Source/date
Operational BESS	3,027.85 MW / 9,080.20 MWh (18 projects)	CEA, 31.08.2026
BESS under construction	28,210.24 MW / 79,923.92 MWh (63 projects)	CEA, 31.08.2026
BESS awarded (not started)	7,317 MW / 24,126.20 MWh (23 projects)	CEA, 31.08.2026
BESS in tender stage	18,311.31 MW / 63,534.34 MWh (83 projects)	CEA, 31.08.2026
VGF-supported BESS capacity	43.22 GWh (Tranche I: 13.22 GWh; Tranche II: 30 GWh)	MoP, Jan 2026
Operational PSP (installed / pumping-capable)	7,425.6 MW / ≈5,985.6 MW (10 stations)	CEA, Aug. 2026
PSP under construction	15,870 MW (11 projects)	CEA, Aug. 2026
PSP concurred, not started	10,400 MW (8 projects)	CEA, Aug. 2026
PSP under survey and investigation (S&I)	≈75 GW (54 projects; 52 off-stream)	CEA roadmap, Dec 2025
National Electricity Plan 2031-32 storage requirement	47.24 GW / 236.22 GWh (BESS) 26.69 GW / 175.18 GWh (PSP)	CEA, 2023
Long Term National Resource Adequacy Plan 2035-36 storage requirement	174 GW / 888 GWh	CEA, Apr 2026

Source: GIL Research, compiled from the CEA, MoP and NEP sources.

7.2. Battery Energy Storage Systems (BESS)

[163] Central Electricity Authority, Status of Development and Deployment of BESS Projects in India as on 31.08.2026; Central Electricity Authority, In-Operation Pumped Storage Plants in the Country (Above 25 MW), Status Report (Central Electricity Authority, Ministry of Power, Government of India, 2026); Central Electricity Authority, Pumped Storage Projects under Construction, Status Report (Central Electricity Authority, Ministry of Power, Government of India, 2026); Central Electricity Authority, Report on Roadmap to 100 GW of Hydro Pumped Storage Projects by 2035–36; Central Electricity Authority, National Electricity Plan, Volume I: Generation; Central Electricity Authority, Long Term National Resource Adequacy Plan (2026–27 to 2035–36).

7.2.1 Installed Capacity and Project Pipeline

Grid-connected BESS capacity in India grew rapidly in the first eight months of 2026. The CEA's monthly status report recorded 18 projects of at least 1 MWh in operation on 31 August 2026, totalling 3,027.85 MW / 9,080.20 MWh.[164] A further 63 projects totalling 28,210.24 MW / 79,923.92 MWh were under construction; 23 projects totalling 7,317 MW / 24,126.20 MWh had been awarded but not yet started; and 83 projects totalling 18,311.31 MW / 63,534.34 MWh were at the tender stage. Together, these constitute a pipeline of 187 projects and 56,866.40 MW / 176,664.66 MWh (Table 50 and Figure 53). CEA's Long-Term National Resource Adequacy Plan recorded only 275.85 MW / 791.8 MWh of operational BESS on 31 January 2026,[165] and IEEFA and JMK Research reported that 2.9 GW / 8.3 GWh had been commissioned by June 2026, of which 2.44 GW / 7.53 GWh was added in April–June 2026 alone.[166]

Table 50: Status of BESS projects (≥1 MWh) in India as on 31 August 2026

Status	Projects	Power (MW)	Energy (MWh)	Average duration (h)	Remarks
In operation	18	3,027.85	9,080.20	3.0	Includes merchant, co-located & standalone projects; Khavda (Gujarat); around ~3.37 GWh
Under construction	63	28,210.24	79,923.92	2.8	Dominated by VGF-supported state tenders and co-located RE + BESS
Awarded	23	7,317.00	24,126.20	3.3	Financial-closure and cell-procurement risk
In the tender stage	83	18,311.31	63,534.34	3.5	Visible shift to 4-hour systems
Total pipeline	187	56,866.40	176,664.66	3.1	Equivalent to ~75% of the NEP 2031-32 BESS energy requirement (236 GWh)

[164] Central Electricity Authority, Status of Development and Deployment of BESS Projects in India as on 31.08.2026.

[165] Central Electricity Authority, Long Term National Resource Adequacy Plan (2026–27 to 2035–36).

[166] Institute for Energy Economics and Financial Analysis (IEEFA) and JMK Research & Analytics, EnergyWatts: Monthly Update on India's Energy Storage Market – June 2026 (IEEFA and JMK Research & Analytics, 2026).

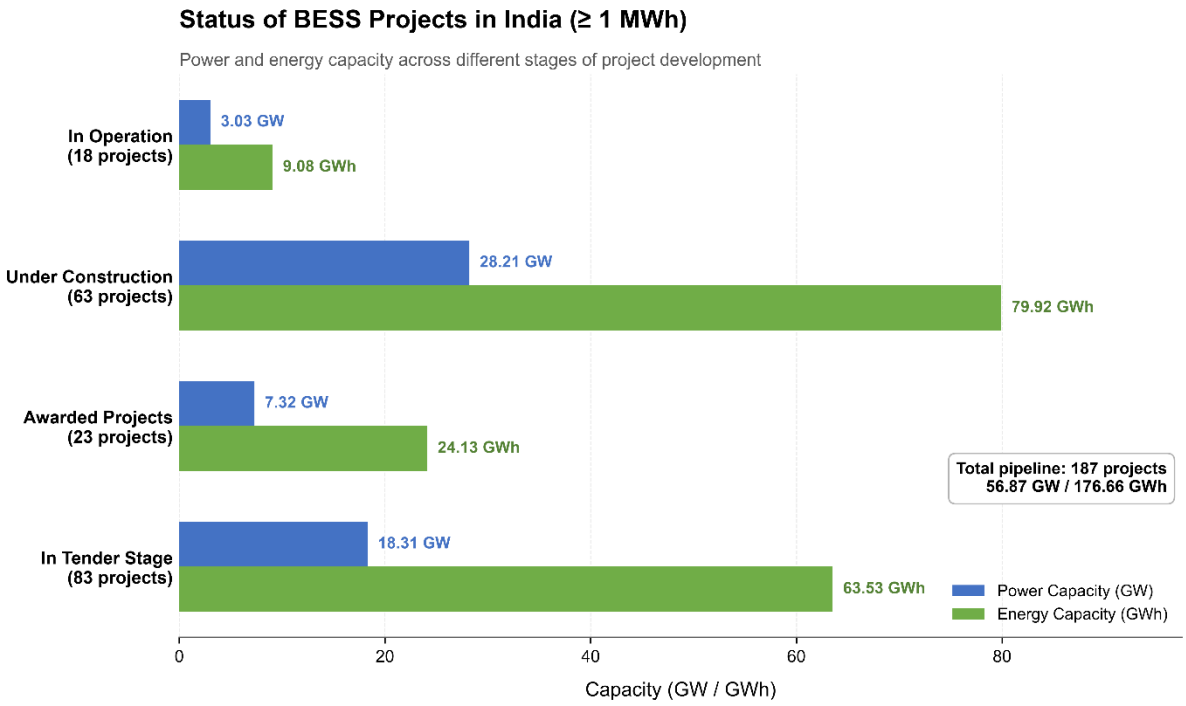


Figure 53: BESS pipeline in India by status, power (GW) and energy (GWh), 31 August 2026

Data from relevant sources also indicate when this pipeline is expected to be commissioned (Figure 54). About 10.15 GW / 26.36 GWh is expected in 2026-27, 23.47 GW / 74.07 GWh in 2027-28 and 21.47 GW / 69.44 GWh in 2028-29.

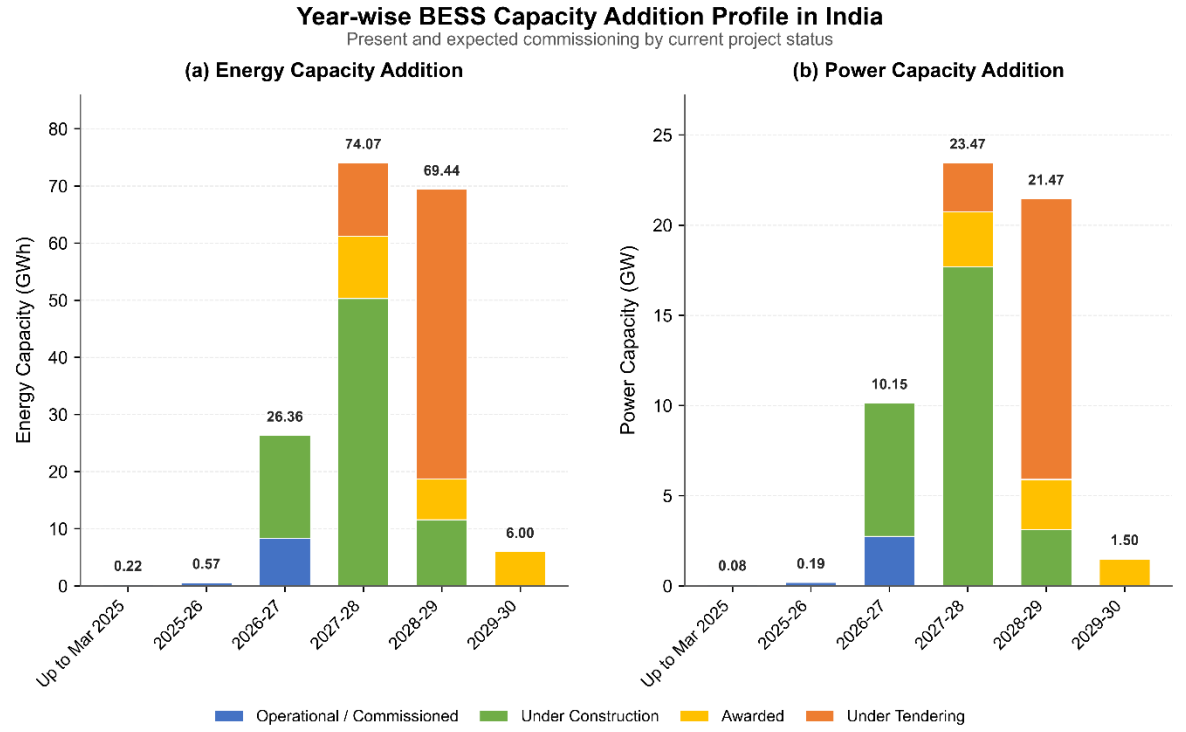


Figure 54: Year-wise BESS capacity addition profile in India

Source: CEA

These figures are best read as indicative of a development portfolio. Awarded and tender-stage capacity does not automatically convert into operating assets since product delivery depends on financial closure, equipment

procurement, transmission connectivity, land readiness, technical compliance, and commissioning arrangements. The main risks to delivery are discussed at the end of this section.

7.2.2 Market Trends: Duration, Scale and Merchant Projects

Project durations are gradually getting noticeably prolonged. Two-hour configurations dominated the early standalone BESS tenders and most of the capacity allocated in 2025. But four-hour systems have gained ground in 2026; in August 2026 they accounted for about 87% of the standalone BESS capacity tendered.[167] The shift reflects the growing need to support the evening peak and to move surplus daytime solar generation into non-solar hours.

Very large single-site projects are also being delivered quickly. By May 2026, Adani Green Energy had commissioned 3.37 GWh of BESS at Khavda, Gujarat, about ten months after on-site construction began. 1.37 GWh of this was commissioned in March 2026. The company describes it as the largest single-location BESS outside China.[168]

A merchant segment has emerged in Rajasthan and Gujarat, where developers have built BESS to earn from intraday price differences on the power exchanges. ACME Solar's projects include 120 MW / 240 MWh at Jaisalmer and 33 MW / 120 MWh near Phalodi, and the company commissioned a further 300 MWh of BESS in Rajasthan in September 2026.[169] Much of the operational BESS capacity, both merchant and contracted, is located alongside solar PV plants.

7.2.3 Procurement Channels and Discovered Tariffs

ESS is procured in India through six main channels, as follows:

i. VGF-supported standalone BESS tenders by state utilities and NTPC
ii. Central standalone tenders by SECI, NTPC/NVVN, NHPC and SJVN
iii. Co-located RE-plus-storage, FDRE, round-the-clock (RTC) and peak-supply tenders
iv. State-specific energy-based storage tenders, such as UPPCL's
v. PSP storage procurement through bilateral agreements and, since 2025, tariff-based competitive bidding (TBCB)
vi. Merchant and commercial and industrial (C&I) deployments

Error! Reference source not found. lists selected procurements in the ESS sector from 2022 to 2026.

Table 51: Selected storage procurements in India, 2022–2026

Date/Year	Procurer	Capacity	Configuration	Price discovered	Remarks
2022	SECI	500 MW / 1,000 MWh	Standalone, 2 h	≈₹10.8 lakh/MW/month	First standalone BESS benchmark
Aug 2025	NTPC	4,000 MWh (300 MW 4-h; 1,400 MW 2-h)	Standalone, VGF	—	NTPC's 5 GWh VGF share
Oct 2025	RVUNL (Rajasthan)	1,000 MW / 2,000 MWh[170]	2 h, 2 cycles; 95% availability	₹1.775-1.785 lakh/MW/month	11 winners; VGF 20/50/30
Nov 2025	RVUNL (Rajasthan)	500 MW / 2,000 MWh	4 h, 1 cycle	₹2.85 lakh/MW/month	Lowest 4-h tariff at the time

[167] Power Foundation of India, Strategic Pathways for Energy Storage in India, India Energy and Climate Center, 2025. JMK Research & Analytics and Institute for Energy Economics and Financial Analysis (IEEFA), EnergyWatts: Monthly Update on India's Energy Storage Market—Sep 2026.

[168] Adani Green Energy Limited, 'Adani Green Energy Commissions the World's Largest Single-Location Battery Energy Storage System of 3.37 GWh; Strengthens Reliable and Clean Power Access', Ahmedabad, India, 26 May 2026.

[169] Institute for Energy Economics and Financial Analysis (IEEFA) and JMK Research & Analytics, EnergyWatts: Monthly Update on India's Energy Storage Market – June 2026; ACME Solar Holdings Limited, 'ACME Solar Commissions 66.68 MW Solar Capacity and 300 MWh BESS Capacity in Rajasthan', 16 September 2026.

[170] Sharma et al., Viability of Standalone Battery Energy Storage Tariffs Discovered in 2025; Institute for Energy Economics and Financial Analysis (IEEFA) and JMK Research & Analytics, EnergyWatts: Monthly Update on India's Energy Storage Market – June 2026; Rajasthan Electricity Regulatory Commission, "Order on adoption of capacity charges for 1000 MW/2000 MWh standalone battery energy storage systems under tariff-based competitive bidding with viability gap funding support," Petition No. 2372/2025, Jan. 12, 2026;

Date/Year	Procurer	Capacity	Configuration	Price discovered	Remarks
Nov–Dec 2025	GUVNL Phases VII–VIII	2,000 MW × 2 h; 335 MW × 2 h	2 h	≈₹1.8-2.1 lakh	Gujarat VGF
Jan 2026	KSEB (Kerala)	250 MW / 500 MWh[171]	2 h; 420 cycles/yr; 15 yr	₹1.81 lakh/MW/month	—
Jan 2026	TNGECL (Tamil Nadu)	375 MW / 1,500 MWh	4 h; 1.5 cycles; 15 yr	₹3.15 lakh/MW/month	First 1.5-cycle 4-h tender
Jan 2026	SECI	1,200 MW solar + 600 MW / 3,600 MWh	6-h storage; peak supply	₹3.12–3.13/kWh	3,000 kWh/MW/day in peak; 1.5× penalty
Mar 2026	SECI (Odisha)	125 MW / 500 MWh	4 h; 15 yr; VGF ≤ ₹18 lakh/MWh	₹3.04–3.75 lakh/MW/month	Coal India won 80 MW
May 2026	UPPCL	375 MW / 1,500 MWh	4 h; 1 cycle; energy-based	₹6.45–6.46/kWh	Developer arranges the charging power
Jun 2026	SECI	1,200 MW / 4,800 MWh	Assured peak supply with 4-h storage	Bidding	Bidding stage
Jun 2026	GUVNL, KREDL, MSEDCL	450 / 900; 450 / 900; 2,000 / 4,000 (MW / MWh)	VGF, 2 h	≈₹2.10–2.12 lakh (GUVNL)	—

Source: Compiled from tender documents, regulatory adoption orders and market updates.

The following trends are evident from **Error! Reference source not found.**:

i. **From two to four hours and beyond:** four-hour designs and six-hour storage in solar-plus-storage tenders such as SECI's 1,200 MW solar tender with 600 MW / 3,600 MWh of storage became common in 2025–26.[172]

ii. **From central to state procurement:** state utilities, supported by VGF, awarded most of the 10.4 GW of standalone BESS in 2025; GUVNL, MSEDCL and RVUNL alone accounted for 6,165 MW (59%).[173]

iii. **From capacity-based to energy-based structures:** UPPCL's tender and SECI's peak-supply tenders transfer the charging-energy risk to developers. This can be efficient when developers can source cheap midday power, but it exposes them to exchange-rate risk.

iv. **From price to performance:** recent tenders specify stricter availability, round-trip efficiency and cycling requirements, and the CEA's 2026 draft technical standards introduce capacity-retention and grid-support requirements.

Aggregate figures published by industry trackers, such as 103.4 GW of storage-linked capacity tendered and 50 GW awarded by June 2026, include hybrid and FDRE projects in which storage is embedded. They are therefore not directly comparable with the CEA's BESS-only status data.[174]

7.2.4 Co-located Storage, FDRE and Hybrid Structures

[171] Kerala State Electricity Regulatory Commission, "Order on adoption of tariff discovered through tariff-based competitive bidding for 250 MW/500 MWh grid-scale battery energy storage system at Brahmapuram, Ernakulam," OP No. 16/2026, Jun. 2026

[172]Solar Energy Corporation of India Ltd. (SECI), Request for Selection of Solar Power Developers for Setting up of 1200 MW ISTS-Connected Solar PV Power Projects with 600 MW/3600 MWh Energy Storage Systems (SECI-ISTS-XXI), RfS No. SECI/C&P/IPP/11/0006/25-26, Jun. 2025; Ministry of Power, Government of India, Guidelines to Promote Development of Pumped Storage Projects, Apr. 2023; U.S. Department of Energy, Achieving the Promise of Low-Cost Long Duration Energy Storage, Aug. 2024..

[173] P. Sharma, V. Mor, M. Srivastava, V. Garg and C. Konda, *Viability of Standalone Battery Energy Storage Tariffs Discovered in 2025*. Institute for Energy Economics and Financial Analysis and JMK Research & Analytics, May 2026.

[174] Institute for Energy Economics and Financial Analysis and JMK Research & Analytics, *EnergyWatts: Monthly Update on India's Energy Storage Market – June 2026*, 2026.

An advisory issued in February 2025 asked RE Implementing Agencies (REIAs) and state utilities to include co-located storage of at least two hours, equal to 10% of installed solar capacity, in future solar tenders. The storage may operate in single-cycle mode, charging from solar and discharging in the evening, or in double-cycle mode. The advisory projected about 14 GW / 28 GWh of storage by 2030 to meet this requirement.[175] In 2026, the CEA went further in draft amendments to its technical standards, proposing compulsory co-located storage for new ground-mounted solar and onshore wind projects. The drafts propose an ESS of at least 10% of installed plant capacity, with two hours of storage from 1 July 2027 to 30 June 2029 and four hours from 1 July 2029 to 30 June 2031, together with grid-forming capability for at least 15% of inverters and for all BESS power conversion systems.[176] These measures will place substantial storage close to RE plants. How much value that storage provides to the grid will depend on three design questions:

- **Dispatch rights:** whether the storage can be dispatched by the system operator or the contracted buyer, or is used only to smooth or shift the RE plant's own output to a fixed schedule.
- **Coupling architecture:** AC-coupled systems share the point of connection but have separate inverters, which allows grid charging and independent operation. DC-coupled systems share inverters, recapture clipped DC energy and reduce conversion losses, but limit simultaneous export of PV and storage output.
- **Metering and accounting:** charging energy drawn from the grid and from the co-located RE plant needs to be metered separately for RE attributes and network charges.

7.2.5 Transmission Access for Storage

Access to the ISTS was originally granted for the full day, which left transmission capacity at many renewable pooling stations unused after sunset. The CERC (Connectivity and General Network Access to the inter-State Transmission System) (Third Amendment) Regulations, 2025 separated ISTS access into solar-hour and non-solar-hour access.[177] Solar hours are declared weekly by the NLDC for each State based on anticipated solar insolation, and all other time blocks are non-solar hours. A wind-based generating station, with or without storage, or a standalone ESS of 50 MW or more may now seek non-solar-hour access at an ISTS terminal bay by using transmission capacity already allotted to solar plants for daytime use. Storage connected in this way specifies a maximum injection and a maximum drawal for charging within its connectivity quantum, and additional drawal may be allowed where transmission margins permit. According to the Ministry of Power, this allows more RE capacity to connect at existing substations and enables storage to shift power to the evening and night.[178]

In May 2026, CERC proposed further changes in the draft Fourth Amendment to the same regulations.[179] The draft would extend non-solar-hour access to substations beyond those currently listed, require an ESS seeking connectivity to have a discharge capability of at least twice its connectivity quantum (that is, at least two hours), and reduce the land bank guarantee for ESS other than pumped storage from ₹10 lakh/MW to ₹5 lakh/MW. In October 2026, the CTUIL specified, under the same regulations, a minimum discharge duration of two hours for BESS in the

[175] Central Electricity Authority, Advisory on Co-Locating Energy Storage Systems with Solar Power Projects to Enhance Grid Stability and Cost Efficiency.

[176] Central Electricity Authority, 'Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026'; Draft Central Electricity Authority (Technical Standards for Construction of Electrical Plants and Electric Lines) Amendment Regulations, 2026.

[177] Central Electricity Regulatory Commission, "Central Electricity Regulatory Commission (Connectivity and General Network Access to the inter-State Transmission System) (Third Amendment) Regulations, 2025," Notification No. L-1/261/2021/CERC, New Delhi, India, Aug. 31, 2025.

[178] Ministry of Power, "Development of battery energy storage systems," Press Information Bureau, Government of India, Mar. 30, 2026.

[179] Central Electricity Regulatory Commission, "Draft Central Electricity Regulatory Commission (Connectivity and General Network Access to the inter-State Transmission System) (Fourth Amendment) Regulations, 2026," Notification No. L-1/261/2021/CERC, New Delhi, India, May 20, 2026.

right-of-first-refusal category and four hours for other applications and for standalone BESS at renewable pooling stations, with charging from the ISTS permitted subject to available transmission margins.[180]

Together, these provisions give storage a defined route to the transmission capacity that solar plants leave unused after sunset. How much of that capacity storage can use will depend on the drawal margins available at each substation and on how the minimum-duration requirements are applied to projects already in the connectivity queue

7.2.6 Notable BESS Projects

Utility-scale BESS projects are being developed by central agencies, public sector undertakings, state utilities, and distribution companies in standalone, RE-plus-storage, and thermal-site configurations. Selected projects are included here:

7.2.6.1. Central Agencies and Public Sector Undertakings

SECI's 100 MW solar PV plant with a 40 MW / 120 MWh BESS at Rajnandgaon, Chhattisgarh, is one of its flagship integrated projects. In Lakshadweep, the 1.4 MW solar plant with 1.4 MWh of BESS at Kavaratti was the islands' first on-grid solar project with battery storage; together with a 300 kW plant at Agatti, SECI operates 1.7 MW of solar and 1.4 MWh of storage there.[181] SECI and the Government of Andhra Pradesh are also jointly developing a 1,200 MWh BESS with a 50 MW solar plant at Nandyal, with SECI responsible for the investment.[182]

NTPC is studying the use of BESS in place of diesel generator sets for backup power at its thermal stations, and has announced a 160-MWh CO_2 battery at its Kudgi station, in Karnataka, a long-duration technology being deployed with Energy Dome and Triveni Turbine.[183] NTPC has also tendered a 2,500 MW/10,000 MWh standalone BESS programme across its thermal plant sites. Its trading arm, NVVN, has run tenders on behalf of state utilities, including 250 MW / 500 MWh of standalone BESS for the Kerala State Electricity Board and 500 MW/1,000 MWh for Tamil Nadu in early 2025.

7.2.6.2. State Utility Projects

Gujarat Urja Vikas Nigam Ltd. (GUVNL) has tendered standalone BESS in successive phases.[184] Maharashtra State Electricity Distribution Company Ltd. (MSEDCL) issued a 2,000 MW/4,000 MWh standalone BESS tender backed by viability gap funding,[185] and Rajasthan Rajya Vidyut Utpadan Nigam Ltd. (RVUNL) tendered 1,000 MW/2,000 MWh of standalone BESS.[186] In Bihar, the Kajra solar project is integrating BESS in two phases: 254 MWh in Phase I and 241 MWh in Phase II; the first phase has been commissioned.[187]

7.2.6.3. Distribution-Level Projects and Pilots

The Kilokari BESS in Delhi, a 20 MW/40 MWh standalone system commissioned in 2025, is one of the larger distribution-level deployments. It was developed by IndiGrid in partnership with BSES Rajdhani Power Ltd. (BRPL), with support from the Global Energy Alliance for People and Planet (GEAPP), and is connected to a 33/11 kV

[180]Central Transmission Utility of India Ltd., "Advisory on minimum discharge duration for battery energy storage systems seeking connectivity under the GNA Regulations," Gurugram, India, Oct. 2026.

[181] Solar Energy Corporation of India Ltd. (SECI), "Own Projects," Ministry of New and Renewable Energy, Government of India.

[182] Ministry of New and Renewable Energy, Government of India, "India's clean energy transition gets major boost as SECI and Andhra Pradesh finalise 1200 MWh battery energy storage system (BESS) and 50 MW hybrid project," Press Information Bureau (PIB), Nov. 15, 2025.

[183] Press Information Bureau, "NTPC rolls out state-of-the-art CO2 battery at Kudgi: A landmark 'long duration' electrical energy storage solution," Ministry of Power, Government of India, Jan. 29, 2025.

[184] Gujarat Urja Vikas Nigam Limited, "Notice Inviting Tender (NIT) for Procurement of Battery Energy Storage Systems (Long Duration Energy Storage) under Tariff-Based Global Competitive Bidding (Phase-V)," Oct. 19, 2024.

[185] Maharashtra State Electricity Distribution Company Limited, "Request for Selection (RfS) for Setting up of 2,000 MW/4,000 MWh Battery Energy Storage Systems under Tariff-Based Global Competitive Bidding (Phase-II)," Jul. 25, 2025.

[186] Rajasthan Rajya Vidyut Utpadan Nigam Limited, "Request for Selection (RfS) for Setting up of 1000 MW/2000 MWh Standalone Battery Energy Storage Systems under Tariff-Based Global Competitive Bidding with Viability Gap Funding Support (BOO Model)," Jul. 10, 2025.

[187] Bihar State Power Generation Company Limited, "Bid for Survey, Design, Engineering, Supply, Procurement, Installation, Erection, Construction, Commissioning and Operation & Maintenance of 185 MW (AC) Solar PV Project along with 45.4 MW/254 MWh Battery Energy Storage System on EPC Basis at Kajra, Lakhisarai, Bihar," Dec. 2023.

substation. It is used for peak management, local grid support and energy time-shifting, and has been used to test participation in automatic generation control.[188]

A 12.5 MW / 25 MWh grid-forming BESS at the 33/11 kV Shivalik Grid substation in New Delhi has received in-principle approval from the Delhi Electricity Regulatory Commission. Once built, it will be among the first demonstrations of grid-forming capability at the distribution level in India.[189]

Tata Power Delhi Distribution Limited (TPDDL) has signed an agreement with the Asian Development Bank for distribution network upgrades that include a battery energy storage system, alongside the expansion of transformers, substations, and feeders, and the installation of smart meters.[190] Among earlier pilots, TERI worked with West Bengal State Electricity Distribution Company Ltd. (WBSEDCL) in Kolkata to test BESS at the distribution transformer level for peak management and storage of rooftop solar output.[191]

7.2.7 Domestic Manufacturing and Cell Supply

Cell supply is one of the key constraints on BESS growth. CEEW projected battery storage demand from the grid at about 27 GW/108 GWh by 2029–30 and estimated that only about 13% of battery-cell demand for electric vehicles would be met domestically by 2030, with the rest imported.[192] With about 3 GW/9 GWh of BESS installed in August 2026 and a much larger pipeline, the need to build domestic manufacturing capacity is evident. The Ministry of Power has made a minimum of 20% domestic content a condition for VGF support for BESS projects.[193]

7.2.8 Risks to Delivery

About 80 GWh of BESS is under construction. The principal risks to its timely delivery are:

i. financial closure challenges arising from aggressively priced bids;
ii. battery-cell supply constraints and input-price volatility, particularly the sharp recovery in lithium prices during 2025–2026;
iii. delays in power evacuation infrastructure and grid-connection readiness;
iv. additional technical, grid-forming and safety requirements introduced or revised after the original bidding; and
v. limited project execution experience among some successful bidders.[194]

7.3. Pumped Storage Projects (PSP)

Pumped storage remains India's largest energy storage resource. The CEA lists ten PSPs with a combined installed capacity of 7,425.6 MW, including Greenko's 1,680 MW Pinnapuram PSP in Andhra Pradesh, commissioned in 2025, and THDC's 1,000 MW Tehri PSP in Uttarakhand, whose units were commissioned in 2025-26.[195] Of this capacity, 1,440 MW at Sardar Sarovar (1,200 MW) and Kadana (240 MW) in Gujarat is not operational in pumping mode, so the pumping-capable fleet is about 5.99 GW. Even this figure describes installed capability rather than the capacity available for pumping at a given time, which is why storage is better characterised by demonstrated capability than

188 IndiGrid Infrastructure Trust, "Kilokari BESS Private Limited (KBPL)," 2022

189 Delhi Electricity Regulatory Commission, "Order granting in-principle approval for commissioning of a 12.5 MW/25 MWh grid-scale Battery Energy Storage System at the 33/11 kV Shivalik Grid substation," Petition No. 44/2025, 2025.

190 Tata Power, "ADB, Tata Power Sign Deal to Enhance Delhi's Power Distribution Through Grid Enhancements and Battery Energy Storage System,".

191 The Energy and Resources Institute, "TERI Launches Pilot Study to Introduce Battery Energy Storage System (BESS) to Upgrade Power Infrastructure," Nov. 22, 2018.

192 D. Warrior, et al., "Strengthening India's Clean Energy Supply Chains: Building Manufacturing Competitiveness in a Globally Fragmented Market," Council on Energy, Environment and Water (CEEW), New Delhi, India, Sep. 2024.

193 Ministry of Power, "Domestic Battery Manufacturing and Energy Storage", Govt. of India. July 2026

194 International Energy Agency, Global Critical Minerals Outlook 2026. Paris, France: IEA, 2026.; P. Sharma, V. Mor, M. Srivastava, V. Garg, and C. Konda, Viability of Standalone Battery Energy Storage Tariffs Discovered in 2025. Institute for Energy Economics and Financial Analysis and JMK Research & Analytics, May 2026.

195 Central Electricity Authority, *Status of Pumped Storage Development in India* (Central Electricity Authority, Ministry of Power, Government of India, 2026).

by nameplate capacity. The Tehri PSP, fully commissioned in April 2026, provides an Indian example of variable-speed reversible units that allow pumping power to be controlled.

7.3.1 Capacity by Stage of Development

Table 52 and Figure 55 summarise PSP capacity by stage of development. The pipeline behind the operating fleet is large. Eleven projects totalling 15,870 MW are under construction; eight projects totalling 10,400 MW have detailed project reports (DPRs) concurred by the CEA but have not yet started construction; and 54 projects totalling about 75 GW were under survey and investigation (S&I) at the end of 2025, 52 of them off-stream closed-loop schemes. The assessed national PSP potential has risen from 97.6 GW at the end of 2022 to about 267 GW at the end of 2025, comprising 58 GW on-stream and 209 GW off-stream.[196] Most of this increase reflects off-stream closed-loop sites identified by developers. Assessed potential, however, does not establish land availability, water security, environmental clearance, economic feasibility or transmission connectivity.

Table 52: Pumped storage capacity in India by development stage (CEA, August 2026)[197]

Stage	Projects	Capacity (MW)	Notes
In operation (installed)	10	7,425.6	Of which 1,440 MW (Sardar Sarovar, Kadana) is not operational in pumping mode; pumping-capable ≈ 5,985.6 MW
Under construction	11	15,870	State sector 3,850 MW; private 12,020 MW; CODs Dec 2026-May 2032
DPR concurred, construction not started	8	10,400	Includes Chichlik and Jhariya (Uttar Pradesh) and Indira Sagar–Omkareshwar (Madhya Pradesh), concurred in Jul–Aug 2026
Survey & investigation (Dec 2025)	54	≈75,000	52 of 54 are closed-loop off-stream schemes
Assessed potential (Dec 2025)	-	≈266,800	58 GW on-stream + 209 GW off-stream
Planned new capacity by 2031-32	-	53,950	CEA year-wise PSP capacity addition plan
Roadmap target in operation by 2035-36	-	≈100,810	CEA Roadmap to 100 GW of PSPs (Jan 2026)

[196] Central Electricity Authority, Report on Roadmap to 100 GW of Hydro Pumped Storage Projects by 2035–36.

[197] Central Electricity Authority, *Report on Roadmap to 100 GW of Hydro Pumped Storage Projects by 2035–36*, Report (Central Electricity Authority, Ministry of Power, Government of India, 2026).

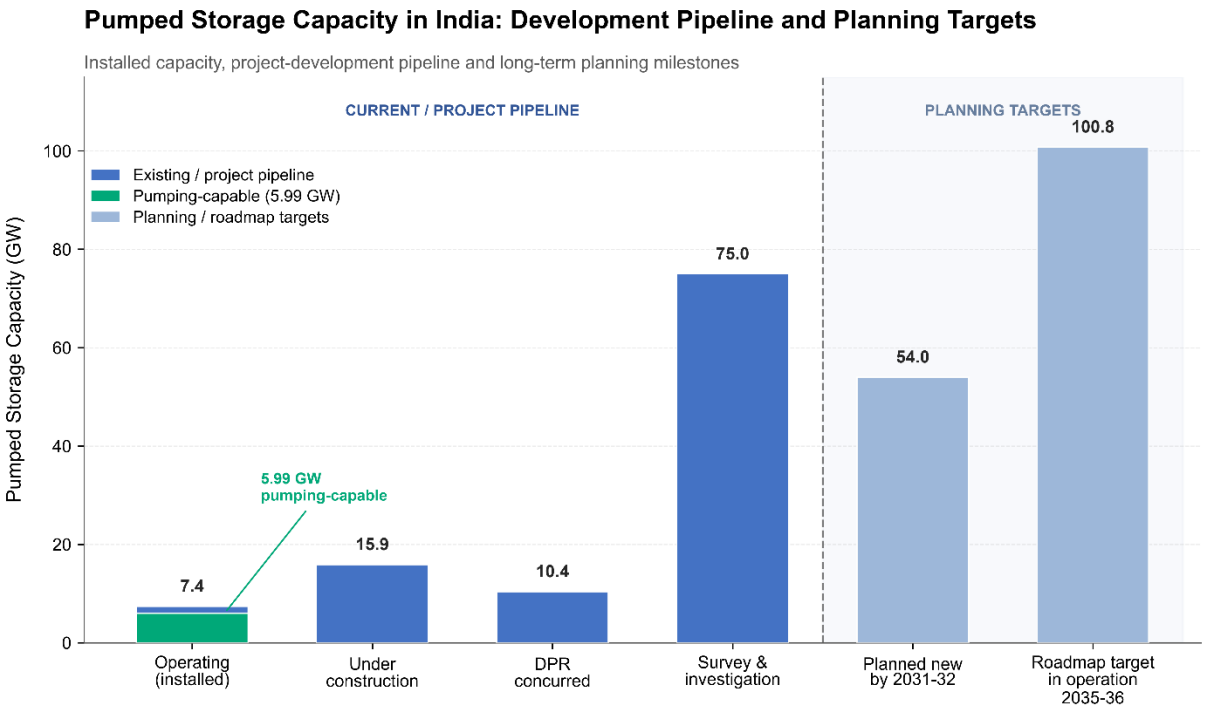


Figure 55: Pumped storage capacity by development stage (as of August 2026)

Source: Plotted from the CEA pumped storage status lists.

7.3.2 Operating Fleet

Table 53 lists the ten operating PSPs.[198] The fleet is small relative to its potential and varied in age: Bhira dates back to 1927, most stations were built between 1980 and 2008, and the two recent additions, Pinnapuram and Tehri, account for more than a third of the installed capacity. Sardar Sarovar and Kadana have not operated in pumping mode, owing to incomplete downstream (tail-pond) works or operational constraints.

Table 53: In-operation pumped storage projects in India, as of August 2026 (above 25 MW)

Sl. No.	Utilities/ Stations	Developer	State	Type	Capacity (MW)	Year of Commissioning
1	Ghatgarh	MAHAGENCO	Maharashtra	Onstream	250	2008 (250 MW)
2	Bhira	Tata Power Company	Maharashtra	Onstream	150	1927 (125 MW) 1949 (25 MW)
3	Nagarjuna Sagar	TSGENCO	Telangana	Onstream	705.6	1980 (100.8 MW) 1981 (100.8 MW) 1982 (100.8 MW) 1983 (100.8 MW) 1984 (100.8 MW) 1985 (201.6 MW)
4	Srisailam LBPH	TSGENCO	Telangana	Onstream	900	2001 (300 MW) 2002 (450 MW) 2003 (150 MW)
5	Kadamparai	TANGEDCO	Tamil Nadu	Onstream	400	1987 (100 MW) 1988 (200 MW) 1989 (100 MW)

[198] Central Electricity Authority, In-Operation Pumped Storage Plants in the Country (Above 25 MW).

6	Purulia	WBSEDCL	West Bengal	Off-stream (Closed Loop)	900	2007
7	Kadana#	GSECL	Gujarat	Onstream	240	1990 (120 MW) 1998 (120 MW)
8	Sardar Sarovar RBPH#	SSNNL	Gujarat	Onstream	1200	2005 (800 MW) 2006 (400 MW)
9	Tehri	THDC	Uttarakhand	Onstream	1000	2025 (750 MW) 2026 (250 MW)
10	Pinnapuram	Greenko AP01 IREP Private Limited	Andhra Pradesh	Off-stream (Closed Loop)	1680	2025 (1680 MW)
	Total				**7425.60**	

#At present, Sardar Sarovar RBPH (1200 MW) & Kadana PSP project (240 MW) are not operational in pumping mode, and provisions are being undertaken to enable the required operation shortly.

7.3.3 Projects under Construction

Eleven projects totalling 15,870 MW are under construction (Table 54 and Figure 56).[199] The private sector now accounts for most of this capacity (12,020 MW), with state utilities accounting for 3,850 MW. Ten of the eleven projects are expected by the end of 2029, with Sharavathy (2,000 MW) expected in May 2032. PSP projects have often faced delays, however, and several of these depend on evacuation transmission that is not yet commissioned.

Table 54: Pumped storage projects under construction (CEA, August 2026)

Project	State	Developer	Capacity (MW)	Anticipated commissioning
Gandhi Sagar	Madhya Pradesh	Greenko MP01 IREP	1,920	Dec 2026
Kundah (Phases I–III)	Tamil Nadu	TNGECL	500	Feb 2027
Chitravathi	Andhra Pradesh	Adani Renewable Energy 42	500	Feb 2027
Saundatti	Karnataka	Greenko KA01 IREP	1,600	Dec 2027
Bhavali	Maharashtra	JSW Energy PSP Two	1,500	Dec 2028
Upper Sileru	Andhra Pradesh	APGENCO	1,350	Feb 2029
Bhivpuri	Maharashtra	Tata Power	1,000	Feb 2029
Gandikota	Andhra Pradesh	Adani Renewable Energy 51	1,000	Mar 2029
Tarali	Maharashtra	Adani Renewable Energy One	1,500	Jun 2029
Saidongar-1 (Karjat)	Maharashtra	Torrent Energy Storage	3,000	Dec 2029
Sharavathy	Karnataka	KPCL	2,000	May 2032

[199] Central Electricity Authority, Pumped Storage Projects under Construction.

Project	State	Developer	Capacity (MW)	Anticipated commissioning
Total		**15,870**		

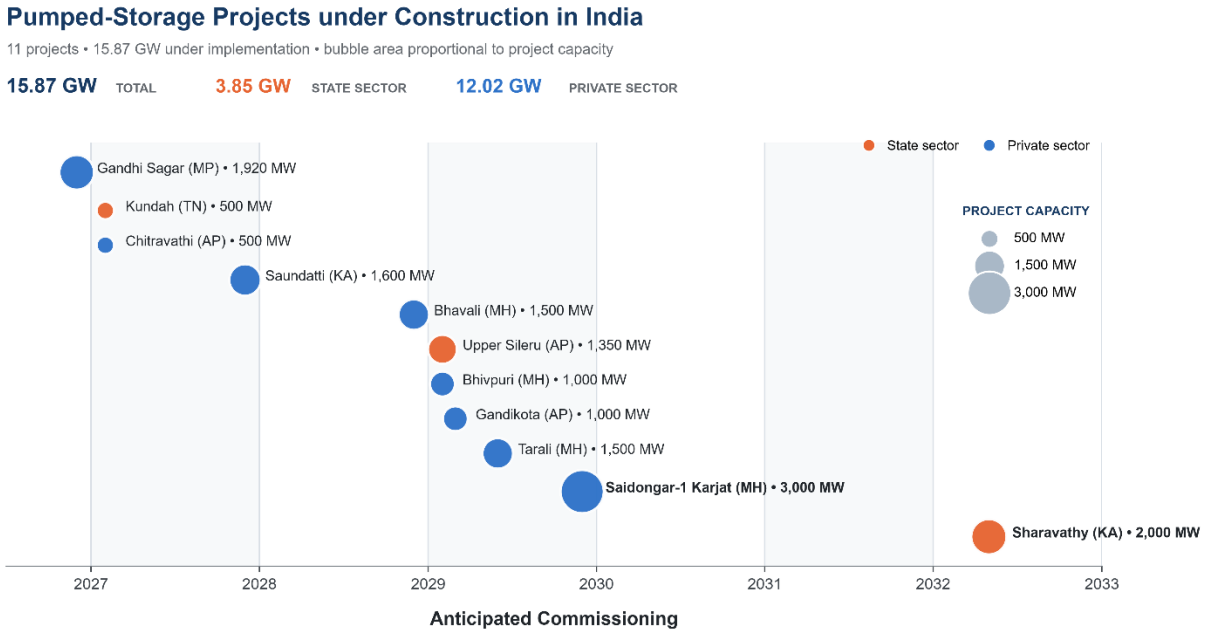


Figure 56: Pumped storage projects under construction by anticipated commissioning date and capacity

Source: Plotted from the CEA list of PSPs under construction.

7.3.4 Concurred Projects and the Investigation Pipeline

Eight projects totalling 10,400 MW have DPRs concurred by the CEA but have not yet started construction (Table 56).[200] Two of them, Chichlik (1,560 MW, Avaada) and Jhariya (1,620 MW) in Uttar Pradesh, were concurred in July and August 2026, joining Kandhaura (1,680 MW, JSW), concurred in 2025. Uttar Pradesh is thus emerging as a PSP destination, supported by state incentives such as stamp duty exemption, investment subsidies, and GST reimbursement.[201] The Ministry of Power's July 2026 status statement listed six projects under concurrence, totalling 8,140 MW. The difference reflects Jhariya and Indira Sagar–Omkareshwar (640 MW), both of which were concurred in August 2026. The same statement noted that eligible off-stream closed-loop PSPs are exempt from mandatory CEA concurrence, so DPR-concurred capacity does not represent the full development pipeline.[202]

Table 55: PSPs with DPR concurred by CEA, yet to be taken up for construction

Project	State	Developer	Capacity (MW)	Date of concurrence
Turga	West Bengal	WBSEDCL	1,000	05.10.2016
Upper Indravati	Odisha	OHPC	600	19.08.2024
Kandhaura	Uttar Pradesh	JSW Energy PSP Six	1,680	13.06.2025

[200] Central Electricity Authority, *PSPs* Concurred *by* CEA *and* Yet to Be Taken Up for Construction.

[201] Central Electricity Authority, *Report on Roadmap to 100 GW of Hydro Pumped Storage Projects by 2035–36*. New Delhi, India: Ministry of Power, Government of India, Jan. 2026.

[202] Ministry of Power, "Status on Pumped Storage Projects," Press Information Bureau, Government of India, Jul. 20, 2026

Shirwata	Maharashtra	Tata Power	1,800	07.09.2025
Pane	Maharashtra	JSW Energy	1,500	18.09.2025
Chichlik	Uttar Pradesh	Avaada	1,560	08.07.2026
Jhariya	Uttar Pradesh	Jhariya AnantUrja	1,620	13.08.2026
Indira Sagar–Omkareshwar	Madhya Pradesh	NHDC	640	17.08.2026
Total			**10,400**	

Developers are also building up the pipeline further. THDC India has signed a memorandum of understanding with the Government of Maharashtra for six PSPs totalling 6,790 MW: Malshej Ghat (700 MW), Aruna (1,950 MW), Kharari (1,250 MW), Humbarli Birmani (1,000 MW), Aruna Kolamb (1,200 MW) and Morawadi Majarewadi (690 MW).[203] NHPC's development list similarly includes PSPs under survey and investigation in Uttarakhand, Andhra Pradesh, Odisha, Gujarat and Maharashtra.

7.3.5 Regional Distribution of Potential and Development

PSP potential is unevenly distributed, with the Western and Southern regions accounting for the largest shares (Figure 57).

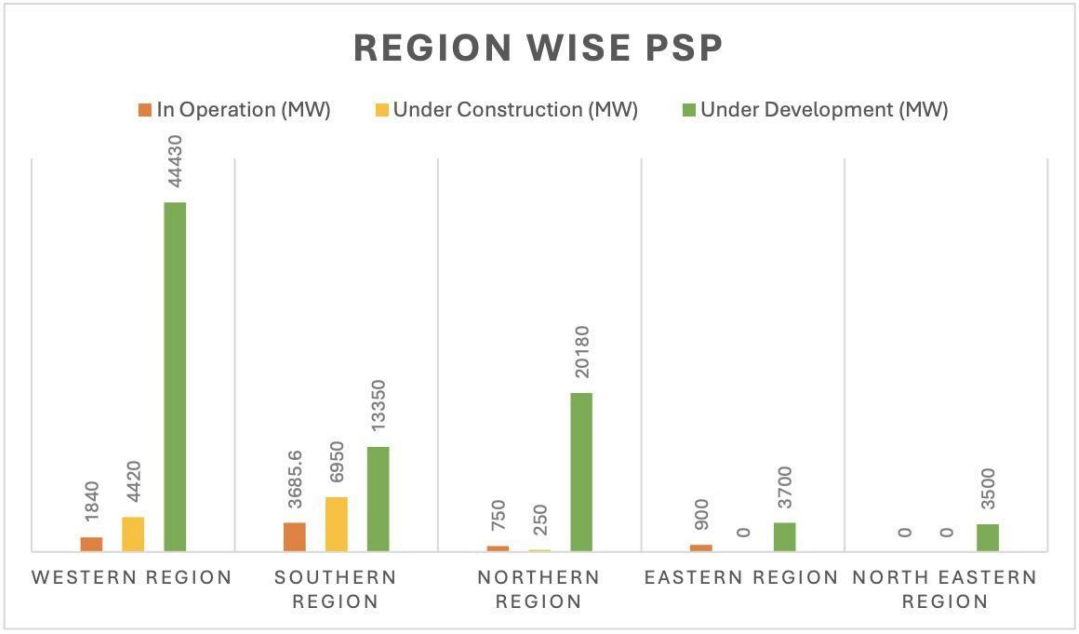


Figure 57: Region-wise pumped storage potential and development status (December 2025)[204]

In the Northern Region, the operating capacity is 1,000 MW, comprising four 250 MW units at the 1,000 MW Tehri PSP in Uttarakhand. In the Western Region, Maharashtra has the highest potential in the country, at 56,355 MW. Two of its projects, Bhira (150 MW) and Ghatgarh (250 MW), are operating; four projects totalling 7,000 MW are under construction (Bhavali, 1,500 MW; Bhivpuri, 1,000 MW; Tarali, 1,500 MW; and Saidongar-1, 3,000 MW); and Shirwata

[203] THDC India Limited, "THDC inks ambitious MoU with Maharashtra Government for harnessing 6,790 MW pumped storage projects with an investment of over ₹33,600 crore".

[204] Central Electricity Authority (CEA), "Roadmap to 100 GW of Hydro Pumped Storage Projects (PSPs) by 2035–36," Ministry of Power, Government of India, New Delhi, India, Jan. 2026.

(1,800 MW) and Pane (1,500 MW) have concurred DPRs. In the Southern Region, Andhra Pradesh, with 32,750 MW of potential, has 1,680 MW operating, 2,850 MW under construction and 12,050 MW under S&I, making it one of India's leading PSP states. In the Eastern Region, Odisha has potential of 41,525 MW, of which 600 MW (Upper Indravati) has been concurred by the CEA and 2,100 MW is under S&I. In the North-Eastern Region, the potential stands at 10,930 MW, with most activity still at the preliminary investigation stage.

Maharashtra, Odisha and Andhra Pradesh together account for about 131 GW, or 49%, of the national assessed potential of 266.85 GW. This potential should not be equated with implementable capacity: development depends on site investigations, land and water availability, statutory clearances, transmission connectivity and commercial viability.

7.3.6 Capacity-Addition Plan and the Roadmap to 100 GW

The CEA's year-wise plan anticipates cumulative new PSP capacity of 53,950 MW by 2031-32, with additions peaking at 22,390 MW in 2029-30 (**Error! Reference source not found.**).[205] The January 2026 *Roadmap to 100 GW of Hydro Pumped Storage Projects* goes further, targeting about 100.81 GW in operation by 2035-36, which would require average additions of about 9 GW per year and peak additions of about 21 GW in 2030-31.[206] At the CEA's average cost of about ₹6 crore per MW, the roughly 93 GW of new capacity implied by the roadmap would need investment of the order of ₹5.6 lakh crore. Transmission is a major constraint: of about 94 GW of planned PSP capacity, the roadmap records only 2.68 GW with commissioned transmission, 11.37 GW with transmission under construction, 60.4 GW with transmission planned but not implemented, and 19.78 GW without transmission planning.

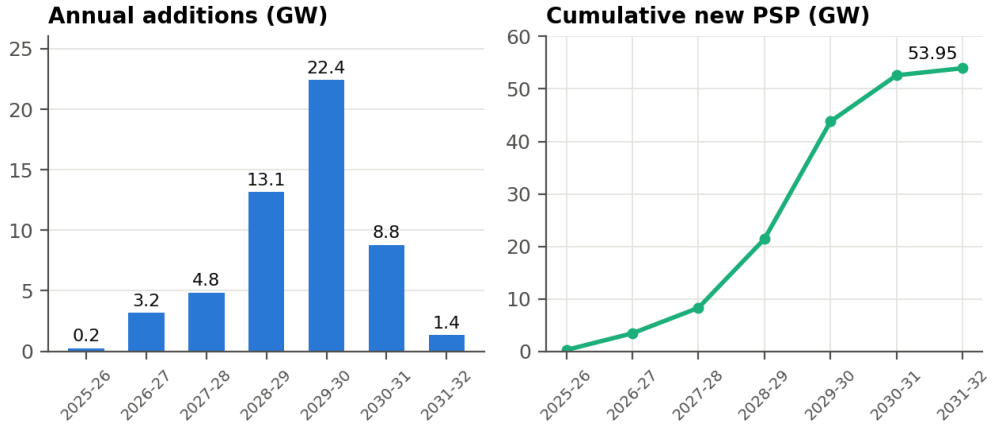


Figure 58: CEA year-wise PSP capacity addition plan, 2025-26 to 2031-32 (annual and cumulative, MW)

Source: Plotted from the CEA PSP capacity-addition plan to 2031-32.

Table 56 compares the roadmap requirements with current capability.

Table 56: PSP delivery-risk assessment against the CEA roadmap[207]

Requirement for 100 GW by 2035-36	Current capability/status	Gap and implication
≈9 GW/yr average; ≈21 GW in peak year	Record additions to date ≈2.7 GW in a year (2025-26)	3-8× scale-up of construction capacity needed
E&M equipment: 321 units of 100-400 MW	Domestic reversible turbine unit capacity ≈6.5–8.5 GW/yr (Andritz 5–6 GW; Voith 1.5–2.5 GW)	Limited local manufacturing capability. Need for active participation local stakeholders.

[205] Central Electricity Authority, *Capacity Addition Plan of PSPs till 2031–32*.

[206] Central Electricity Authority, Report on Roadmap to 100 GW of Hydro Pumped Storage Projects by 2035–36.

[207] Press Information Bureau, "Pumped Storage Hydropower", Oct 2026.

Transmission for 100.81 GW	Only 2.68 GW commissioned; 19.78 GW without transmission planning	Transmission is a binding constraint; integrated planning required
Land, forest and water clearances	Off-stream closed-loop exempt from CEA concurrence; some clearances simplified	Forest and land acquisition remain slow
Skilled tunnelling workforce and TBMs	Scarce	Training and equipment programmes needed

The CEA roadmap treats storage durations of six hours or more as relevant to India's renewable-integration needs. The appropriate duration for an individual PSP, however, depends on the net-load profile, usable reservoir volume, hydraulic head, water constraints, charging opportunities, and the required operating cycles, and calls for project-specific lifecycle and system-value assessment rather than a uniform design criterion. Battery procurement is moving in the same direction, as SECI's six-hour solar-plus-storage tender shows, but six hours remains an emerging procurement configuration rather than an established standard.

7.4. Hydrogen-Based Storage and the National Green Hydrogen Mission

Hydrogen is relevant to this review in two ways: as a potential long-duration storage medium and as a large new source of flexible electricity demand. The production and manufacturing targets of the National Green Hydrogen Mission are not electricity storage capacity and are not counted as such in this chapter.

7.4.1 Mission Status

The National Green Hydrogen Mission (NGHM), launched in January 2023 with an outlay of ₹19,744 crore, targets production of at least 5 million tonnes of green hydrogen a year by 2030, with about 125 GW of associated renewable capacity. The outlay comprises ₹17,490 crore for the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, ₹1,466 crore for pilot projects, ₹400 crore for R&D and ₹388 crore for other components.[208] By September 2026, 8.62 lakh tonnes a year of green hydrogen production capacity and 3,000 MW a year of electrolyser manufacturing capacity had been allocated under SIGHT. Competitive procurement of green ammonia allocated 7.24 lakh tonnes a year across 13 fertiliser units, at discovered prices of ₹49.75–64.74/kg. Green hydrogen procurement for refineries has also progressed, with 30,000 tonnes a year awarded across IOCL Panipat, BPCL Bina, HPCL Visakhapatnam and NRL Numaligarh; the NRL award was discovered at ₹279/kg.[209] The Green Hydrogen Certification Scheme of India (GHCI) provides a standardised framework for certifying green hydrogen based on verified greenhouse gas emission intensity.[210]

Table 57 summarises the current status of the NGHM and its relevance to the power system.

Table 57: Current NGHM implementation and power system relevance

Area	Current status	Why it matters to the power system
Electrolysers	3,000 MW/year manufacturing capacity awarded	Domestic supply capability; technology and controls determine flexibility.
Green H_2	8.62 lakh MTPA production capacity awarded	Potentially very large new electricity demand.

[208] Ministry of New and Renewable Energy, National Green Hydrogen Mission, Government Report (Ministry of New and Renewable Energy, Government of India, 2023).

[209] Press Information Bureau, Government of India, 'National Green Hydrogen Mission Advances Green Hydrogen Adoption in Petroleum and Refining Sector', Ministry of New and Renewable Energy, Government of India, 11 August 2026; ICN Bureau, 'India's Green Hydrogen and Ammonia Bids Hit Global Cost Competitiveness Benchmark', Indian Chemical News, 25 September 2026.

[210] Ministry of New and Renewable Energy, Green Hydrogen Certification Scheme of India (Ministry of New and Renewable Energy, Government of India, 2025).

Green NH_3	7.24 lakh MTPA allocated; ₹49.75/kg lowest discovered price	Anchor demand and transportable derivative; can separate production from end-use location.
Refineries	30 KTPA awarded across four refineries	Firm industrial offtake; opportunity for co-optimised RE, electrolysers and buffer storage.
Ports / hubs	Kandla, Paradip and Tuticorin are designated as hubs	Concentrates grid demand, storage, pipelines, derivative production and export infrastructure.
HVICs	Four Hydrogen Valley Innovation Clusters sanctioned	Integrated demonstrations across production, storage, transport and end use.
Standards	Green H_2 Standard (2023); Certification Scheme (2025)	Creates an auditable definition and verification framework.
Commercial model	Electrolyser-as-a-Service model agreement, July 2026	Can reduce entry barriers and allocate technology/performance risk.

Source: GIL Research, compiled from MNRE and PIB releases.

7.4.2 Demonstration Projects

Several hydrogen demonstration projects are now operating. Adani New Industries Limited commissioned a 5 MW off-grid green hydrogen plant in Kutch, Gujarat, in 2025. It uses a fully automated, closed-loop electrolyser system designed to follow variable renewable input in real time, which makes it a useful test of flexible electrolyser operation.[211] THDC India has piloted an electrolyser and fuel-cell system at Rishikesh, where hydrogen produced from a 1 MW rooftop solar plant feeds a 70 kW PEM fuel-cell microgrid that supplies night-time loads at its office complex.[212] At V.O. Chidambaranar Port in Thoothukudi, a pilot plant producing about 10 Nm^3/h of green hydrogen supplies local uses such as street lighting and EV charging, alongside plans for hydrogen-based methanol bunkering as part of a green shipping corridor.[213]

In transport, the MNRE has sanctioned five pilot projects comprising 37 vehicles (15 fuel-cell and 22 hydrogen internal-combustion buses and trucks) and nine hydrogen refuelling stations.[214] India's first indigenous hydrogen fuel-cell passenger vessel began commercial service in Varanasi under the Harit Nauka initiative in December 2025.[215] These projects are at demonstration scale; hydrogen is not yet used in India as electricity-to-electricity storage on the grid.

7.5. Other Storage Technologies

Other forms of storage remain small in the Indian power system. Concentrated solar power with thermal storage is limited to a few plants, such as the 25 MW Gujarat Solar One parabolic-trough plant in Kutch and the 1 MW India One

211 Adani Group, "Adani Commissions India's First Off-Grid Green Hydrogen Pilot Plant of 5 MW Capacity," Jun.23, 2025.

[212] THDC India Limited, "36th Annual Report 2023–24," for the financial year ended Mar. 31, 2024, including Directors' Report, audited financial statements, and corporate governance disclosures.

[213] Press Information Bureau, "Development of Green Hydrogen Ecosystem including Hydrogen Hubs and Bunkering Infrastructure in India," Ministry of New and Renewable Energy, Government of India, Press Release

[214] Press Information Bureau, "Pilot Projects on Hydrogen Fuelled Buses and Trucks Launched under the National Green Hydrogen Mission," Ministry of New and Renewable Energy, Government of India.

[215] Press Information Bureau, "India's First Indigenous Hydrogen Fuel Cell Passenger Vessel Begins Commercial Service in Varanasi," Ministry of Ports, Shipping and Waterways, Government of India, Dec. 11, 2025.

solar thermal plant at Mount Abu, Rajasthan, which uses cast-iron cavity receivers. Ice and chilled-water storage is used in some commercial buildings and district-cooling schemes but is not tracked as grid storage. Behind-the-meter batteries in telecom towers, data centres, commercial and industrial premises and, increasingly, rooftop-solar homes form a sizeable but poorly measured resource that is not yet visible to system operators.

7.6. Summary of Observations

India's storage fleet is changing quickly. Pumped storage still provides most of the installed capacity, but BESS is now the fastest-growing segment: operational BESS capacity rose from under 0.3 GW to about 3 GW in the first eight months of 2026, and about 54 GW / 168 GWh is in the pipeline. The BESS market is moving towards four-hour and longer durations, state-led procurement supported by VGF, energy-based contracts and stricter performance requirements. Pumped storage has a large pipeline on paper, but construction capacity, equipment supply and, above all, transmission connectivity will determine how much of the 100 GW roadmap is delivered by 2035-36. Hydrogen remains at demonstration scale as a storage medium. Across all technologies, the gap between pipeline and operating capacity, and the delivery risks identified in this chapter, are the main points for stakeholders to monitor.

Chapter 8.

Economics, Markets, and Business Models of Energy Storage in India



India's energy storage market is rapidly evolving as a foundational pillar in the country's energy transition. The market encompasses a wide range of technologies, but the clearest momentum today is in BESS and PSP, reflecting India's strategy to balance a rapidly growing renewable energy fleet with grid reliability and flexibility.

By Sept. 2026, India's cumulative installed energy storage capacity including both battery and pumped storage had grown significantly. This rapid expansion was supported by strong policy and market incentives. The government implemented a Viability Gap Funding (VGF) scheme for BESS projects and included mandates requiring co-located storage in solar tenders, aiming to create long-term demand and improve project economics. Such measures have helped lower battery storage costs and tender pricing substantially, making storage a more competitive component of India's energy mix.

8.1. Price Discovery: Tariffs, Payment Structures and Viability

8.1.1 Structural Differences in Payment Mechanisms

Indian storage procurement uses multiple payment structures and quoted 'tariffs' are not comparable across them without normalisation (Table 58). The most common for standalone BESS is a fixed *capacity charge* in ₹/MW/month (often expressed in ₹ lakh/MW/month), paid against demonstrated availability, with the procurer supplying and owning the charging energy. Some state utilities (e.g., Uttar Pradesh Power Corporation Limited (UPPCL)) and SECI's peak-supply tenders use *energy-based* structures in ₹/kWh of discharged energy, in which the developer arranges the charging energy. Bundled renewable-plus-storage contracts, firm and dispatchable renewable energy (FDRE), round-the-clock (RTC) and "assured peak" supply quote a single ₹/kWh tariff for a delivery profile. Merchant BESS earns exchange price spreads and ancillary-service revenues without a long-term contract.

Table 58: Storage payment structures used in India

Structure	Unit	Charging Energy Cost and Risk Allocation	Comparison Caveats
Capacity charge [216,217]	₹/MW/month or ₹/MW/year	Procurer supplies charging energy; developer bears availability, performance and degradation risk	Must be converted using duration, cycles/day, availability and RTE requirements
Energy-based storage tariff	₹/kWh discharged	Developer sources charging energy and bear associated electricity price and procurement risks, depending on tender conditions.	Embeds the developer's view of charging-energy prices and exchange risk. For example, UPPCL's 375 MW/1,500 MWh tender discovered ₹6.45–6.46/kWh in May 2026.
Two-part tariff (Capacity + Energy)	₹/MW/month + ₹/kWh	Charging-energy responsibilities are contract-specific. Fixed payments compensate for storage availability, while variable payments compensate for energy supplied or dispatched.	Both fixed and variable components must be considered, along with dispatch assumptions and minimum offtake obligations.

[216] Ministry of Power, Government of India, Guidelines for Procurement and Utilization of Battery Energy Storage Systems as part of Generation, Transmission and Distribution assets, along with Ancillary Services by Ministry of Power, 11 Mar. 2022.

[217] Central Electricity Regulatory Commission (CERC), Staff Paper on Capacity Market for Electricity in India, New Delhi, India, Apr. 2026.

Bundled RE + storage[216]	₹/kWh delivered	Developer bears RE resource and storage risk; penalties for shortfall	Includes RE generation cost; storage "adder" must be inferred
PSP storage[216]	₹/MW/year or ₹/kWh	Varies with composite vs tolling model	Long asset life (40+ years) versus 12–15-year BESS contracts
Merchant / ancillary services	₹/kWh spread; ₹/MW for reserves	Developer bears full price and volume risk	Revenues volatile; depend on DAM/RTM spreads and AS market design

8.1.2 Discovered Tariffs, 2022–2026

India's utility-scale battery storage market has moved from early, high-cost price discovery to a highly competitive procurement phase. SECI's first major standalone 500 MW/1,000 MWh BESS tender in 2022 discovered a capacity charge of about ₹10.83 lakh/MW/month. IEEFA–JMK's May 2026 review found that standalone BESS accounted for 60% of storage capacity tendered in 2025 and that the lowest 2-hour tariff reached ₹1.48 lakh/MW/month; it also cautioned that the commercial viability of the most aggressive bids remained a concern[218]. The 2025 auctions established exceptionally low benchmarks. RVUNL's 1,000 MW/2,000 MWh VGF-supported tender in Rajasthan discovered ₹1.775–1.785 lakh/MW/month for 2-hour systems, while its later 500 MW/2,000 MWh, 4-hour single-cycle procurement cleared uniformly at ₹2.85 lakh/MW/month. The Rajasthan Electricity Regulatory Commission subsequently recorded the ₹2.85 lakh/MW/month result and benchmarked it against comparable 4-hour procurements: ₹4.41 lakh/MW/month for SECI/Kerala, ₹4.34 lakh/MW/month for NHPC/Kerala, ₹4.40 lakh/MW/month for BSPGCL and ₹3.59 lakh/MW/month for SJVN/UP.[219] [220]

During 2026, tariffs remained far below the 2022 starting point, but the market stopped moving in a single downward direction. Kerala's 250 MW/500 MWh BESS procurement produced a tariff of ₹1.81 lakh/MW/month; GUVNL Phase VIII (335 MW/670 MWh) discovered ₹2.10-2.12 lakh/MW/month for 2-hour systems with VGF; TNGECL's 4-hour tender discovered ₹3.15-3.16 lakh/MW/month; and SECI's 125 MW/500 MWh Odisha auction produced ₹3.04-3.75 lakh/MW/month across awarded clusters. [221]

The clearest indication of a correction in BESS tariffs emerged in August 2026. GUVNL Phase IX (450 MW/900 MWh) discovered a tariff of approximately ₹2.32 lakh/MW/month, while WBSEDCL's 500 MW/2,000 MWh, four-hour procurement recorded an L1 tariff of ₹4.35 lakh/MW/month. The September 2026 *EnergyWatts* update by IEEFA and JMK Research reported that these tariffs were approximately 10.5% and 25% higher, respectively, than those discovered in comparable earlier tenders. Although these developments do not negate the substantial structural decline in BESS costs since 2022, they suggest that the exceptionally low bids observed in 2025 may not represent a sustainable, continuously declining tariff floor. [222,223]

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[218] P. Sharma, V. Mor, M. Srivastava, V. Garg, and C. Konda, Viability of Standalone Battery Energy Storage Tariffs Discovered in 2025. Institute for Energy Economics and Financial Analysis (IEEFA) and JMK Research & Analytics, May 19, 2026.

[219] Rajasthan Electricity Regulatory Commission, "Order on adoption of tariff (capacity charges) for 1000 MW/2000 MWh standalone battery energy storage systems in Rajasthan under tariff-based global competitive bidding with viability gap funding support," Petition No. 2372/2025, Jan. 12, 2026.

[220] Rajasthan Electricity Regulatory Commission, "Order on adoption of tariff for 500 MW/2,000 MWh standalone battery energy storage systems through tariff-based global competitive bidding with viability gap funding support," Petition No. 2394/2026, Mar. 6, 2026.

[221] Kerala State Electricity Regulatory Commission, Petition No. OP 16/2026, concerning the 250 MW/500 MWh Brahmapuram BESS procurement; Gujarat Electricity Regulatory Commission, Order in Petition No. 2641/2026, May 8, 2026; Solar Energy Corporation of India Ltd. (SECI), "List of Successful Bidders," Tender Ref. SECI/C&P/IPP/15/0015/25-26, 125 MW/500 MWh standalone BESS in Odisha, 2026; Institute for Energy Economics and Financial Analysis (IEEFA) and JMK Research & Analytics, EnergyWatts: Monthly Update on India's Energy Storage Market, 2026. .

[222]Gujarat Electricity Regulatory Commission, "Order on adoption of tariff for 450 MW/900 MWh standalone battery energy storage systems under GUVNL BESS Phase IX," Petition No. 2732/2026, Oct. 28, 2026.

[223] Gujarat Electricity Regulatory Commission, "Order on adoption of tariff for 450 MW/900 MWh standalone battery energy storage systems under GUVNL BESS Phase IX," Petition No. 2732/2026, Oct. 28, 2026; NTPC Green Energy Ltd., "NTPC Green Energy Limited wins 200 MW/800

Table 59: Selected discovered storage tariffs in India, 2022–2026)[224] [225] [226] [227]

Year	Procurer / tender	Size	Configuration	Discovered tariff	Structure
2022	SECI – first standalone BESS	500 MW / 1,000 MWh	2 h	₹10.83 lakh/MW/month	Capacity charge
2025	SECI/Kerala	125 MW / 500 MWh	4 h; 1 cycle	₹4.41 lakh/MW/month	VGF-supported comparator
2025	NHPC/Kerala	125 MW / 500 MWh	4 h; 1 cycle	₹4.34 lakh/MW/month	VGF-supported comparator
2025	BSPGCL, Bihar	125 MW / 500 MWh	4 h; 1 cycle	₹4.40 lakh/MW/month	VGF-supported comparator
2025	SJVN/UP	375 MW / 1,500 MWh	4 h; 1 cycle	₹3.59 lakh/MW/month	VGF-supported comparator
2025	RVUNL, Rajasthan (Oct)	1,000 MW / 2,000 MWh	2 h	₹1.775–1.785 lakh/MW/month	VGF-II; capacity charge
2025	RVUNL, Rajasthan (Nov)	500 MW / 2,000 MWh	4 h; 1 cycle	₹2.85 lakh/MW/month	VGF-II; capacity charge
2026	KSEB, Kerala	250 MW / 500 MWh	2 h; 420 cycles/yr	₹1.81 lakh/MW/month	VGF; capacity charge
2026	GUVNL Phase VIII	335 MW / 670 MWh	2 h; 2 cycles/day	₹2.10–2.12 lakh/MW/month	VGF; 12-year BESPA
2026	TNGECL, Tamil Nadu	375 MW / 1,500 MWh tender*	4 h; 1.5 cycles	₹3.15–3.16 lakh/MW/month	VGF; BOO; 15 years
2026	SECI/Odisha	125 MW / 500 MWh	4 h	₹3.04–3.75 lakh/MW/month	VGF; capacity charge

MWh BESS capacity in WBSEDCL's 500 MW/2,000 MWh standalone BESS tender," Stock Exchange Disclosure and Press Release, Aug. 7, 2026; JMK Research & Analytics and Institute for Energy Economics and Financial Analysis (IEEFA), EnergyWatts: Monthly Update on India's Energy Storage Market—September 2026, Sep. 2026.

[224]IEEFA and JMK Research, Viability of Standalone Battery Energy Storage Tariffs Discovered in 2025, May 2026. IEEFA and JMK Research, "EnergyWatts: Monthly update on India's energy storage market – June 2026", Aug. 2026.

[225] Rajasthan Electricity Regulatory Commission, "Petition for Adoption of Tariff (Capacity Charges) for 1000 MW/2000 MWh Standalone Battery Energy Systems in Rajasthan under Tariff Based Global Competitive Bidding with Viability Gap Funding Support under BOO Model," Petition No. 2372/2025, Order dated Jan. 12, 2026.

[226]Rajasthan Electricity Regulatory Commission, "Adoption of Tariff for 500 MW/2000 MWh Standalone Battery Energy Systems through Tariff Based Global Competitive Bidding with Viability Gap Funding Support under BOO Model," Petition No. 2394/2026, Order dated Mar. 6, 2026.

[227]Kerala State Electricity Board Ltd., "Letter of Award for Setting Up of 250 MW/500 MWh Standalone Battery Energy Storage Systems at Brahmapuram," filed before the Kerala State Electricity Regulatory Commission, Petition No. OP 16/2026, 2026; Tamil Nadu Electricity Regulatory Commission, "Order adopting capacity charges for 375 MW/1,500 MWh standalone battery energy storage systems procured by Tamil Nadu Green Energy Corporation Ltd.," Feb. 26, 2026.

Year	Procurer / tender	Size	Configuration	Discovered tariff	Structure
2026	GUVNL Phase IX (Aug)	450 MW / 900 MWh	2 h; 2 cycles/day	₹2.32 lakh/MW/month	VGF; 12-year BESPA
2026	WBSEDCL (Aug)	500 MW / 2,000 MWh	4 h; 1 cycle/day	₹4.35–4.39 lakh/MW/month	No VGF; BOO; 15 years
2026	SECI solar + ESS	1,200 MW solar + 600 MW / 3,600 MWh ESS	6 h ESS	₹3.12–3.13/kWh	Bundled solar + ESS; not comparable with standalone capacity charges

*TNGECL awarded 350 MW/1,400 MWh of the 375 MW/1,500 MWh tender at reported ₹3.15-3.16 lakh/MW/month bids.

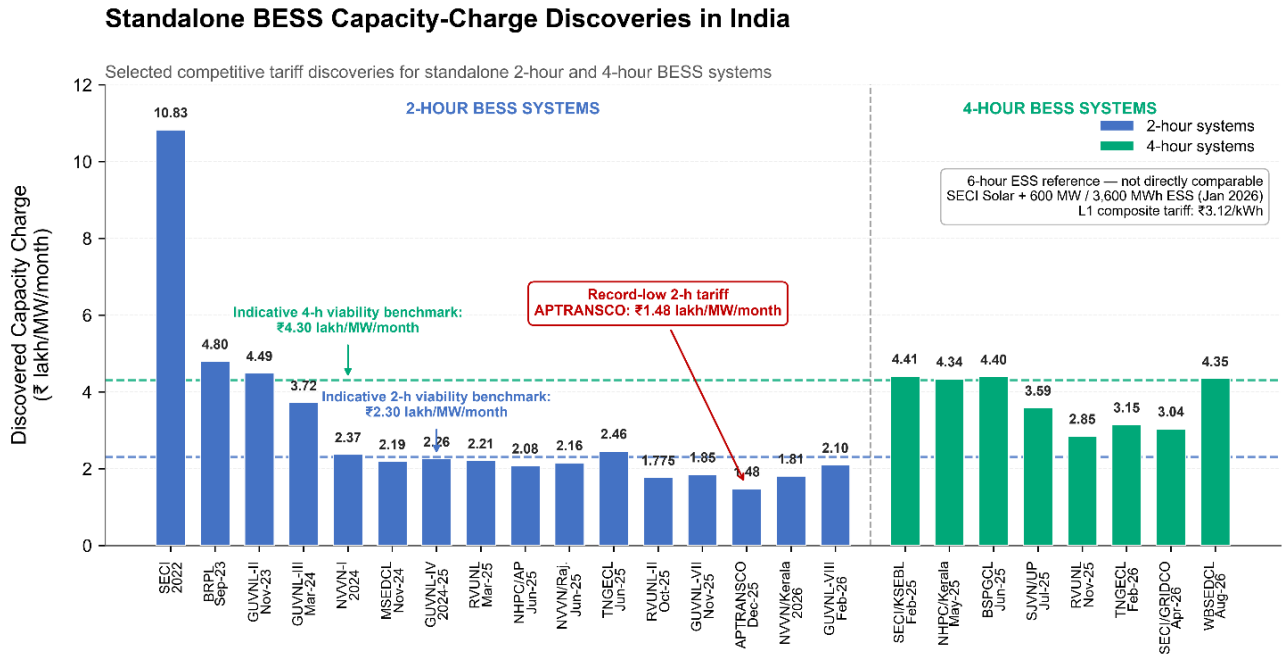


Figure 59: Selected discovered standalone BESS capacity charges in India (₹ lakh/MW/month), 2022-2026, by duration

(Source: This figure has been plotted using data sources from IEEFA and JMK Research)

MoP has also highlighted the scale of the decline and reported in December 2025 that the discovered cost of two-cycle BESS without VGF had fallen from about ₹10.18/kWh in 2022–23 to about ₹2.1/kWh in 2025[228], while ICRA Ltd. estimated the levelised cost of a typical 2–4-hour BESS in India at about ₹4–7/kWh, down from ₹8–9/kWh a few years earlier.[229] IEEFA has further cautioned that, despite declining tariffs, the viability and timely deployment of BESS projects remain constrained by aggressive bidding, financing challenges, supply-chain dependencies and delays in execution and grid connectivity.[230]

8.1.3 What the tariff trajectory indicates

[228]Press Information Bureau (PIB), Ministry of Power, "Per kWh cost of battery energy storage system falls steeply", 15 Dec. 2025.

[229]ICRA Limited, "Storage adoption critical for grid integration of renewable energy projects", Press Release, 20 Nov. 2025.

[230]P. Sharma, V. Mor, M. Srivastava, V. Garg, and C. Konda, Viability of Standalone Battery Energy Storage Tariffs Discovered in 2025. Institute for Energy Economics and Financial Analysis (IEEFA) and JMK Research & Analytics, May 2026..

The evolving tariff trajectory for BESS includes several important insights into the changing economics, market maturity, and risk allocation of projects in India.

a. The long-run cost reduction is unambiguous. The Ministry of Power reported that the discovered cost of BESS used for two cycles per day fell from about ₹10.18/kWh in 2022–23 to about ₹2.1/kWh in recent competitive bidding without VGF; at 1.5 cycles/day, it estimated a storage cost of about ₹2.8/kWh.[231]
b. The lowest capacity-charge bids are not automatically equivalent to a sustainable levelised cost of storage. IEEFA–JMK explicitly flagged tariff viability as a concern in the 2025 auction cohort. Bid economics differ materially with VGF, storage duration, number of cycles, annual availability, round-trip efficiency, contract tenor, degradation and augmentation assumptions, land and grid-connection scope, charging-energy responsibility, financing cost and the timing of battery procurement.[232]
c. The August 2026 outcomes suggest that price discovery is beginning to differentiate more clearly by tender design and risk allocation. The ₹2.32 lakh/MW/month GUVNL Phase IX result remains very competitive for a VGF-supported 2-hour system but is above GUVNL's Phase VIII ₹2.10–2.12 lakh/MW/month range. The WBSEDCL ₹4.35-4.39 lakh/MW/month result is materially higher than the ₹2.85 lakh/MW/month Rajasthan 4-hour low; however, WBSEDCL's procurement was without VGF, making a direct headline comparison misleading.

Longer-duration storage is entering procurement, but tariff metrics are becoming less uniform. SECI's January 2026 solar-plus-storage auction paired 1.2 GW of solar with 600 MW/3,600 MWh of ESS and discovered a composite tariff of ₹3.12-3.13/kWh. This 6-hour result should be presented separately from standalone BESS capacity charges because the commercial product, denominator, and revenue structure differ.[233]

8.1.4 Normalising tariffs

To compare a capacity charge with an energy tariff or with the cost of alternatives, e.g., a gas peaker or an evening-hour exchange price, the capacity charge must be converted into a levelised storage-service cost per kWh discharged, and the cost of charging energy and losses must then be added. For a capacity charge T (₹/MW/month), duration h (hours), cycles per day n, and annual availability A, the storage-service cost per kWh of discharge is given by Eq. (1), and the delivered cost including charging energy at price p_c and round-trip efficiency η_{RT} by Eq. (2).

$$c_s = \frac{(12 \cdot T)}{1{,}000 \cdot h \cdot n \cdot 365 \cdot A} \left[\frac{₹}{kWh}\right] \quad (1)$$

$$c_{del} = cs + \frac{p_c}{\eta_{RT}} \left[\frac{₹}{kWh}\right] \quad (2)$$

As a worked example, a two-hour, two-cycle BESS contracted at ₹2.10 lakh/MW/month with 95% availability yields a storage-service cost of $\frac{12 \times 2.10 \times 105}{1{,}000 \times 2 \times 2 \times 365 \times 0.95} \approx 1.82/kWh$. With midday charging energy at ₹2.5/kWh and an AC round-trip efficiency of 85%, the delivered cost is about ₹4.76/kWh. A four-hour, one-cycle BESS at ₹2.85 lakh/MW/month yields ≈₹2.47/kWh for the storage service and ≈₹5.41/kWh delivered under the same assumptions. These values compare favourably with evening exchange prices, which frequently reach the ₹10/kWh ceiling in summer (Section 3.5), and with the variable cost of gas-based peaking generation.

The normalisation also exposes the significance of cycle-count assumptions. The same ₹2.10 lakh/MW/month capacity charge amounts to ₹3.64/kWh if the asset is cycled only once per day. Procurement documents should therefore specify, and payment mechanisms should verify, the *usable energy per cycle*, the *number of cycles*, and the availability window, rather than just the MW rating.

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[231] Press Information Bureau, Ministry of Power (15 Dec 2025), "Per kWh Cost of Battery Energy Storage System Falls Steeply." https://www.pib.gov.in/PressReleasePage.aspx?PRID=2204118

[232] Press Information Bureau, Ministry of Power (15 Dec 2025), "Per kWh Cost of Battery Energy Storage System Falls Steeply."

[233] Central Electricity Regulatory Commission, "Order on adoption of tariff for 1200 MW ISTS-connected solar PV power projects with 600 MW/3600 MWh energy storage systems (SECI-ISTS-XXI)," Petition No. 146/AT/2026, Sep. 12, 2026.

8.1.5 The Viability Question

Low tariffs are a promising factor in promoting energy storage, but they raise genuine concerns about viability. At the global level, an average lithium-ion battery-pack price of US$108/kWh in 2025, with stationary-storage packs at US$70/kWh, the lowest-priced segment for the first time, and LFP packs averaging US$81/kWh[234]. For utility-scale BESS projects with storage durations of four hours or longer, an installed capital cost of approximately US$125/kWh is estimated in competitive markets outside China and the United States, comprising US$75/kWh for core equipment and US$50/kWh for installation and grid connection.[235] These developments reflect declining equipment costs and intensified global competition, although India's dependence on imported battery cells continues to expose project economics to international supply-chain and price risks.[236]

8.2. Revenue Streams and Market Access

Beyond long-term contracts, storage in India can now earn from several markets and regulatory provisions (Table 60). DAM and Real-Time Market (RTM) prices are capped at ₹10/kWh, and BESS may sell in the High-Price DAM, capped at ₹20/kWh.[237] The average May intraday spread widened from ₹5.27/kWh in 2023 to ₹8.60/kWh in 2026.[238] It is estimated that a merchant BESS installed in 2025 could earn about ₹2.7 million/MWh a year from DAM arbitrage and ₹0.7 million/MWh from ancillary services, with internal rates of return (IRR) of 15–22% for 1–2-hour systems.[239] The CERC (Ancillary Services Regulations), 2022 allow storage to provide secondary and tertiary reserves;[240] 86 plants of 83.63 GW were under automatic generation control in 2026, including a 20 MW / 40 MWh BESS.[241]

Table 60: Revenue streams available to storage in India

Revenue stream	Regulatory basis	Status for storage
DAM/RTM arbitrage	CERC Power Market Regulations; ₹10/kWh price cap	Open; spreads of ₹8–9/kWh in summer 2026
High-Price DAM	CERC order of Apr 2023	BESS eligible to sell up to ₹20/kWh
Secondary and tertiary reserves	CERC Ancillary Services Regulations, 2022	Storage eligible; BESS AGC participation at pilot scale
Capacity / resource adequacy	MoP Resource Adequacy Guidelines, 2023; CERC staff paper on capacity markets[242]	Through long-term DISCOM contracts; capacity market under consultation
Non-solar-hour transmission access	CERC GNA (Third Amendment) Regulations, 2025[243]	Storage of 50 MW or more may seek separate non-solar-hour access

[234]BloombergNEF, "Lithium-ion battery pack prices fall to $108 per kilowatt-hour, despite rising metal prices", 9 Dec. 2025.

[235]K. Rangelova, How Cheap Is Battery Storage? Ember, Dec. 2025.

[236] International Energy Agency, Batteries and Secure Energy Transitions, World Energy Outlook Special Report. Paris, France: IEA, Apr. 2024.

[237]Central Electricity Regulatory Commission, Order in Petition No. 05/SM/2023, New Delhi, India, Apr. 9, 2023.

[238]S. Sanyal and S. Dev, "The duck and the camel: Tracing the net load on the Indian power grid," Economic Advisory Council to the Prime Minister, EAC Working Paper EAC-PM/WP/53/2026, Jul. 2026.

[239]D. Das and N. Rodrigues, *The Age of Storage: Batteries Primed for India's Power Markets*. London, U.K.: Ember, Aug. 2025.

[240]Central Electricity Regulatory Commission, "Central Electricity Regulatory Commission (Ancillary Services) Regulations, 2022," New Delhi, India, Jan. 31, 2022.

[241]Grid Controller of India Ltd., CIGRE-India Study Committees C2, C4 and C5, and Forum of Load Despatchers, "Participation of battery energy storage in ancillary services: Challenges and opportunities," CIGRE-India, New Delhi, India, May 2026.

[242]Central Electricity Regulatory Commission, "Staff paper on capacity market for electricity in India," New Delhi, India, Apr. 2026.

[243]Central Electricity Regulatory Commission, "Central Electricity Regulatory Commission (Connectivity and General Network Access to the inter-State Transmission System) (Third Amendment) Regulations, 2025," Notification No. L-1/261/2021/CERC, Aug. 31, 2025.

Consumer-side ToD savings and backup	Electricity (Rights of Consumers) Amendment Rules, 2023[244]	Solar-hour tariff ≥20% lower; C&I peak tariff ≥1.2× normal

From September 2025, consumers may develop, own, lease or operate storage.[245] The ISTS-charge waiver applies to co-located BESS commissioned by 30 June 2028 and to PSPs whose construction is awarded by that date.[246]

8.3. Business models for BESS

India's energy storage market is evolving around multiple business models, particularly for BESS and PSP. These models differ in ownership structure, revenue mechanisms, risk allocation, and bankability.

The most common model in India today is the Build-Own-Operate (BOO) model with long-term storage purchase agreements. Under this framework, a private developer finances, builds, owns, and operates the storage system, while a utility or government agency signs a long-term contract, typically 10-25 years to procure storage services. Revenue is secured through fixed capacity payments (₹/MW/month or ₹/MWh/month), sometimes supported by VGF. This model offers high revenue visibility and lower market risk, making it attractive to lenders. However, it depends heavily on strong counterparts and timely payments.

A second structure is the Build-Own-Operate-Transfer (BOOT) model, which is less common but used in certain infrastructure projects. Here, the developer operates the project for a concession period and transfers ownership to the government at the end. This reduces long-term asset risk for public authorities but can lower the developer's terminal value. It is more common in pumped hydro or large infrastructure-linked projects than in modular BESS deployments.

Another growing model is the Merchant or Market-Based Model, where storage operators earn revenue by participating directly in electricity markets through energy arbitrage, ancillary services, and peak shaving. This model provides potentially higher returns but carries significant price volatility risk. In India, this model is still emerging because ancillary service markets and real-time markets are evolving, and regulatory clarity is improving but not fully mature.

The Hybrid Renewable + Storage Model is also increasingly common. In this structure, developers bundle solar or wind projects with co-located storage and bid in renewable tenders that require firm or dispatchable power. Revenue is tied to a Power Purchase Agreement that rewards firm delivery rather than just generation. This model reduces intermittency risk and improves renewable project competitiveness. It is currently one of the fastest-growing formats in India's storage deployment pipeline.

For large pumped hydro projects, a State-Owned or Public-Private Partnership (PPP) Model is frequently used. Given the capital intensity and long gestation period of pumped storage, state utilities or central PSUs often take a lead role, sometimes with private participation. These projects typically rely on long-term regulated returns rather than competitive short-term bidding. The risk profile is lower in operational terms but higher in construction and environmental clearance phases.

A relatively new concept is the Energy-as-a-Service (EaaS) Model, particularly in the commercial and industrial (C&I) segment. Under this structure, third-party providers install and operate storage at a customer's site, and the customer pays a service fee or shares savings from peak demand reduction and energy optimization. This model minimizes upfront capital expenditure for end users and is gaining traction among industrial consumers seeking cost efficiency and resilience.

In comparison, BOO with long-term contracts remains the most bankable and dominant model in India today, especially for utility-scale BESS supported by VGF schemes. Hybrid renewable-plus-storage models are rapidly

[244]Ministry of Power, "Implementation of time of day electricity tariff system," Press Information Bureau, Government of India, Aug. 2, 2023.

[245]Ministry of Power, "Development of battery energy storage systems," Press Information Bureau, Government of India, Mar. 30, 2026.

[246]Ministry of New and Renewable Energy, "Government takes multi-pronged steps to scale up energy storage capacity in the country," Press Information Bureau, Government of India, Feb. 3, 2026.

scaling due to renewable integration mandates. Merchant models offer higher upside but are limited by evolving market structures. Pumped hydro relies more on regulated or PPP frameworks due to its infrastructure nature. Meanwhile, Energy-as-a-Service is emerging as a flexible solution in the C&I segment.

A comparison of the storage business models is presented in Table 61: Comparison of storage business models in IndiaTable 61.

Table 61: Comparison of storage business models in India

Model	Revenue basis and counterparty	Main risks borne by owner	Indian status and examples	Bankability
BOO standalone BESS (BESPA)	Capacity charge from DISCOM or SECI/NTPC/NHPC/SJVN; 12–15 years; often VGF	Availability, RTE, degradation, cell prices	Dominant; RVUNL, GUVNL, KSEB, TNGECL	High
Energy-based storage supply	₹/kWh discharged from DISCOM	Charging-energy price, dispatch	UPPCL 375 MW / 1,500 MWh; SECI peak supply	Medium
Hybrid RE + storage (FDRE, RTC, peak)	Single ₹/kWh tariff; 25-year PPA with REIA	RE resource, storage performance, shortfall penalties, PPA signing delays	SECI 1,200 MW + 600 MW / 3,600 MWh at ₹3.12–3.13/kWh	High once PPA signed
Pumped storage (TBCB or regulated)	Tolling or composite tariff, 15–40 years; or cost-plus tariff	Construction, clearances, geology, transmission	Tehri (THDC), Pinnapuram (Greenko); TBCB from 2025	Medium–high
Merchant / market-based	DAM, RTM, HP-DAM spreads; SRAS/TRAS	Price and volume volatility, regulatory change	Early merchant projects in Rajasthan and Gujarat	Low–medium
C&I behind-the-meter / energy-as-a-service	ToD savings, demand-charge reduction, diesel replacement	Customer credit, tariff changes	Emerging after the 2023 and 2025 consumer rules	Medium

About 69 GW of capacity had been awarded by the four renewable energy implementing agencies by 31 December 2025, but power sale agreements had been signed for only about 24.3 GW, a gap that affects the bankability of hybrid models.[247]

8.4. Cost trajectory in the Indian context

In India, the cost of energy storage, particularly BESS, has fallen sharply over the past decade, making storage increasingly viable alongside renewable power generation. The substantial reduction has been driven by improvements in battery technology, manufacturing scale, and competitive market bidding. These trends have also boosted revenue potential for merchant storage projects, with potential earnings rising significantly over the same period.

[247]Ministry of New and Renewable Energy, "Government takes multi-pronged steps to scale up energy storage capacity in the country," Press Information Bureau, Government of India, Feb. 3, 2026.

From about INR 7.9 million/megawatt-hour (MWh) in 2015 to INR 1.7 million/MWh in 2025 (an average year-over-year fall of 14%), battery costs have drastically decreased over the last ten years. Concurrently, market participation revenues have grown fivefold, from INR 0.5 million/MWh in 2015 to INR 2.4 million/MWh in 2025[248].

A clear indicator of the recent cost trajectory in India is the plunge in tariff outcomes from competitive bidding. In 2022–23, the cost of electricity delivered from BESS was reported at around ₹10.18 per unit (kWh) when assuming two daily charge/discharge cycles. In more recent auctions, this figure has dropped dramatically to approximately ₹2.1 per unit on a similar basis a roughly five fold reduction in just a couple of years. Adjusting for typical usage patterns, the effective cost works out to roughly ₹2.8 per unit, which is comparable to current solar generation tariffs (~₹2.5/kWh) [249].

Battery pack costs which constitute the largest component of BESS capital expenditure have similarly trended downward over recent years. The average price of lithium ion battery packs dropped to $115 USD/kWh in 2024, a 20% cost reduction from the year before and 84% lower than the average cost a decade ago. As the price has fallen, annual installations of battery storage capacity have increased dramatically at an average rate of 67% per year over the last decade[250]. While India's battery costs are somewhat higher than the lowest global figures, this broad decline influences project economics here as well and signals further cost savings as domestic and global manufacturing scales up.

Several policy and market mechanisms are reinforcing this downward cost trajectory in India. Government support through Viability Gap Funding (VGF) schemes, transmission charge waivers for storage projects, and Production-Linked Incentive (PLI) programmes targeting domestic Advanced Chemistry Cell manufacturing aim to lower upfront costs and reduce reliance on imports over time. These interventions are expected to sustain competitive tariff discovery and encourage local supply chain development, ultimately reducing energy storage system costs further. Associated GST HSN Codes and Tariffs are described in detail in Annexure.

8.5. Financing, risk, and barriers

In India, the financing, risk, and barriers associated with energy storage projects are key factors shaping the pace and scale of deployment, especially for BESS and utility-scale installations.

From a financing perspective, energy storage projects are capital-intensive, with upfront costs still significant despite declining battery prices. Most utility-scale BESS projects rely on a combination of equity from developers, debt from commercial banks or infrastructure funds, and government support such as VGF. Long-term Power Purchase Agreements or storage service agreements (BESPA) are crucial for bankability, providing predictable cash flows and enabling lenders to underwrite loans. For commercial and industrial (C&I) projects, the Energy-as-a-Service (EaaS) model reduces upfront capital requirements for end users, but the financing risk is transferred to the third-party service provider.

Risk factors are a major consideration for investors and developers. Technical risks include battery degradation, safety hazards, and under performance, especially in extreme climatic conditions. Financial risks arise from aggressive bidding in tenders, delayed payments from state utilities, or fluctuations in ancillary service revenues in merchant storage models. Regulatory risk is also significant, the absence of a fully mature ancillary services market and evolving guidelines for storage tenders can create uncertainty in revenue streams. Additionally, foreign exchange exposure is relevant for projects relying on imported lithium-ion cells or other components, particularly given India's ongoing dependence on imports for high-capacity cells.

Despite strong growth potential, several barriers remain. First, high upfront costs and limited domestic manufacturing capacity for advanced lithium-ion cells continue to constrain widespread adoption. Second, grid

[248] D. Das and N. Rodrigues, The Age of Storage: Batteries Primed for India's Power Markets. London, U.K.: Ember, Aug. 2025

[249] Ministry of Power, Government of India, "Per kWh Cost of Battery Energy Storage System Falls Steeply: VGF Schemes, ISTS Charges Waiver Boosts Affordable Battery Storage," Press Information Bureau (PIB), Release ID:
2204118, Dec. 15, 2025.

[250] N. Fulghum, E. Graham, and K. Altieri, Global Electricity Review 2025. London, U.K.: Ember, Apr. 2025.

integration challenges including inadequate transmission infrastructure and the need for smart energy management systems can limit deployment efficiency. Third, policy fragmentation across states creates variability in tender rules, local content requirements, and incentive structures, complicating investment decisions. Fourth, limited technical expertise and project management experience among smaller developers can lead to delays or suboptimal project performance. Finally, perceived technology risk and life-cycle uncertainty affects investor confidence and long-term project economics.

Chapter 9.

ESS Policy, Regulations, and Standards in India



Policy, regulatory, and standards framework for energy storage has been evolving rapidly in India, reflecting the country's ambition to integrate large scale renewable energy and develop a domestic storage ecosystem. Energy storage is still considered a relatively new asset class in Indian power sector, and accordingly the regulators have focused on enabling frameworks, technical standards, and incentives to facilitate deployment.

On the policy side, the Ministry of Power (MoP) along with Ministry of New and Renewable Energy (MNRE) have issued various initiatives to promote storage. Key policies include Viability Gap Funding (VGF) support for utility-scale BESS, which reduces upfront capital costs for developers, and inclusion of domestic content requirements in certain tenders to encourage local manufacturing. The government has also launched Production Linked Incentive (PLI) schemes for Advanced Chemistry Cells, aimed at establishing domestic cell production. These policies support India's 2030 RE targets and beyond.

From a regulatory perspective, the Central Electricity Authority (CEA), Central Electricity Regulatory Commission (CERC) and State Electricity Regulatory Commissions (SERCs) have issued guidelines for storage, including definitions, tariff structures, and grid participation mechanisms. Storage is increasingly being recognized as a separate asset class that can provide energy arbitrage, peak shaving, ancillary services, frequency regulation, and other grid support services.

Standards and technical requirements are another key area. The Bureau of Indian Standards (BIS) has issued standards for lithium-ion batteries and BESS integration, including safety, performance, and lifecycle criteria. These include standards for battery management systems (BMS), thermal management, and fire safety, which are critical given India's diverse climate and high ambient temperatures. In addition, international standards (IEC, IEEE, etc.) are also referenced in tenders to ensure global best practices, especially for imported cells or turnkey solutions.

9.1. Policy and Support Architecture: An Overview

India has assembled, between 2022 and 2026, one of the most comprehensive storage policy frameworks among emerging economies. The main instruments are summarised in Table 62. The architecture has evolved in three phases: *recognition* (2022-23: legal status of storage, bidding guidelines, energy-storage obligation, national framework), *support* (2023-25: viability gap funding, transmission-charge waivers, co-location advisory, PSP guidelines), and *performance and security* (2025-26: local-content and indigenous-EMS conditions, BESS safety and construction standards, grid-forming mandates and draft mandatory co-located storage).

Table 62: Principal national policy instruments, schemes and advisories on ESS, 2021-2026

Date	Instrument	Issued by	Key provisions relevant to storage
June 2021	Production Linked Incentive (PLI) scheme, 'National Programme On Advanced Chemistry Cell (ACC) Battery Storage' for implementation of giga-scale ACC manufacturing facilities in India.	Ministry of Heavy Industries and Public Enterprises	Provides financial support for setting up manufacturing units for ACC Battery Storage in India[251]
Mar 2022	Guidelines for Procurement and Utilization of Battery Energy Storage Systems as part of Generation, Transmission and Distribution	MoP	Standard bidding framework for BESS as a generation,

[251] Ministry of Heavy Industries and Public Enterprises, Production Linked Incentive (PLI) scheme, 'National Programme On Advanced Chemistry Cell (ACC) Battery Storage' for implementation of giga-scale ACC manufacturing facilities in India. Notified on June 2021

Date	Instrument	Issued by	Key provisions relevant to storage
	assets, along with Ancillary Services		transmission or distribution asset and for ancillary services[252]
April 2022	Electricity (Rights of Consumers) Amendment Rules, 2022	MoP	Advisory for consumers utilizing diesel gensets to shift to cleaner technology including RE with BESS[253]
Jul 2022	Renewable Purchase Obligation (RPO) and Energy Storage Obligation Trajectory till 2029-30	MoP	Energy Storage Obligation rising from 1% (FY24) to 4% (FY30), with ≥85% of stored energy from RE; later not carried into the Oct 2023 RCO notification[254]
Oct 2022	Harmonized Master List of Infrastructure	Ministry of Finance	Facilitates access to long tenure and lower cost financing for ESS[255]
Dec 2022	Electricity (Amendment) Rules	MoP	ESS recognised and permitted as a standalone or co-located asset for generation, transmission and distribution[256]
Apr 2023	Guidelines to promote development of Pump Storage Projects (PSP)	MoP	Site allotment, cost reliefs, faster clearances etc. in regard to PSP[257]
June 2023	Guidelines for Tariff Based Competitive Bidding Process for Procurement of Firm and Dispatchable Power from Grid Connected Renewable Energy Power Projects with Energy Storage Systems	MoP	Facilitate RE capacity addition and fulfilment of the RPO and ESO requirements of DISCOMs[258]
Jun 2023	Guidelines for Resource Adequacy Planning Framework for India	MoP	LOLP ≤ 0.2% and NENS ≤ 0.05%; utilities to plan adequacy including storage[259]

[252] Ministry of Power, Guidelines for Procurement and Utilization of Battery Energy Storage Systems as part of Generation, Transmission and Distribution assets, along with Ancillary Services, 10 Mar. 2022 (as amended).

[253] Ministry of Power, Electricity (Rights of Consumers) Amendment Rules, 2022, April, 2022

[254] Ministry of Power, Renewable Purchase Obligation (RPO) and Energy Storage Obligation Trajectory till 2029-30, notified 22 July 2022

[255] Ministry of Finance, Harmonized Master List of Infrastructure, Notified Oct 2022

[256] Ministry of Power, Electricity (Amendment) Rules, 2022 (recognition and treatment of energy storage systems), notified 29 Dec. 2022.

[257] Ministry of Power, Guidelines to Promote Development of Pump Storage Projects (PSPs), Apr. 2023.

[258] Ministry of Power, Guidelines for Tariff Based Competitive Bidding Process for Procurement of Firm and Dispatchable Power from Grid Connected Renewable Energy Power Projects with Energy Storage Systems, notified 9th June 2023

[259] Ministry of Power, Guidelines for Resource Adequacy Planning Framework for India, 28 Jun. 2023.

Date	Instrument	Issued by	Key provisions relevant to storage
Aug 2023	National Framework for Promoting ESS	MoP	Umbrella framework for storage deployment, financing and market design[260]
Sept 2024	Budgetary support for the cost of Enabling Infrastructure for Hydro Electric Projects (HEP)	MoP	Provides financial support for development of enabling infrastructure for hydro plants including PSP[261].
Sep 2023 / June 2025	Viability Gap Funding Scheme	MoP	₹3,760 crore; initially 4,000 MWh, later expanded to 13.2 GWh at revised support levels[262] Development of additional 30 GWh of BESS with financial support of ₹5,400 crore from Power Sector Development Fund[262]
Feb 2025	Advisory on co-locating Energy Storage Systems with Solar Power Projects to enhance grid stability and cost efficiency	CEA	Minimum 2-hour ESS equal to 10% of installed solar capacity in solar tenders[263]
Feb 2025	Tariff-based Competitive Bidding Guidelines for Procurement of Storage Capacity/ Stored Energy from Pumped Storage Plants	MoP	Competitive procurement of PSP storage capacity/energy (composite or tolling)[264]
Jun 2025	ISTS charge waiver extension	MoP	100% waiver for PSPs awarded and co-located BESS commissioned by 30 Jun 2028[265]
Apr 2026	CEA Long-Term National Resource Adequacy Plan	CEA	174 GW / 888 GWh storage by 2035-36[266]
Aug 2025	CERC (Connectivity and General Network Access to the ISTS) (Third Amendment) Regulations, 2025	CERC	Separate solar-hour and non-solar-hour ISTS access; wind-based stations and ESS of 50 MW

[260] Ministry of Power, National Framework for Promoting Energy Storage Systems, Aug. 2023.

[261] Ministry of Power, Budgetary support for the cost of Enabling Infrastructure for Hydro Electric Projects (HEP), notified 11 Sept. 2024

[262] Ministry of Power, Lok Sabha Unstarred Question No. 957 on VGF Scheme for battery Energy Storage Systems answered on 27 July. 2026.

[263] Ministry of Power, Advisory to REIAs and States on co-location of energy storage (minimum 2-hour ESS equal to 10% of installed solar capacity), 19 Feb. 2025, as reported by Mercom India.

[264] Ministry of Power, Guidelines for Tariff Based Competitive Bidding for Procurement of Storage Capacity/Stored Energy from Pumped Storage Projects, Feb. 2025.

[265] Ministry of Power, Order on waiver of inter-state transmission charges for hydro pumped storage projects and co-located BESS (projects awarded/commissioned on or before 30 Jun. 2028), Jun. 2025, as reported by SolarQuarter, 16 Jun. 2025.

[266] Central Electricity Authority (CEA), Long-Term National Resource Adequacy Plan (2026-27 to 2035-36), Ministry of Power, Government of India, Apr. 2026.

Date	Instrument	Issued by	Key provisions relevant to storage
			or more may seek non-solar-hour access; storage specifies maximum injection and maximum drawal for charging[267]
May 2026	Draft CERC GNA (Fourth Amendment) Regulations, 2026	CERC	Non-solar-hour access at further substations; minimum ESS discharge of twice the connectivity quantum (≥2 h); land bank guarantee for ESS reduced to ₹5 lakh/MW[268]

Source: Compiled by this report from the sources footnoted in each row. Status as of 30 September 2026.

9.2. Overview of ESS National Policies

India's energy storage policy landscape has evolved rapidly in response to the growing penetration of renewable energy and the need for grid flexibility. The Ministry of Power (MoP), Ministry of New and Renewable Energy (MNRE), Central Electricity Authority (CEA), and NITI Aayog have collectively introduced policies and frameworks to support the deployment of BESS and PSP. These policies aim to improve renewable energy integration, enhance grid reliability, support peak demand management, and strengthen India's energy security.

The Ministry of Power released the "National Framework for Promoting Energy Storage Systems" in 2023. The framework recognizes energy storage as an independent asset class and allows storage systems to participate in electricity markets and ancillary services. It promotes round-the-clock renewable power supply, reduction in greenhouse gas emissions, and improved grid reliability. The framework also enables standalone storage projects to operate as merchant assets capable of participating in energy and capacity trading. Additionally, the government introduced Energy Storage Obligations (ESO), mandating increasing levels of storage integration with renewable energy procurement[269]. On June 10, 2025, the Ministry of Power authorized an increased Viability Gap Funding (VGF) plan for 30 GWh of Battery Energy Storage Systems (BESS), marking a significant regulatory push to boost grid-scale energy storage.

NITI Aayog has played a strategic role through long-term planning and industrial policy initiatives. Its "Energy Storage System Roadmap for India: 2019–2032" highlighted the importance of storage for renewable integration, electric mobility, and grid modernization. The roadmap emphasized domestic manufacturing, reduction in battery costs, and development of a complete supply chain ecosystem. In parallel, the National Mission on Transformative Mobility and Battery Storage was launched to support localization of battery manufacturing and advanced battery technologies.

The Central Electricity Authority (CEA), through the National Electricity Plan (NEP) 2023, projected that India will require approximately 74 GW / 411 GWh of energy storage capacity by 2031–32 to reliably integrate renewable energy

[267]Central Electricity Regulatory Commission, "Central Electricity Regulatory Commission (Connectivity and General Network Access to the inter-State Transmission System) (Third Amendment) Regulations, 2025," Notification No. L-1/261/2021/CERC, New Delhi, India, Aug. 31, 2025.

[268]Central Electricity Regulatory Commission, "Draft Central Electricity Regulatory Commission (Connectivity and General Network Access to the inter-State Transmission System) (Fourth Amendment) Regulations, 2026," Notification No. L-1/261/2021/CERC, New Delhi, India, May 20, 2026.

[269] Ministry of Power, Government of India, National Framework for Promoting Energy Storage Systems. New Delhi, India: Ministry of Power, Aug. 2023.

into the grid. This includes nearly 47.24 GW / 236.22 GWh of Battery Energy Storage Systems and 26.69 GW / 175.18 GWh of PSP.

9.3. Assessment of National Policy and Regulatory Architecture

Table 63 assesses how each part of the framework is performing and identifies potential focus directions.

Table 63: Assessment of India's storage policy framework (2026)

Area	Status	Strengths	Identified Focus Directions
Planning targets	NEP 2023 (2026-27, 2031-32); LT-NRAP 2026 (2035-36); MNRE 2047	Clear power and energy targets; duration-based capacity credit	Targets not yet fully translated into state-wise, location-specific requirements
Capital support	VGF I (13.22 GWh) and II (30 GWh); PSDF funding; PSP infrastructure grants	Rapid tender uptake; cost reduction	Aggressive bidding, particularly by new but inexperienced players; addressing viability concerns; VGF tied to 2-h/1.5-cycle designs in part
Procurement guidelines	MoP BESS guidelines (2022); PSP TBCB (2025); state Battery Energy Storage Purchase Agreement (BESPA)/ Battery Energy Storage Sale Agreement (BESSA)	Standardised documents; competitive price discovery	Weak bidder-experience criteria; limited performance and augmentation clauses; frequent corrigenda
Transmission charges	ISTS waiver for PSP awarded and co-located BESS commissioned by Jun 2028	Reduces cost of establishing PSP	Standalone BESS treatment and post-2028 regime unclear; lack of adequate locational signal
Obligations and mandates	ESO (2022); co-location advisory (2025); draft 10% ESS mandate (2026)	Signals for co-location	Mandates without dispatch/market rules risk under-used storage (China lesson)
Market access	DAM, RTM, TRAS; administered SRAS; draft IEGC for ESS (Sep 2026)	ESS allowed in AS	Limited stacking rules; charging treatment inconsistent across states; Absence of FFR Products and Capacity market
Safety	CEA safety and construction amendments (2026)	BESS-specific rules	Type testing, separation distances and fire-service readiness to be operationalised
Manufacturing	PLI ACC (50 GWh); 20% local content and indigenous EMS in VGF	Industrial-policy intent	PLI delivery shortfall; >80% cell import dependence; no battery-specific ALMM

9.4. BESS Viability Gap Funding (VGF) Programmes

The Ministry of Power is administering two VGF schemes for the development of BESS in India

9.4.1 VGF I

The Central Govt. initially approved ₹3,760 crore for the development of 4 GWh of BESS with support of ₹96 lakh/MWh. However, with the declining prices of BESS, the capacity has been increased to 13.22 GWh while retaining the same budget with support of ₹27 lakh/MWh[270]. As of July 2026, Letters of Awards have been issued to 12. GWh of BESS and corresponding Battery Energy Storage Purchase Agreements (BESPAs) have been executed & financial closure has been achieved for 6.54 GWh[271].

9.4.2 VGF II (2025-26)

A second VGF scheme, approved on 10 June 2025, provides ₹5,400 crore from the Power System Development Fund (PSDF) to support 30 GWh of BESS: 25 GWh across 15 states and 5 GWh for NTPC. Support provided is ₹18 lakh/MWh[270]. In August 2025, the Ministry added conditions requiring that the EMS application software be developed indigenously, that refurbished cells not be used, and that projects meet a minimum of 20% local content. The state-wise allocation is presented in Figure 60.

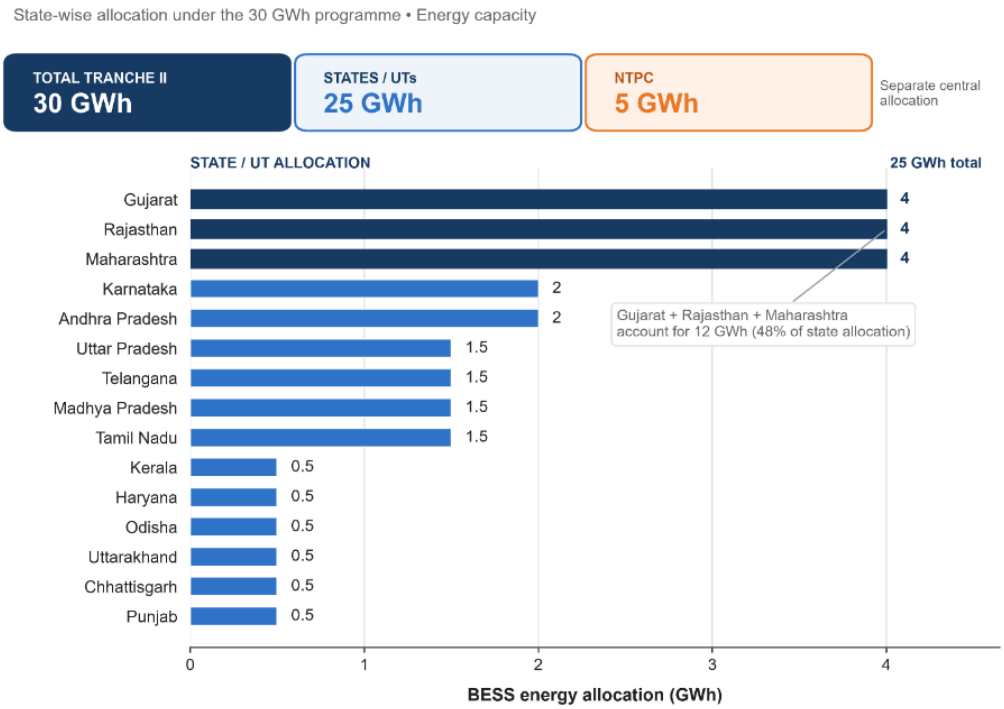


Figure 60: State-wise BESS energy-capacity allocation under VGF II. The 30 GWh programme comprises 25 GWh allocated across States/UTs and a separate 5 GWh allocation to NTPC; Gujarat, Rajasthan and Maharashtra together account for 48% of the state allocation.

(Source: This figure has been plotted using data sources from Ministry of Power, Guidelines for VGF Scheme for Development of BESS supported through PSDF (June 2025))

9.4.3 Assessment of the VGF Programme

The VGF has been highly effective in mobilising tenders and reducing BESS prices, but it has also contributed to aggressive bidding by inexperienced entrants, raising concerns about the project's quality, effectiveness, and long-

[270] PIB, Government Takes Multi-Pronged Steps to Scale Up Energy Storage Capacity in the Country, Feb 2026

[271] Ministry of Power, Lok Sabha Unstarred Question No. 957 on VGF Scheme for battery Energy Storage Systems answered on 27 July. 2026

term performance. In this context, some refinements are recommended to potentially to enhance the scheme's effectiveness, as illustrated below.

a. VGF disbursement should be linked more closely to *verified performance*; for example, a larger share could be allocated after certain period (one or two years) of demonstrated availability and compliance with the deliverables.
b. Eligibility should be broadened from a preferred two-hour design to service-based specifications (including four- to eight-hour systems and GFM capability), consistent with the shift in system needs.
c. Future VGF rounds should target locations and services with the highest system value, such as GFM storage at weak RE-pooling stations and storage that defers transmission, using a suitable placement and siting methodology.

Overall, the VGF programme has accelerated procurement and helped establish a competitive market for standalone BESS. As deployment scales, future rounds could potentially place greater weight on verified operational performance, service-specific requirements, and locational system value. Potential options to consider include linking a portion of support to demonstrated availability and compliance, allowing a wider range of storage durations were justified by the contracted service, and using network or resource-adequacy studies to identify locations where storage provides better marginal value to the system.

9.5. Grid codes and technical standards

The regulatory framework governing the integration of ESS in India has evolved considerably with the increasing deployment of standalone and RE integrated BESS and PSP in the country. The regulatory requirements comprise of technical connectivity standards by the Central Electricity Authority (CEA), operational requirements under the Indian Electricity Grid Code (IEGC) and the corresponding safety, metering, communication and protection requirements. Broadly, the regulations covering the operation of ESS can be categorized into 5 different layers.

Table 64: Selected regulatory and technical compliance framework for grid-connected ESS

Layer	Regulator	Instrument
Grid Connectivity	CEA	Technical Standards for Connectivity to the Grid, 2007 (amended 2013, 2019),
Operation and Market Participation	CERC	Indian Electricity Grid Code (IEGC), 2023, CERC (Connectivity and GNA Network Access to the ISTS) (Third Amendment) Regulations, 2025 CERC Deviation Settlement Mechanism Regulations, 2026 CERC Ancillary Services Regulations, 2022
Communication and Cybersecurity	CEA, CERC	IEGC 2023, CEA Cyber Security Regulations 2026 (in force from 2027),
Protection and Metering	CEA, CERC	IEGC 2023 CEA Metering Regulations 2026,
Battery Safety	CEA, BIS	CEA (Measures relating to Safety and Electric Supply) Regulations, 2023, as amended in 2026

	CEA (Technical Standards for Construction of Electrical Plants and Electric Lines) Regulations, 2022, as amended in 2026 Corresponding BIS standards

9.5.1 Regulatory Instruments and their Status

Table 65 lists the regulatory instruments that govern the connectivity, operational and safety regulations for ESS in India, the regulatory bodies that govern these regulations, the aspect of storage it addresses and its current status as of Sept 2026.

Table 65: Principal instruments governing the technical integration of ESS in India

Instrument	Issuer	What it sets for ESS	Status
Electricity (Amendment) Rules, 2022	Ministry of Power	Recognises ESS as a grid asset; allows standalone use or with generation, transmission or distribution	In force
Indian Electricity Grid Code (IEGC), 2023	CERC	Operating bands, scheduling, protection coordination, commissioning, load despatch coordination and other connectivity requirements	In force, amended
Technical Standards for Connectivity to the Grid, 2007 (amended 2013, 2019)[272]	CEA	Voltage and frequency capability, protection, reactive power, power quality, fault ride-through	In force
Draft Technical Standards for Connectivity to the Grid, 2026[273]	CEA	Fast frequency response, weak-grid operation, grid-forming, black start	Draft (Aug 2026);
Cyber Security Regulations, 2026[274]	CEA	Cyber-security management in the power sector	Published Aug 2026 (in force from April 2027)
Ancillary Services Regulations, 2022[275]	CERC	SRAS and TRAS, including eligible storage	In force

1. **Indian Electricity Grid Code 2023:** The Indian Electricity Grid Code 2023 establishes the principal operational framework for ESS entities connected to the inter-state transmission system. The Grid Code sets requirements for system security, frequency and voltage management, protection coordination, scheduling, communication, commissioning and operational compliance.

[272] Central Electricity Authority. Technical Standards for Connectivity to the Grid Regulations, 2007. New Delhi: Central Electricity Authority, 2007. As amended in 2013 and 2019.

[273] Central Electricity Authority. Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026. New Delhi: Central Electricity Authority, 2026.

[274] Central Electricity Authority. Cyber Security Regulations, 2026. New Delhi: Central Electricity Authority, 2026.

[275] Central Electricity Regulatory Commission. Ancillary Services Regulations, 2022. New Delhi: Central Electricity Regulatory Commission, 2022.

2. **CEA Grid Connectivity Standards:** The CEA Technical Standards for Connectivity to the Grid Regulations, 2007, together with the amendments of 2013 and 2019, establish the technical requirements for connecting electrical installations to the grid. The amendments widened the framework to cover evolving technologies, including inverter-based generation and energy storage. The standards address voltage and frequency operating capability, protection coordination, reactive power support, power quality and equipment performance during grid disturbances. Fault ride-through (FRT) capability is particularly important for inverter-based BESS. During short-circuit faults or other grid disturbances, an inverter-based resource may experience a substantial reduction in terminal voltage. Premature disconnection of many such resources at once can aggravate the disturbance and adversely affect system stability. The connectivity requirements therefore set conditions under which connected resources must remain operational, including Low Voltage Ride-Through (LVRT), High Voltage Ride-Through (HVRT) and reactive-current support during voltage disturbances.
3. **Draft CEA Grid Connectivity Standards 2026:** In August 2026, the CEA published the Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026, proposing a substantially expanded framework for CBRs and energy storage systems. Few of the key additions proposed in the draft regulations are:
    a. The draft introduces more detailed requirements for frequency response, voltage regulation, fault ride-through, grid-forming control and black-start capability.
    b. A significant development is the explicit treatment of inverter performance under weak-grid conditions. The draft requires stable operation at a reference short-circuit ratio (SCR) of 5, or at the actual system SCR where that is lower. This is particularly relevant to BESS connected to renewable energy pooling substations, electrically remote transmission networks and systems with limited synchronous generation.
    c. The draft introduces black-start requirements for BESS installations with an aggregate capacity of 50 MW and above. Black start allows a generating or storage resource to energise selected network elements without relying on an already energised external supply.
    d. The draft CEA standards introduce grid-forming capability as an important technical requirement for future CBRs. Conventional grid-following inverters rely on an externally established voltage waveform and typically use phase-locked-loop-based synchronisation. Grid-forming inverters, in contrast, establish and regulate their own voltage reference and can contribute to voltage and frequency stability under appropriate operating conditions.

The evolution of the CEA Connectivity Standards have been shown in Figure 61.



Figure 61: Energy market access and trading regulations for energy storage systems

The integration of energy storage systems into electricity markets requires a regulatory framework that accommodates their dual role as electricity consumers during charging and electricity suppliers during discharging. Unlike a conventional generating station, an ESS can withdraw electricity from the network, store it and inject it later, during periods of higher demand or favourable market conditions. Market participation therefore depends on the combined provisions of electricity market regulations, transmission access arrangements, scheduling requirements and deviation settlement mechanisms.

Four separate permissions are set for ESS: connectivity, network access, market participation and scheduling and settlement. An ESS developer may obtain connectivity without automatically receiving unrestricted network access, or eligibility for every market segment. The four permissions for BESS connected to ISTS for market participation is given in Figure 62.

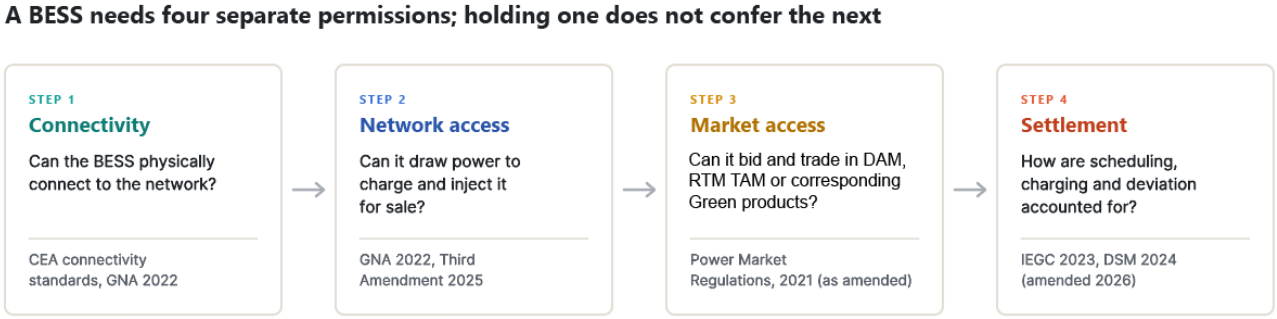


Figure 62: Regulatory permissions required for a BESS to purchase, store, sell and settle electricity when connected to ISTS

9.5.1.1. Market instruments, transmission access and settlement

At the central level, the CERC Power Market Regulations, 2021 govern organised electricity markets, including transactions through recognised power exchanges in the Day-Ahead Market (DAM), Real-Time Market (RTM) and Term-Ahead Market (TAM). Eligible ESS operators may participate in these markets, subject to the applicable market rules, network access arrangements and scheduling requirements. Table 66 lists the instruments that together define market access for storage, with their status. These instruments serve different purposes: market eligibility does not automatically confer transmission access, and transmission connectivity does not automatically establish permission to participate in every market product.

Table 66: Instruments governing energy market access for ESS

Instrument	Relevance to BESS	Status
CERC Power Market Regulations, 2021	Organised markets: Day-Ahead (DAM), Real-Time (RTM), Term-Ahead (TAM)	In force
CERC Connectivity and General Network Access (GNA) Regulations, 2022	ISTS connectivity, network access, charging drawal and injection	In force, amended
CERC (Connectivity and GNA Network Access to the ISTS) (Third Amendment) Regulations, 2025	Provisions for ESS connectivity and time-restricted access	In force
CERC IEGC, 2023	Scheduling, dispatch, metering, operational coordination; QCA arrangements for renewable-plus-storage	In force, amended
CERC Deviation Settlement Mechanism Regulations, 2024	Settlement of deviations from schedule, for both charging and discharging	In force; Third Amendment notified 2026
CERC Ancillary Services Regulations, 2022	Eligibility and procurement for SRAS and TRAS	In force
State Open Access Regulations	Network access and transactions inside state networks	State-specific

1. **Arbitrage and market participation:** For a standalone BESS, participation in energy markets creates opportunities for arbitrage, whereby electricity is purchased when market prices are relatively low and

discharged when they are higher. The economic viability of such transactions depends on round-trip efficiency, battery degradation, network charges, market prices and the availability of transmission capacity. Market participation must also account for the distinction between the BESS charging schedule and its electricity injection schedule.

2. **Scheduling and dispatch.** IEGC 2023 establishes the scheduling and dispatch framework for grid-connected entities, including eligible ESS installations. Depending on their classification and connectivity arrangements, operators must coordinate with the relevant load despatch centres and follow the applicable scheduling procedures, which must account for bidirectional operation. For renewable energy projects with storage, the Grid Code also provides for scheduling coordination through Qualified Coordinating Agencies (QCAs), where applicable.
3. **Participation in ancillary services.** In addition to energy-market transactions, ESS may participate in ancillary services under the CERC Ancillary Services Regulations, 2022, which provide for eligible energy storage resources to take part in Secondary Reserve Ancillary Services (SRAS) and Tertiary Reserve Ancillary Services (TRAS), subject to technical qualification and operational requirements. Participation adds operating constraints, because a BESS must keep enough charging or discharging capability in hand to deliver the committed service.
4. **State-level market access.** ESS connected to intrastate transmission or distribution networks are subject to the regulations of the relevant State Electricity Regulatory Commission. These may include open access provisions, trading arrangements, time-of-day tariffs, wheeling charges, banking provisions and other charges on electricity withdrawal and injection. For behind-the-meter storage the commercial framework may differ substantially from that of a standalone grid-connected BESS: such systems mainly provide bill savings through peak-demand reduction, load shifting and increased self-consumption of distributed renewable generation, and the ability to export stored electricity or participate in wholesale markets depends on state regulations, metering and permissions.
5. **Deviation settlement.** The CERC Deviation Settlement Mechanism and Related Matters Regulations, 2024, with their amendments, govern the accounting for deviations between scheduled and actual injection or withdrawal. The Third Amendment was notified on 7 September 2026. Deviations may arise during either charging or discharging, and because storage can move between withdrawal and injection within short periods, the scheduling and settlement framework must reflect the operating status and regulatory classification of the facility. The financial consequence of a deviation depends on the applicable provisions, the scheduling category and the prevailing settlement methodology.

9.5.1.2. Technical capability versus commercial recognition

An important distinction remains between technical capability and commercial service provision. A requirement for ESS to possess a particular capability does not necessarily establish a corresponding market product, procurement arrangement or compensation mechanism. Although ESS can technically provide frequency response, reactive power support, oscillation damping and black-start assistance, the commercial arrangements including adequate regulations for such services are not equally developed.

The CERC Ancillary Services Regulations, 2022 establish mechanisms for SRAS and TRAS, including participation by eligible energy storage resources. In contrast, the technical and commercial arrangements for other emerging services, particularly grid-forming support, synthetic inertia and dedicated oscillation damping, require further regulatory development.

Table 67: Services a BESS can provide, and the commercial mechanism for each as of Sept 2026

Service	Technical basis	Commercial mechanism	Status
Energy arbitrage	Scheduling under IEGC 2023	Exchange trading in DAM, RTM, TAM (Power Market Regulations, 2021)	Established
Secondary reserve (SRAS)	Technically qualified	Ancillary Services Regulations, 2022	Established
Tertiary reserve (TRAS)	Technically qualified	Ancillary Services Regulations 2022 / Procurement through market	Established
Primary Frequency response	• CEA Technical Standard 2007 • As laid out in Draft Technical Standards for Connectivity to the Grid, 2026[276]	None	Established With proposed changes
Reactive power and voltage support	• CEA Technical Standard 2007 • As laid out in Draft Technical Standards for Connectivity to the Grid, 2026	None	Established With proposed changes
Black start	As laid out in Draft Technical Standards for Connectivity to the Grid, 2026 BESS of 50 MW and above	None	Proposed
Grid-forming support	As laid out in Draft Technical Standards for Connectivity to the Grid, 2026	None	Proposed

For PSP, technical standards align with conventional hydroelectric power plant requirements. These include synchronous generator compliance with excitation control systems, governor response characteristics, and grid synchronization protocols. Because PSP units are synchronous machines, they inherently provide inertia, short-circuit strength, and voltage support, simplifying certain grid compliance aspects compared to inverter-based BESS.

[276] Central Electricity Authority. Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026. New Delhi: Central Electricity Authority, 2026.

However, civil engineering, dam safety, and hydro-mechanical standards under the Dam Safety Act and CEA hydro guidelines are stringent.

9.6. Transmission Charges and Network Treatment of ESS

In June 2025, the Ministry of Power extended the 100% waiver of inter-state transmission (ISTS) charges to hydro PSPs awarded for construction on or before 30 June 2028 and to co-located BESS commissioned on or before 30 June 2028, subject to conditions (including connection at the same ISTS substation as the associated RE project), for 25 years; standalone BESS remained governed by earlier orders and CERC regulations.[277] For RE generally, the ISTS waiver is being phased out in steps after June 2025.

The waiver has supported the early deployment of storage projects; however, a blanket waiver provides limited locational signals and may therefore incentivise ESS deployment at locations that do not deliver the greatest value to the transmission network.

Over the longer term, it may therefore be useful to examine alternatives that avoid inefficient double charging of stored energy while progressively reflecting network conditions and locational value. Any such updates would require a detailed assessment of market impacts, metering arrangements and consistency across standalone and co-located storage.

9.7. Safety standards for BESS

The rapid deployment of Battery Energy Storage Systems (BESS) in India has increased the importance of establishing comprehensive safety standards governing their design, installation, operation, maintenance, and end-of-life management. Unlike conventional electrical equipment, BESS installations integrate electrochemical energy storage devices, power electronic converters, thermal management systems, and multiple layers of monitoring and protection. Consequently, their safe operation requires coordinated management of electrical, thermal, chemical, mechanical, and environmental risks.

Among these risks, thermal runaway in lithium-ion batteries is of particular concern. Thermal runaway occurs when heat generation within a battery cell exceeds its ability to dissipate heat, potentially initiating a self-sustaining increase in temperature. Depending on the battery chemistry, state of charge, and failure conditions, this may result in the release of flammable gases, fire, or propagation of failure to adjacent cells and modules. Other significant safety concerns include electrical short circuits, insulation failures, overcharging, excessive temperatures, mechanical damage, ventilation failures, and exposure to hazardous substances.

These considerations are particularly relevant to India, where high ambient temperatures, seasonal humidity, dust exposure, and the increasing deployment of energy storage near electrical substations, renewable energy installations, industrial facilities, and urban load centres impose additional requirements on system design and operation. Effective BESS safety management therefore extends beyond the selection of battery chemistry or individual component certifications. It requires a system-level approach incorporating preventive engineering, continuous monitoring, fault detection, emergency isolation, fire protection, and periodic safety assessment.

In India, the safety framework for BESS is being developed through a combination of statutory regulations issued by the Central Electricity Authority (CEA), Indian Standards published by the Bureau of Indian Standards (BIS), international technical standards developed by the International Electrotechnical Commission (IEC), and fire safety and certification frameworks developed by organisations such as the National Fire Protection Association (NFPA) and Underwriters Laboratories (UL). Additional requirements arise from building and fire safety regulations, electrical inspection procedures, environmental legislation, and project-specific procurement specifications.

The following subsections examine the principal regulatory instruments and technical standards governing BESS safety, with particular emphasis on stationary and grid-connected energy storage installations.

[277] MNRE, Government Ensures Seamless Grid Integration for Renewable Energy Through Strong ISTS Framework (Ministry of New and Renewable Energy, Ministry of Power (MoP), Govt. of India, 2026).

9.7.1 Regulatory Framework for BESS Safety in India

The Indian regulatory framework distinguishes between statutory safety requirements and technical standards used to establish conformity with those requirements. While statutory regulations establish legally enforceable obligations, Indian and international standards provide detailed specifications, testing procedures, and design practices. The applicability of an individual standard depends on whether it has been incorporated into a regulation, mandatory certification order, statutory approval condition, or contractual requirement.

Historically, stationary battery installations were largely governed by general electrical safety regulations, relevant equipment standards, and building-level fire protection requirements. However, the increasing scale of grid-connected BESS deployment has necessitated a more comprehensive regulatory framework addressing the characteristics of electrochemical energy storage systems. In 2026, the CEA introduced BESS-specific provisions through amendments to the existing electrical safety and construction regulations. These developments represent an important transition from general electrical installation requirements towards dedicated provisions for grid-scale energy storage.

Table 68: Principal regulatory instruments and standards governing BES safety in India

Instrument / authority	Scope	Status / applicability
CEA (Measures relating to Safety and Electric Supply) Regulations, 2023, as amended in 2026[278]	Electrical safety, fire protection, thermal management, installation and audits	Statutory; BESS-specific Chapter XA effective 1 April 2027
CEA (Technical Standards for Construction of Electrical Plants and Electric Lines) Regulations, 2022, as amended in 2026[279]	Technical requirements for BESS construction, electrical equipment, monitoring, protection, and grid-support capabilities	Statutory technical requirements
BIS / Indian Standards	Indian Standards for electrical energy storage systems, battery management, lithium batteries, electrical installations, and associated equipment	Applicability depends on legal incorporation and product scope
National Building Construction Standards, SP 7:2026	Building safety, fire protection, emergency access and clearances	National standards; enforceability depends on adoption under applicable regulations
State fire safety authorities	Fire prevention, fire protection infrastructure, emergency access, and fire safety clearances	Applicable according to state and local legislation
Environmental authorities	Battery waste and hazardous material management	Applicable environmental legislation
IEC, UL, NFPA and IEEE	International testing, safety, interconnection and fire protection	Technical references; binding where appropriately incorporated

9.7.1.1. CEA Safety Regulations for Battery Energy Storage Systems

A significant regulatory development has been the introduction of Chapter XA, titled Additional Safety Requirements for Battery Energy Storage Systems, through the CEA (Measures relating to Safety and Electric Supply) Amendment Regulations, 2026. The BESS-specific provisions are scheduled to come into effect on 1 April 2027. Chapter XA establishes additional safety requirements for BESS installations connected at voltage levels exceeding 650 V. Installations connected at 650 V and below are addressed through provisions requiring compliance with relevant standards. These requirements supplement the general electrical safety obligations already applicable under the existing CEA regulatory framework.

[278] Central Electricity Authority (CEA). 2026. Central Electricity Authority (Measures Relating to Safety and Electric Supply) Amendment Regulations, 2026. New Delhi: Ministry of Power, Government of India. Gazette of India, March 2026

[279] Central Electricity Authority (CEA). 2026. Central Electricity Authority (Technical Standards for Construction of Electrical Plants and Electric Lines) Amendment Regulations, 2026. New Delhi: Ministry of Power, Government of India

The provisions cover the complete BESS installation, including battery cells and modules, racks, containers, associated electrical equipment, monitoring systems, and site-level safety infrastructure. A particularly important requirement is the incorporation of *two-fault tolerance*, under which the battery system must be capable of maintaining a safe condition or shutting down safely following two independent faults. This approach recognises that protection against catastrophic failure should not rely exclusively on a single monitoring system or protective device.

The regulations also emphasise continuous monitoring through the Battery Management System (BMS), appropriate protection against thermal runaway, adequate ventilation, separation of equipment, fire detection and suppression arrangements, emergency provisions, earthing, and independent fire safety assessment.

9.7.1.2. CEA Technical Standards for Construction of BESS Installations

Complementing the electrical safety provisions, the CEA (Technical Standards for Construction of Electrical Plants and Electric Lines) Amendment Regulations, 2026 introduce technical requirements for the construction and integration of BESS installations. These regulations address the major subsystems of a BESS, including batteries, power conversion systems, monitoring and communication infrastructure, electrical protection, and associated auxiliary systems. In addition to equipment safety, the construction standards address the operational capabilities required for integration with the electricity grid. An important distinction is the introduction of additional technical requirements for BESS installations with capacities of 50 MW and above, including automatic generation control, grid-forming inverter capability, and black-start capability.

Although these functions are primarily associated with grid performance and system restoration, their implementation also requires appropriate coordination between converter controls, battery operating limits, electrical protection, and system monitoring.

9.7.2 Indian Standards Applicable to Battery Energy Storage Systems

The Bureau of Indian Standards has developed and adopted several standards relevant to the safety and performance of electrical energy storage systems. These include indigenous Indian Standards addressing system-level safety and battery management, alongside Indian adoptions of international IEC standards.

The BIS Electrical Energy Storage Systems Sectional Committee (ETD 52) is responsible for standardisation relating to grid-integrated electrical energy storage systems[280]. The committee's scope extends to system-level aspects of electrical energy storage, including safety, performance assessment, testing, and environmental considerations.

An important development is the adoption of selected parts of the IEC 62933 series under the Indian Standard IS 17067. Consequently, several international safety and testing requirements already have corresponding Indian Standards. Table 69 summarises the principal Indian Standards relevant to stationary BESS installations.

Table 69: Important Indian Standards applicable to BESS

Indian Standard	Subject	Principal relevance
IS 17092:2019[281]	Electrical energy storage systems: safety requirements	System-level safety
IS 17387:2020[282]	BMS safety and performance requirements	Monitoring and control
IS 17067 (Part 1):2018[283]	EES vocabulary	Terminology
IS 17067 (Part 2/Sec 1):2019[284]	General unit parameters and testing methods	Performance characterisation

[280] Bureau of Indian Standards (BIS). ETD 52: Electrical Energy Storage Systems.

[281] Bureau of Indian Standards (BIS). 2019. Electrical Energy Storage Systems: Safety Requirements. IS 17092:2019. New Delhi: BIS.

[282] Bureau of Indian Standards (BIS). 2020. General Safety and Performance Requirements of Battery Management Systems. IS 17387:2020. New Delhi: BIS.

[283] Bureau of Indian Standards (BIS). 2018. Electrical Energy Storage Systems, Part 1: Vocabulary. IS 17067 (Part 1):2018. New Delhi: BIS.

[284] Bureau of Indian Standards (BIS). 2019. Electrical Energy Storage Systems, Part 2: Unit Parameters and Testing Methods, Section 1: General Specification. IS 17067 (Part 2/Sec 1):2019. New Delhi: BIS.

IS 17067 (Part 2/Sec 2):2025[285]	Application and performance testing	System performance evaluation
IS 17067 (Part 4/Sec 1):2019	Guidance on environmental issues	Environmental considerations
IS 17067 (Part 5/Sec 2):2021	Safety of grid-integrated electrochemical EES	System-level electrochemical safety
IS 16805[286]	Industrial lithium-cell and battery safety	Battery-component safety
IS 16894 (Part 2):2018[287]	Stationary battery installation safety	Installation practices
IS 3043	Code of practice for earthing	Grounding
IS 16270:2023	Secondary batteries for solar PV applications	Applicable PV-battery products

Among these standards, IS 17092 and IS 17067 (Part 5/Sec 2) are particularly relevant to grid-scale BESS because they address safety considerations beyond individual battery cells.

IS 17387 addresses the BMS, which serves as the principal interface between battery operating conditions and the protective control architecture. Effective BMS operation requires continuous monitoring of parameters such as cell voltage, temperature, current, and operating status, alongside appropriate protective responses to abnormal conditions.

Standards relating to lithium cells and batteries, such as IS 16805, establish an additional layer of safety assurance at the component level. However, compliance with a cell-level or battery-level standard does not necessarily demonstrate the safety of the complete storage installation.

[285] Bureau of Indian Standards (BIS). 2025. Electrical Energy Storage Systems, Part 2: Unit Parameters and Testing Methods, Section 2: Application and Performance Testing. IS 17067 (Part 2/Sec 2):2025. New Delhi: BIS

[286] Bureau of Indian Standards (BIS). 2018. Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes: Safety Requirements for Secondary Lithium Cells and Batteries for Use in Industrial Applications. IS 16805:2018. New Delhi: BIS.

[287] Bureau of Indian Standards (BIS). 2018. Safety Requirements for Secondary Batteries and Battery Installations, Part 2: Stationary Batteries. IS 16894 (Part 2):2018. New Delhi: BIS.

9.8. State and Union Territory Wise ESS Policy and Regulations

State / UT	Official policy / regulatory instrument(s) located	Issuing authority	Date / notification	Scope	Key regulatory provisions relevant to ESS	Incentives / subsidies / tax benefits	Compliance requirements
Andhra Pradesh	Andhra Pradesh Integrated Clean Energy Policy 2024; earlier AP Pumped Storage Power Promotion Policy 2022 incorporated/revised through the newer clean-energy framework	Government of Andhra Pradesh, Energy Department; NREDCAP as nodal agency	ICE Policy: 2024; official NREDCAP site carries policy, operational guidelines and amendment. PSP Policy: 20 Dec 2022	Utility-scale BESS; standalone/co-located storage; PSP; RE hybrids; distributed resources; storage-as-a-service	Interconnection: coordinated through state transmission/distribution agencies under policy/project approvals. Net metering: dedicated battery-export rule unspecified. Capacity: no universal BESS cap located. Licensing: storage envisaged as standalone or complementary asset. Tariff/market: policy recognises spot-market, arbitrage, capacity, RE firming and ancillary-service revenue; encourages BESS/DER aggregators and Storage-as-a-Service. AS: expressly contemplated.	ICE-policy investment facilitation applies; technology-specific BESS incentive quantum not clearly surfaced in the accessible official summary: unspecified	National Baseline (NB); NREDCAP/state approvals; grid connectivity; electrical safety; BWM/EPR; land/environmental approvals as applicable
Arunachal Pradesh	No standalone BESS/ESS policy located in the official policy sources reviewed; existing hydro/renewable framework is the closest category	State Government / power and renewable-energy authorities	Unspecified for ESS-specific instrument	Hydro/RE; potential PSP context; stationary BESS-specific scope unspecified	Interconnection, BTM storage, storage net metering, BESS capacity limits, state storage tariff and ancillary participation: unspecified; national rules govern where applicable	ESS-specific state incentive: unspecified	NB; hydro/PSP projects additionally require applicable water, land, forest and environmental approvals
Assam	Assam Renewable Energy Policy 2022. A later integrated clean-energy policy announced in 2025 was reported as having been withdrawn; a formal publicly indexed withdrawal instrument was not located in this review	Government of Assam / state energy authorities	RE Policy: 13 Oct 2022	Renewable energy; ESS-specific stationary framework limited/unspecified	Dedicated standalone-BESS interconnection, net-metering treatment of stored power, capacity limits and BESS tariff: unspecified in the official policy summary reviewed	Storage-specific subsidy: unspecified	NB plus state RE/project approvals
Bihar	Policy for Promotion of New and Renewable Energy Sources 2017 is the latest Bihar policy confirmed in the official MNRE	Government of Bihar / energy department and nodal agency	8 Jun 2017	Renewable energy; ESS-specific scope unspecified	Standalone BESS, bidirectional storage interconnection, battery export under net metering, storage tariffs, AS participation and storage registration: unspecified	ESS-specific incentives: unspecified	NB

State / UT	Official policy / regulatory instrument(s) located	Issuing authority	Date / notification	Scope	Key regulatory provisions relevant to ESS	Incentives / subsidies / tax benefits	Compliance requirements
	catalogue used in this review; any later replacement was not verified from a primary source						
Chhattisgarh	Chhattisgarh State Solar Energy Policy 2017-27, as amended; older wind/small-hydro/non-conventional-energy instruments	Government of Chhattisgarh / energy authorities	Solar-policy amendment 20 Nov 2020; older wind 2006 and small-hydro instruments also listed	Solar and other RE; BESS-specific scope unspecified	ESS interconnection, charging/discharging settlement, storage capacity limits and ancillary-service rules: unspecified	ESS-specific subsidy/tax incentive: unspecified	NB; applicable state solar/grid approvals
Goa	Goa State Solar Policy 2017; no standalone stationary-ESS framework located	Government of Goa; electricity/renewable-energy authorities	2017	Rooftop/distributed and other solar; EV infrastructure may be addressed separately; stationary BESS unspecified	Generic solar/net-metering regime should not be interpreted as a battery-export entitlement without an express JERC/DISCOM provision. BESS tariff, capacity and AS rules: unspecified	ESS-specific incentive: unspecified	NB and applicable JERC/electrical-inspector requirements
Gujarat	Gujarat Integrated Renewable Energy Policy 2025, superseding the earlier 2023 RE policy	Government of Gujarat, Energy & Petrochemicals Department; GEDA; GETCO/SLDC/DISCOMs have implementation roles	2025; launched/notified in late 2025	Standalone/grid-connected BESS, co-located BESS, solar/wind/hybrid storage, transmission support, distribution support, end-consumer storage	Interconnection: strategic BESS locations to be identified by SNA with GETCO, SLDC and DISCOMs; RE connectivity streamlined through state arrangements. Net metering: dedicated BTM battery-export rule not surfaced. Tariff/market: expressly enables BESS for transmission support and participation in ancillary and capacity markets with compensation/revenue stacking. Charging: policy contains specific treatment of input energy for BESS services. Cap: universal limit unspecified.	Policy provides RE/storage facilitation and transmission/connectivity measures; precise BESS tax/subsidy quantum depends on project route and is not stated in the official HTML highlight: project-specific	NB plus GEDA registration/connectivity and state utility procedures
Haryana	Haryana Solar Power Policy 2016; Haryana's EV policy is relevant to EV batteries/charging but a stationary-grid BESS code was not located in the reviewed sources	Government of Haryana / renewable-energy authorities	Solar policy 2016	Solar; rooftop/captive; EV charging separately; stationary ESS unspecified	ESS-specific bidirectional interconnection, storage export settlement, standalone BESS tariff and AS participation: unspecified	ESS-specific stationary-storage incentive: unspecified	NB
Himachal Pradesh	Himachal Pradesh Energy Policy 2021; 2026 building/planning amendments also	Government of Himachal Pradesh; HIMURJA; Town & Country Planning	Energy Policy: 2021; EV/building amendment: 2026	RE/hydro; EV charging in covered buildings; PSP context; stationary BESS-specific	Dedicated BESS interconnection, tariff and net-metering rules: unspecified. EV charging is increasingly embedded in building	ESS-specific BESS incentive: unspecified	NB; hydro/PSP environmental and water/land approvals; building/fire compliance where EV infrastructure installed

State / UT	Official policy / regulatory instrument(s) located	Issuing authority	Date / notification	Scope	Key regulatory provisions relevant to ESS	Incentives / subsidies / tax benefits	Compliance requirements
	expand EV-charging requirements	authorities for building-related EV provisions		framework unspecified	planning, but that does not create a stationary BESS market rule		
Jharkhand	Jharkhand State Solar Policy 2022	Government of Jharkhand / state renewable-energy agency	5 Jul 2022	Solar, including distributed applications; ESS-specific treatment not established in the official summary reviewed	Standalone BESS connectivity, capacity cap, stored-energy net metering, charging/discharging tariff and AS: unspecified	Storage-specific incentive: unspecified	NB and policy/project registration as applicable
Karnataka	Karnataka Renewable Energy Policy 2022-2027 and amendments	Government of Karnataka, Energy Department; KREDL	16 Apr 2022; amendment dated 1 Mar 2023 was also identified	Utility RE with or without ESS, rooftop solar, hybrid projects	Policy explicitly allows planned RE expansion with or without energy storage. Standalone BESS licensing, battery net-metering treatment, universal storage capacity caps and a separate merchant-storage tariff are unspecified in the high-level policy. SERC/grid rules continue to govern interconnection	RE-policy benefits may extend according to project category; separate quantified BESS subsidy: unspecified	NB; KREDL/state grid procedures
Kerala	Kerala Solar Energy Policy, 2013; KSERC (Renewable Energy and Net Metering) Regulations, 2020, amended in 2022 and 2024; KSERC (Renewable Energy and Related Matters) Regulations, 2025	Government of Kerala / energy authorities	25 Nov 2013 (Solar Policy); 7 Feb 2020 (RE Regulations); Aug 2024 (ESS-related amendment); 1 Mar 2025 (Floating Solar Guidelines); 5 Nov 2025 (new RE Regulations)	Rooftop and distributed solar PV; floating solar; solar-plus-BESS; behind-the-meter ESS; grid-scale standalone BESS; renewable energy integration and energy storage obligations	2024 amendment: ESO of 0.50% for FY 2026–27, increasing to 2% by FY 2029–30; at least 85% of stored energy must originate from RE sources to qualify. 2025 regulations: ESO of 1% for FY 2026–27, increasing to 4% by FY 2029–30; domestic net metering up to 20 kW, with 10–20% storage requirements for specified capacities; standalone grid-scale BESS tariff determination on capacity/energy basis, minimum 85% round-trip efficiency and 95% annual availability. Floating Solar Guidelines: encourage storage up to 50% of generated energy. Draft Power Policy: proposes at least 10% BESS capacity with new RE projects.	ESS-specific incentive: unspecified	NB; SERC/DISCOM solar interconnection rules where applicable
Madhya Pradesh	Madhya Pradesh Renewable Energy Policy 2025; Scheme for implementation of Pumped Hydro Storage Projects in Madhya Pradesh	Government of Madhya Pradesh / New & Renewable Energy Department; state implementing agencies	RE Policy 2025; PSP scheme current under state framework	BESS; PSP; other commercially viable storage; renewable/hybrid projects	Policy definition expressly encompasses energy-storage projects across technologies. Projects seeking policy incentives are required to be registered with the state NRE framework. PSP has a dedicated development/allocation scheme. Battery net-metering and uniform merchant-BESS tariff remain unspecified.	Benefits available to eligible registered projects under the policy/schemes; precise BESS-specific subsidy rate unspecified in accessible primary summary. PSP has separate land/project-support provisions	NB; NRE registration for benefits; PSP projects also require water /land/environment/forest clearances as applicable

State / UT	Official policy / regulatory instrument(s) located	Issuing authority	Date / notification	Scope	Key regulatory provisions relevant to ESS	Incentives / subsidies / tax benefits	Compliance requirements
Maharashtra	Maharashtra Renewable Energy & Energy Storage Policy 2025-26 to 2035-36; revised implementation FAQs; related PSP framework	Government of Maharashtra, Energy Department; MEDA/MSEDCL and other utilities for implementation	Current policy officially posted 13 May 2026; revised FAQs available in 2026	Utility BESS; PSP; RE-plus-storage; distributed RE/storage; DISCOM storage procurement	One of India's most explicit state frameworks. Official utility implementation material states that new RE projects above 100 kW are required to include energy storage. The policy sets long-term storage deployment/procurement objectives. Interconnection follows state utility/SERC processes. A general BTM right to export grid-charged battery energy through net metering remains unspecified. Tariffs for procured storage are predominantly bid/PPA/regulator based rather than a universal administered storage tariff.	Policy contains investment/fiscal support for qualifying RE/storage projects; exact applicability depends on project class. Storage targets and mandatory integration create demand-side support in addition to fiscal incentives	NB; policy/utility registration and connectivity; project testing/performance requirements; CEIG/fire/environmental approvals as applicable
Manipur	Manipur Grid Interactive Rooftop Solar PV Policy 2014	Government of Manipur / state energy authorities	24 Dec 2014	Rooftop solar; stationary BTM storage not expressly regulated in source summary	ESS-specific net-metering/export treatment, interconnection, storage capacity and tariff: unspecified	ESS-specific incentive: unspecified	NB plus rooftop-PV/DISCOM requirements
Meghalaya	Meghalaya Power Policy 2024	Government of Meghalaya / Power Department and state electricity institutions	2024	Hydro/PSP; renewable energy; BESS; solar-based EV charging; R&D	Policy expressly promotes PPP development of solar-based EV charging stations and BESS, and storage-related research. Dedicated statewide BESS interconnection code, net-metering rule, tariff, universal capacity threshold and ancillary-market procedure: unspecified	Policy contemplates institutional/PPP support and a corpus/R&D support for BESS/green technologies; precise BESS capital subsidy unspecified	NB; project approvals; hydro/PSP environmental requirements where applicable
Mizoram	Mizoram Solar Power Policy 2017	Government of Mizoram	24 Feb 2017	Solar; stationary ESS-specific framework unspecified	Storage interconnection, battery net metering, tariff, capacity limits and AS: unspecified	Storage-specific incentive: unspecified	NB
Nagaland	No dedicated stationary-ESS policy was located in the official state-policy sources reviewed	Government of Nagaland / relevant power and renewable-energy authorities	Unspecified	RE; microgrids may occur project-by-project; ESS-specific statewide framework unspecified	All requested ESS-specific commercial/grid provisions: unspecified; national baseline and project/tender conditions apply	ESS-specific incentive: unspecified	NB
Odisha	Odisha Renewable Energy Policy 2022 plus operational guidelines	Government of Odisha, Department of Energy; OREDA; SLDC; OERC has regulatory role	30 Nov 2022; Resolution referenced in implementation material as No. 11757-ENG-HYD-HYDRO-0009/2022	Explicitly covers pumped-storage hydro and BESS, along with solar, wind, hybrid, hydrogen and other RE	Particularly advanced institutional model. State entities may aggregate the State's ESO requirement and procure PSP/BESS "storage as a service". SLDC may claim storage-service procurement cost in its ARR; OERC may frame regulations for grid-balancing assets and cost recovery.	RE-policy fiscal/land/electricity-duty measures depend on category; exact BESS-specific subsidy rate unspecified in the quoted provisions	NB; operational-guideline registration/approvals; grid and state-agency requirements

State / UT	Official policy / regulatory instrument(s) located	Issuing authority	Date / notification	Scope	Key regulatory provisions relevant to ESS	Incentives / subsidies / tax benefits	Compliance requirements
					Dedicated BTM battery net-metering/export rule and universal BESS cap: unspecified		
Punjab	New and Renewable Sources of Energy Policy 2012	Government of Punjab / renewable-energy agency	26 Dec 2012	Conventional RE categories; modern standalone BESS framework unspecified	ESS-specific interconnection, storage net metering, tariff, capacity limit, licensing and AS: unspecified	Storage-specific incentive: unspecified	NB
Rajasthan	Rajasthan Integrated Clean Energy Policy 2024, replacing the 2023 RE-policy framework; Green Hydrogen Policy also relevant to long-duration energy ecosystem	Government of Rajasthan, Energy Department; RRECL/state utilities	2024; gazette copy reports file F.20(62)Energy/2024	Solar, wind, hybrid, BESS, pumped storage, green hydrogen and other clean-energy technologies	Establishes an integrated Energy Storage Programme, covering battery and pumped-hydro storage in the state's clean-energy planning. Project connectivity, allotment and procurement follow state utility/SERC and policy procedures. BTM battery-export settlement and a universal standalone-BESS retail tariff: unspecified	Policy provides investment/facilitation measures for clean-energy/storage projects; detailed eligibility is project/category dependent	NB; RRECL/state approvals; land/grid and PSP environmental requirements
Sikkim	Sikkim Grid Connected Rooftop Solar PV Policy 2019	Government of Sikkim / energy authorities	30 Aug 2019	Rooftop solar; BTM stationary storage unspecified	Battery net-metering/export, BESS tariff, capacity limits and standalone interconnection: unspecified	ESS-specific incentive: unspecified	NB plus rooftop-PV rules
Tamil Nadu	Tamil Nadu Solar Energy Policy 2019; BESS is increasingly being implemented through project-specific procurement/TNERC approvals rather than a dedicated statewide ESS policy located in this review	Government of Tamil Nadu; TNERC and state generation/distribution entities for regulated projects	Solar Policy 4 Feb 2019; individual storage approvals ongoing	Solar; utility solar-plus-BESS projects; standalone comprehensive ESS framework not located	Generic solar policy does not itself establish a full BESS regime. Project-specific TNERC approvals demonstrate tariff treatment for solar-plus-storage, but these should not be generalised to all BESS. ESS-specific BTM export, licensing and universal ancillary route: unspecified at state-policy level	Project/tender-specific rather than a uniform statewide BESS subsidy located	NB plus TNERC/PPA/tender requirements
Telangana	Telangana Clean and Green Energy Policy 2025	Government of Telangana, Energy Department; TGREDCO; TGTRANSCO; TGDISCOMs	G.O.Ms.No.2, 11 Jan 2025; policy valid for 10 years from issue	BESS, PSP, standalone/co-located storage, Storage-as-a-Service, solar/wind/hybrid, distributed RE and other clean energy	A dedicated BESS chapter creates incentives. Storage-as-a-Service: TGTRANSCO/TGDISCOMs identify land near EHT and distribution substations and select developers through competitive bidding using profit share, capacity charge or another approved bid parameter. Interconnection follows transmission/distribution processes. Battery net-metering treatment remains unspecified.	100% stamp-duty reimbursement for land purchased for BESS; land-ceiling exemption for BESS against qualifying firm orders/PPAs/successful bids; additional project facilitation under the policy	NB; TGREDCO/project application; applicable clearances; grid and safety approvals

State / UT	Official policy / regulatory instrument(s) located	Issuing authority	Date / notification	Scope	Key regulatory provisions relevant to ESS	Incentives / subsidies / tax benefits	Compliance requirements
Tripura	No standalone ESS policy was located in the sources reviewed	State Government / power and renewable-energy agencies	Unspecified	RE and distributed systems; ESS/microgrid projects may be tender/project driven	Statewide BESS interconnection, stored-energy net metering, tariff, capacity limits and AS: unspecified	ESS-specific incentive: unspecified	NB
Uttar Pradesh	Uttar Pradesh Solar Energy Policy 2022 plus implementation GOs/guidelines	Government of Uttar Pradesh, Department of Additional Sources of Energy; UPNEDA	2022; official English policy posted 29 Nov 2022; implementation GOs from Dec 2022 onward	Utility solar; solar with four-hour BESS; rooftop solar; solar parks; captive/third-party projects	Capacity/design: policy expressly encourages utility-scale solar systems with four-hour battery storage. Grid-connected projects follow UPNEDA/state-utility and UPERC rules. Standalone merchant BESS and a dedicated BTM battery-export regime: unspecified.	State subsidy ₹2.50 crore/MW for qualifying utility-scale solar systems with four-hour battery storage; solar policy also provides 100% stamp-duty exemption on land for solar plant/park and 100% electricity-duty exemption for 10 years for qualifying solar units	NB; UPNEDA guidelines and project approval; grid connectivity; performance conditions of subsidy/tender
Uttarakhand	Uttarakhand State Solar Policy 2023; older micro/mini-hydro policy	Government of Uttarakhand / UREDA and power authorities	Solar Policy 2023; older micro/mini-hydro policy 31 Jan 2015	Solar; distributed energy; hydro; stationary BESS-specific framework not located	BESS interconnection, battery net metering, merchant tariff, state capacity cap and AS rules: unspecified	ESS-specific state subsidy: unspecified	NB; applicable solar/hydro approvals
West Bengal	Policy on Co-generation and Generation of Electricity from Renewable Sources 2012	Government of West Bengal / energy authorities	5 Jun 2012	Renewable generation; modern standalone BESS framework unspecified	Dedicated ESS interconnection, stored-energy net metering, storage tariff, capacity caps and ancillary rules: unspecified	ESS-specific incentive: unspecified	NB
Andaman & Nicobar Islands	No territorial stationary-ESS policy located in reviewed policy repositories; ESS deployment has largely been project/tender driven	UT Administration / Electricity Department; central agencies where applicable	Unspecified	Island microgrids, RE integration and project-specific storage are technically relevant; statewide/UT-wide ESS regulation unspecified	Storage connection/dispatch and tariffs principally project/tender/utility based; generic BTM battery-export rules: unspecified	ESS-specific territorial subsidy: unspecified	NB is especially important: CEA's Chief Electrical Inspectorate expressly performs inspection functions for qualifying Central Government/UT installations under the 2023 safety regulations
Chandigarh	Chandigarh Electric Vehicle Policy 2022, amended multiple times including a 19 Sep 2026 amendment; no stationary-grid BESS policy located	Chandigarh Administration, Department of Science & Technology and Renewable Energy	EV Policy 2022; second amendment Notification S&T&RE/2023/119, 18 Oct 2023; further amendment 19 Sep 2026	EV charging, battery charging and battery swapping; stationary utility/BTM ESS not comprehensively regulated	EV framework addresses battery charging/swapping infrastructure; the policy framework has treated tariffs for battery charging/swapping alongside public charging. This is not equivalent to a stationary BESS tariff or export regime. Stationary BESS interconnection/net metering/AS: unspecified	EV purchase/infrastructure incentives under the EV policy; not a stationary-BESS subsidy	NB; EV charging electrical/building/fire approvals; CEA inspection provisions apply as relevant to UT installations
Dadra & Nagar Haveli and Daman & Diu	No UT-specific stationary ESS framework located	UT Administration / Electricity Department; JERC where	Unspecified	Rooftop RE, industrial/captive use potentially relevant;	ESS-specific interconnection, battery net-metering/export, tariff, cap and AS: unspecified	ESS-specific incentive: unspecified	NB; UT electrical-inspector requirements

State / UT	Official policy / regulatory instrument(s) located	Issuing authority	Date / notification	Scope	Key regulatory provisions relevant to ESS	Incentives / subsidies / tax benefits	Compliance requirements
		jurisdictionally applicable		stationary BESS rules unspecified			
Delhi (NCT)	Delhi Solar Energy Policy 2023, notified in March 2024 and amended in July 2025; Delhi EV framework separately addresses e-mobility	Government of NCT of Delhi; Energy Department/DISCOM implementation; DERC for regulated grid matters	Policy 2023, notified Mar 2024; first amendment effective/notified Jul 2025	Rooftop and procured utility-scale solar; EV charging separately; BTM batteries possible technically but not covered by a comprehensive ESS market framework located here	Solar policy provides net-metering/generation-based incentive architecture for rooftop PV. No general right to net-meter grid-charged battery exports should be inferred. Standalone BESS tariff, capacity cap and state ancillary framework: unspecified	2025 amendment increased residential rooftop state capital subsidy to ₹10,000/kW, capped at ₹30,000 for up to 3 kW; this is a solar incentive, not a dedicated BESS subsidy	NB; DERC/DISCOM solar interconnection and metering; building/fire/electrical approvals
Jammu & Kashmir	J&K Solar Power Policy 2013; Grid Connected Rooftop Solar PV Policy 2016/17; micro/mini hydro policy	UT Government / power-development and renewable-energy authorities	Solar: 18 Mar 2013; rooftop policy 21 Feb 2017; micro/mini hydro 27 Dec 2011	Solar, rooftop and small hydro; comprehensive stationary BESS framework unspecified	ESS-specific bidirectional interconnection, stored-energy net metering, BESS tariff/capacity and AS: unspecified	ESS-specific incentive: unspecified	NB; hydro/land/environmental rules as applicable
Ladakh	Ladakh Electric Vehicle and Allied Infrastructure Policy 2022 was identified as an EV-related instrument; no territory-wide stationary-grid ESS regulation located	UT Administration	2022	EV charging/allied infrastructure; off-grid/microgrid and utility storage are project-relevant but separate	EV policy should not be treated as a stationary BESS interconnection or tariff code. Standalone BESS/net-metering/AS rules: unspecified	EV-related incentives; stationary ESS-specific subsidy unspecified	NB; UT electrical/fire/building requirements; project-specific requirements
Lakshadweep	No territory-wide ESS regulatory policy located; storage deployment is primarily project/tender based	UT Administration / Electricity Department; central agencies	Unspecified	Island microgrid, solar-plus-storage and reliability applications	Project-specific connection/dispatch; general BTM net-metering and storage tariff: unspecified	ESS-specific territorial incentive: unspecified	NB; CEA/UT inspection and safety requirements
Puducherry	Puducherry Solar Energy Policy 2015	UT Government / Renewable Energy Agency and Electricity Department	Policy 2015; notified 19 Feb 2016	Solar/rooftop; stationary ESS-specific framework unspecified	Battery export under net metering, standalone BESS tariff/cap, licensing and AS: unspecified	ESS-specific incentive: unspecified	NB plus applicable JERC/utility solar rules

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9.9. Evolution in Energy Storage Sector in Past Ten Years

Date	Document / initiative	Central authority	status	Scope	Technical / grid / testing / safety provisions	Financial measures	Procurement / implementation	Impact / implication
2016	National Tariff Policy, 2016 — ESS-relevant transmission-policy baseline	Ministry of Power / Government of India	Policy; not an ESS-specific regulation	RE; subsequently BESS/PSP through implementing orders	No standalone ESS technical standard in the policy identified here; later MoP ESS framework explicitly states that ISTS waivers for ESS were pursued in the context of the 2016 Tariff Policy.	No direct ESS subsidy specified.	Implemented later through MoP transmission-charge-waiver orders.	Established the policy foundation subsequently used to lower ISTS costs for storage-linked renewable projects.
22 Nov 2017	India's Energy Storage Mission: A Make-in-India Opportunity for Globally Competitive Battery Manufacturing	NITI Aayog with Rocky Mountain Institute	Advisory / strategy report; non-binding	Primarily batteries; EV and stationary-storage manufacturing	Manufacturing and supply-chain roadmap rather than binding grid standards; proposed a staged strategy for building a competitive domestic battery ecosystem.	Direct central subsidy: Unspecified.	Policy recommendations on creating manufacturing demand, scaling supply chains and cell manufacturing.	Put storage on the national industrial-policy agenda and linked electricity storage with EV-scale battery demand.
9 Aug 2018	National Energy Storage Mission policy-development process	MNRE / Government of India; NITI analytical support	Proposal / policy-development initiative; not a notified statute	BESS / other electricity storage / microgrids / mobility	Government identified grid integration of RE, rural microgrids or standalone systems and electric mobility as major storage applications.	Unspecified.	Government referred to the NITI–RMI three-stage manufacturing pathway; no binding national ESS mission regulation was identified from this stage.	Transitioned the topic from analytical report to an explicit national policy-development agenda.
6 Feb 2019	CEA Technical Standards for Connectivity to the Grid — 2019 Amendment	Central Electricity Authority	Statutory technical regulation	Grid-connected ESS	MoP's later ESS Framework records that the 2019 CEA amendment specifies requirements for ESS connecting to the grid at 33 kV and above.	Unspecified.	Compliance forms part of grid-connectivity process.	One of the earliest explicit incorporations of ESS into national interconnection standards.
7 Mar 2019	National Mission on Transformative Mobility and Battery Storage	Union Cabinet; NITI Aayog-led inter-ministerial mission	Cabinet-approved national mission	ACC batteries; EV and battery-storage manufacturing	Five-year phased manufacturing programme envisaged up to 2024 for large-scale integrated battery/cell manufacturing; technology and manufacturing strategy rather than power-system interconnection rules.	Specific mission-wide direct grant in the Cabinet release: Unspecified.	Inter-ministerial steering involving NITI, MoP, MNRE, DHI, DPIIT, DST, BIS and transport authorities.	Institutionalised batteries as a strategic domestic manufacturing sector and directly preceded ACC PLI policy.
6 Aug 2019	Energy Storage System (ESS) Roadmap for India: 2019–2032	NITI Aayog	Advisory / analytical roadmap	BESS / wider ESS	Long-term deployment and market roadmap; no binding interconnection or safety requirements.	Unspecified.	Planning/advisory document, rather than a procurement order.	Supplied analytical grounding for subsequent national storage targets and market interventions.
Nov 2020	Guidelines for TBCB Procurement of Round-the-Clock Power from Grid-Connected RE, complemented by other source or storage	Ministry of Power	Section 63 competitive-bidding guidelines	RE + ESS / firm power	Permits firm output from storage to balance renewable generation and deliver RTC electricity; detailed ESS technology limits depend on bid design.	Direct subsidy: Unspecified; tariff discovered competitively.	Used by procurers/REIAs for RTC renewable procurement.	Created early utility-scale demand for storage as a firming resource rather than merely a pilot asset.
12 May / 9 Jun 2021	PLI Scheme — National Programme on Advanced Chemistry Cell Battery Storage	Union Cabinet; Department/Ministry of Heavy Industries	Central Sector manufacturing -incentive scheme / notification	ACC battery cells; EV + stationary storage	Technology agnostic; promotes gigascale ACC manufacturing and increasing domestic value addition rather than prescribing grid-connection standards.	₹18,100 crore PLI envelope; original capacity target 50 GWh.	Competitive selection of manufacturers; incentives linked to domestic battery sales/value addition over the incentive period.	Established the principal central supply-side industrial policy supporting future BESS cost reduction and import substitution.
23 Nov 2021	Order on waiver of ISTS charges for solar/wind, including storage-related provisions as amended	Ministry of Power	Administrative / policy order	BESS / PSP associated with qualifying RE	The later National ESS Framework states that full waiver applied to qualifying BESS/PSP commissioned up to 30 Jun 2025, followed by phased charging under the then framework.	ISTS-charge waiver rather than capital subsidy.	Eligibility tied to the conditions of MoP waiver orders and CERC transmission-charge framework.	Reduced delivered cost of interstate renewable energy backed by storage and established the predecessor to the stronger 2025 waiver.

Date	Document / initiative	Central authority	status	Scope	Technical / grid / testing / safety provisions	Financial measures	Procurement / implementation	Impact / implication
29 Jan 2022	Clarification regarding usage of ESS across the entire power-sector value chain	Ministry of Power	Formal clarification / policy interpretation	BESS; PSP; phase-change storage; green hydrogen/ammonia; other ESS	ESS may be standalone or complement generation/T&D; may have status according to use; owner may sell/lease/rent storage space; standalone ESS treated as delicensed at par with generation; CEA registration/capacity verification and CEA safety compliance required; standalone ESS can obtain connectivity under the applicable transmission framework.	Unspecified.	Development/ownership/lease/operation permitted by generating companies, licensees, system operators or standalone service providers.	Removed fundamental ambiguity about ownership, licensing and multi-use deployment.
31 Jan 2022	CERC (Ancillary Services) Regulations, 2022	Central Electricity Regulatory Commission	Statutory CERC regulation	BESS / ESS	ESS is eligible, subject to regulatory conditions, to provide SRAS and TRAS; regulations govern procurement, deployment and payment of ancillary services for frequency control/congestion management.	Compensation through ancillary-services mechanisms; direct subsidy: Unspecified.	NLDC/RLDC/Grid-India system-operation framework; administered and market-based ancillary mechanisms.	Created an additional grid-services revenue stream for storage and gave fast-response ESS a formal market function.
10 Mar 2022	Guidelines for Procurement and Utilisation of BESS as part of Generation, Transmission and Distribution assets, along with Ancillary Services	Ministry of Power	Section 63 procurement guidelines / Gazette resolution	BESS	Covers generation, transmission, distribution, ancillary services, arbitrage and storage-as-a-service; minimum intra-state project/bid quantum 1 MW and inter-state 50 MW, with appropriate energy rating; BESS may charge from RE or non-RE electricity, but electricity represented as RE must meet the prescribed RE-charging condition.	No central subsidy in the guidelines; tariff/storage charge discovered through competition.	BOO/BOOT competitive procurement; permits intermediary procurer/aggregator; standardises risk allocation.	Became the core template for standalone BESS competitive procurement and substantially improved bankability.
12 Apr 2022	Scheme for Flexibility in Generation and Scheduling of Thermal/Hydro Power Stations through bundling with Renewable Energy and Storage Power	Ministry of Power	Scheme / guidelines	Thermal + hydro + RE + ESS	Enables conventional generation portfolios to use renewable energy and storage to improve scheduling/flexibility; specific storage chemistry/capacity limit: Unspecified in the official index.	Unspecified.	Implemented through thermal/hydro generating entities and bundled power arrangements.	Established storage as a flexibility tool for the existing conventional fleet, not only as an RE-specific asset.
20 Apr 2022	Electricity (Rights of Consumers) Amendment Rules — DG replacement provision	Ministry of Power	Statutory rules	Behind-the-meter BESS / RE + storage	Consumers using diesel generators for essential backup are to endeavour to shift to cleaner technologies such as RE with battery storage within five years or according to the timeline determined by the State Commission based on local reliability.	Direct subsidy: Unspecified.	Consumer/distribution-licensee implementation.	Creates a central policy signal for C&I and other behind-the-meter storage, although implementation is state/regulator dependent.
7 Jun 2022	CERC (Connectivity and General Network Access to the ISTS) Regulations, 2022	CERC	Statutory regulation	Grid-connected generation / ESS / transmission access	Replaced the earlier access architecture with GNA-based ISTS access; subsequent amendments and the 2026 draft continue refining connectivity treatment, including ESS-related issues.	Transmission charges under applicable CERC/MoP framework; direct subsidy: Unspecified.	CTUIL/GNA mechanism for ISTS connectivity and access.	Important enabling infrastructure for standalone and co-located storage seeking interstate network access.
22 Jul 2022	RPO and Energy Storage Obligation trajectory to FY2029-30	Ministry of Power	Central policy/order	All qualifying ESS charged predominantly from RE	ESO: 1.0% in FY2023-24; 1.5% 2024-25; 2.0% 2025-26; 2.5% 2026-27; 3.0% 2027-28; 3.5% 2028-29; 4.0% 2029-30. At least 85% of annual energy stored must be from RE for ESO qualification.	No direct subsidy.	Obligation on relevant obligated entities; RE delivered through qualifying storage also counts towards RPO.	Creates a nationally signalled minimum storage-demand trajectory rather than relying only on voluntary utility procurement.

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22 Aug 2022	Battery Waste Management Rules, 2022	Ministry of Environment, Forest and Climate Change	Statutory rules under Environment (Protection) Act	All battery types; stationary BESS ordinarily falls within industrial-battery framework	Applies irrespective of chemistry, size, volume, weight and material composition except specified exclusions; introduces EPR, producer registration, collection, refurbishment/recycling and safe management obligations.	Compliance/EPR obligations rather than deployment subsidy.	Producers, consumers, recyclers/refurbishers and pollution-control authorities; centralised registration/reporting framework.	Brings lifecycle and circular-economy regulation into the BESS value chain; increasingly important as gigawatt-hour deployments age.
11 Oct 2022	Inclusion of ESS in Harmonised Master List of Infrastructure Sub-sectors	Department of Economic Affairs, Ministry of Finance	Notification / infrastructure classification	Grid-scale ESS	National ESS Framework records a qualifying threshold of 200 MWh for grid-scale ESS, provided the project is not established on a merchant basis.	Facilitates institutional credit/concessional finance; no direct grant.	Project financing through infrastructure-finance channels.	Lowered financing barriers for large contracted storage, while the 200 MWh/non-merchant conditions leave smaller and merchant storage outside that benefit.
11 Oct 2022 / 9 Mar 2023 launch	High Price Day Ahead Market framework and launch	Ministry of Power / power-market institutions	Market framework / market-product launch	BESS / high-cost flexible resources	BESS explicitly included among resources eligible to participate in HP-DAM; designed to monetise peak/off-peak price differentials.	Revenue through market price arbitrage rather than subsidy.	Participation through power exchanges subject to market rules.	Adds a merchant revenue stream for storage beyond long-term BESPA or ancillary services.
29 Dec 2022	Electricity (Amendment) Rules, 2022 — Rule on ESS	Ministry of Power	Statutory delegated legislation	All ESS	ESS formally considered part of power system; can be independent, network asset or complementary to G/T/D; status follows application; storage may be sold/leased/rented; independent ESS is delicensed at par with generation but requires CEA registration/capacity verification and compliance with safety requirements.	Unspecified.	Applies nationally under Electricity Rules.	The decade's most important legal-status reform: establishes a statutory basis for standalone and multi-service storage business models.
2022–23	Need for Advanced Chemistry Cell Energy Storage in India — NITI Aayog report series	NITI Aayog	Advisory / analytical reports	ACC batteries; EV and stationary applications	Technology, demand, localisation and supply-chain analysis; binding testing/interconnection limits: None.	Direct support: Unspecified.	Analytical support for ACC manufacturing and storage policy.	Deepened the policy evidence base for ACC demand and domestic manufacturing.
10 Apr 2023	Guidelines to Promote Development of Pumped Storage Projects	Ministry of Power	National policy guidelines	PSP / PSP	Transparent site-allotment criteria; self-identification of off-river sites; removal of upfront premium; mechanisms for ancillary-service monetisation; concessional government-land leasing where available; exemption from free-power obligation; rationalised environmental-clearance approach for off-river PSP; exhausted mines may be used.	Framework also records enabling-infrastructure support for hydro/PSP roads/bridges up to ₹1.5 crore/MW for projects ≤200 MW and ₹1 crore/MW above 200 MW under applicable central support arrangements.	Development led by states/developers with CEA/MoEF approvals.	Established PSP as the second core pillar of India's storage strategy alongside BESS and addressed long project-development cycles.
2023	National Electricity Plan 2023 — storage requirement assessment	Central Electricity Authority	Statutory/planning report	BESS + PSP	Projects storage requirement at 16.13 GW/82.32 GWh in 2026-27, 60.63 GW/336.4 GWh in 2029-30,	Framework estimates investment	Planning benchmark rather than procurement.	Provides the quantitative basis for subsequent storage obligations, VGF and tender scaling.

Date	Document / initiative	Central authority	status	Scope	Technical / grid / testing / safety provisions	Financial measures	Procurement / implementation	Impact / implication
					and 73.93 GW/411.4 GWh in 2031-32; 2031-32 split: 26.69 GW PSP and 47.24 GW BESS.	needs of ₹54,203 crore for PSP and ₹56,647 crore for BESS during 2022-27, with much larger BESS needs in 2027-32.		
9 Jun 2023	Guidelines for Tariff-Based Competitive Bidding for Procurement of Firm and Dispatchable Power from Grid-Connected RE Power Projects with ESS	Ministry of Power	Section 63 procurement guidelines	RE + BESS/ESS	Single-stage two-part e-bidding; commercially established technologies; GNA/ISTS connectivity responsibility on generator; metering at prescribed CTU/STU point; general completion period 24 months for ≤1,000 MW and 30 months above 1,000 MW; RE component including ESS charged from RE qualifies towards applicable renewable obligations; storage can count towards storage obligations where rules permit.	Tariff discovered by competition; EMD and financial qualification prescribed; direct subsidy Unspecified.	REIAs/procurers issue RfS, PPAs/PSAs; enables existing eligible spare capacity as provided in guidelines.	Moves procurement from "renewable plus optional storage" towards a defined product: firm and dispatchable clean electricity.
Jun 2023	CEA Guidelines for formulation/concurrence of DPRs for Pumped Storage Schemes	Central Electricity Authority	Technical/project-development guidelines	PSP / PSP	MoP Framework records DPR-preparation timelines reduced to about 840 days for Himalayan and 690 days for non-Himalayan projects depending on geology; CEA concurrence reduced to 50 days for TBCB/integrated-RE/captive PSP and 90 days for other PSPs.	Unspecified.	CEA DPR scrutiny/concurrence.	Targets one of PSP's biggest disadvantages versus batteries: permitting and development lead time.
28 Jun 2023	Guidelines for Resource Adequacy Planning Framework for India	Ministry of Power in consultation with CEA	National planning guidelines framed under Rule 16 of Electricity (Amendment) Rules, 2022	Generation, demand response and storage resources	Creates uniform forward resource-adequacy planning and procurement framework; storage can be considered as a capacity/flexibility resource in utility planning.	Direct ESS subsidy: Unspecified.	Requires advance resource planning by distribution utilities/appropriate institutions.	Gives storage a demand-side planning route in addition to RPO/ESO and project-specific tenders.
Aug 2023; MNRE publication 5 Sep 2023	National Framework for Promoting Energy Storage Systems	Ministry of Power	National policy framework	Technology-agnostic ESS: BESS, PSP and other technologies	Supports standalone, G/T/D, ancillary, leasing and merchant use; seeks technical standards for performance, safety and interoperability; calls for market redesign, financial incentives, R&D, pilots, recycling and technology-agnostic procurement.	Envisaged VGF up to 40% capital cost for initial BESS deployment, green finance and other fiscal support.	Consolidates existing measures and identifies future central/state regulatory action.	The umbrella policy document that connects legal status, ESO, ISTS waiver, procurement, PSP, markets, standards and finance into one ESS framework.
1 Oct 2023 effective	CERC Indian Electricity Grid Code Regulations, 2023	CERC	Statutory grid-code regulation	ESS and all interstate grid entities	Modern scheduling, reserves and system-operation architecture incorporates ESS within grid-operation arrangements; storage is recognised in reserve/system-response contexts and later CERC orders explicitly refer to ESS scheduling.	Market/settlement treatment under CERC framework;	NLDC/RLDC/SLDC, generators and ESS entities.	Moves storage from policy recognition into the operational rules of the interconnected national grid.

Date	Document / initiative	Central authority	status	Scope	Technical / grid / testing / safety provisions	Financial measures	Procurement / implementation	Impact / implication
						subsidy Unspecified.		
15 Mar 2024	Central Sector Scheme for VGF for development of 4,000 MWh BESS — Operational Guidelines	Ministry of Power	Sanction order / Central Sector Scheme / operational guidelines	Standalone BESS	4,000 MWh; commissioning within 24 months of BESPA; minimum eligible project 100 MWh; one developer ≤50% of a tranche and ≤1,000 MWh cumulative; 10–12-year BOO; system requirement initially assessed at 572 cycles/year; charging through contracted RE and market purchases; discharge through power exchanges, bilateral contracts and ancillary services.	Overall outlay ₹9,400 crore; central budget support ₹3,760 crore; VGF up to 40% of capital cost; 10/45/15/15/15% disbursement schedule across financial closure/COD/three operating years.	Multiple competitive tranches; BESS Implementing Agencies and BESS Nodal Agency; Battery Energy Storage Purchase Agreement; BESS Balancing Pool/payment-security mechanism.	Major transition from regulatory support to direct central capital de-risking and structured BESS capacity procurement.
11 Oct 2024	Operational Guidelines for State Component under the BESS VGF Scheme	Ministry of Power	Operational guidelines	BESS	State-component implementation under the wider VGF architecture; additional technical detail in the present source extraction: Unspecified.	Linked to parent VGF scheme; component-specific amount here: Unspecified.	Provides a route for state-level deployment within a centrally designed/funded framework.	Broadens implementation beyond centrally pooled procurement and enables geographically distributed BESS procurement.
18 Feb 2025	Advisory on co-locating ESS with Solar Power Projects to enhance grid stability and cost efficiency	CEA, Ministry of Power	Advisory, not statutory mandate	Solar + ESS/BESS; rooftop storage also contemplated	REIAs/state utilities advised to include minimum two-hour co-located ESS equal to 10% of installed solar project capacity in future solar tenders; tender should address availability in non-solar hours; DISCOMs may consider two-hour storage with rooftop solar; allows single-cycle solar charging or double-cycle solar + grid charging.	No direct subsidy in advisory.	Future solar tenders by REIAs/state utilities; rooftop implementation may be considered by DISCOMs.	Mainstreams storage into solar procurement; CEA estimates clause could yield around 14 GW/28 GWh by 2030.
9 Jun 2025	VGF Scheme for development of BESS supported through PSDF	Ministry of Power	Scheme / operational guidelines	BESS	Target 30 GWh; preferably two-hour discharge; around 1.5 cycles/day preferred but procurer may vary duration/cycles; commissioning 18 months from BESPA/PPA; may connect to InSTS or ISTS; contracts preferably 12–15 years, BOO/BOOT.	₹18 lakh/MWh VGF, total ₹5,400 crore, fully supported through PSDF.	25 GWh allocated to 15 states; 5 GWh to NTPC; Section 63 TBCB for states/REIAs; CEA monitoring; NTPC may use applicable Section 62 route.	A step-change in deployment scale and explicit use of storage to meet evening/non-solar demand while using existing generation/transmission infrastructure more efficiently.
10 Jun 2025	Waiver of Inter-State Transmission Charges for ESS	Ministry of Power	Order	Co-located BESS + Hydro PSP	100% ISTS waiver for Hydro PSP whose construction work is awarded on/before 30 Jun 2028; 100% waiver for qualifying co-located BESS commissioned on/before 30 Jun 2028, where output is consumed outside host state; co-location means BESS and RE connect at same ISTS substation; no waiver under these provisions after cutoff; non-co-	100% transmission-charge relief for eligible assets; no capital grant.	Implemented through ISTS billing/CERC framework and qualifying project commissioning/award dates.	Extends the investment window and improves economics for interstate co-located storage and long-duration PSP.

Date	Document / initiative	Central authority	status	Scope	Technical / grid / testing / safety provisions	Financial measures	Procurement / implementation	Impact / implication
					located BESS follows extant orders/CERC regulations.			
4 Aug 2025	Amendment to Operational Guidelines for the 30 GWh PSDF-backed VGF Scheme	Ministry of Power	Amendment	BESS	Responsibility for land/grid connectivity to be specified in the RfS; BESS Energy Management System application software must be developed indigenously within India; BESS must meet requisite quality and refurbished battery cells may not be used.	Parent VGF unchanged in the amendment.	Requirements flow into eligible-entity/REIA RfS and project procurement.	Adds localisation, software sovereignty and explicit cell-quality controls to central BESS subsidy conditions.
22 Sep 2025	Further amendment to PSDF-backed BESS VGF Guidelines	Ministry of Power	Amendment	BESS	Developer must achieve financial closure within six months of BESPA signing; eligible entities/REIAs must obtain BG or Insurance Surety Bond equal to VGF prior to release under prescribed conditions.	VGF level unchanged; modifies security requirements.	BG/ISB protects recoverability of public VGF; staged release remains project-performance linked.	Strengthens execution discipline and addresses project-delay / grant-recovery risk.
Feb–Mar 2026	ACC PLI implementation status	Ministry of Heavy Industries / PIB	Implementation progress update	ACC batteries	As at official reporting, 40 GWh of the programme's target had been awarded to four beneficiary firms; 1 GWh beneficiary capacity installed by end-2025.	Cumulative reported investment about ₹3,237 crore; as of the cited 2026 update no beneficiary had yet claimed incentive.	Programme implementation by selected ACC manufacturers.	Shows that domestic cell-manufacturing build-out lagged the original headline 50 GWh ambition and helps explain the subsequent dedicated stationary-storage tranche.
16 Jun 2026	Draft CERC GNA Fourth Amendment — Explanatory Memorandum	CERC	Draft regulation / consultation; not final law in source reviewed	ISTS connectivity including ESS	CERC states that the draft responds to evolving connectivity/GNA issues; the consultation includes ESS-specific treatment within the revised connectivity framework. Technology/capacity limit applicable specifically to ESS in the source extract: Unspecified.	Direct subsidy: None.	Stakeholder consultation; final legal effect depends on notification of final amendment.	Indicates that storage connectivity is becoming sufficiently material to require more explicit treatment inside the GNA regime rather than relying only on generic generation provisions.

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Chapter 10.

Recycling and Reuse of EV Batteries: Estimation of Second-Life Battery Availability in India



The rapid growth of electric vehicles (EVs) is transforming the transportation sector and creating new opportunities and challenges for battery management. In India, the increasing adoption of electric two-wheelers, three-wheelers, passenger vehicles, and commercial vehicles is expected to generate a substantial demand for lithium-ion batteries. As these vehicles accumulate mileage and their batteries degrade, an increasing number of batteries will eventually reach the end of their first-life service in transportation. However, retirement from EV use does not necessarily imply that a battery has exhausted its entire energy-storage potential. Batteries that no longer meet the performance requirements of automotive applications may retain sufficient capacity for less demanding stationary energy-storage applications, creating an opportunity for second-life utilisation[288,289]. The potential for second-life battery utilisation depends on the quantity, condition, and timing of batteries becoming available. In the Indian context, the future scale of second-life battery resources will be closely linked to EV adoption trends, vehicle-category composition, battery capacities, and battery survival characteristics. Consequently, estimating second-life battery availability requires more than projecting EV sales or registrations. It also requires an assessment of the evolution of the EV fleet, the associated battery capacity, and the rate at which batteries reach the end of their first-life service. Survival-based modelling can support this assessment by estimating annual battery retirement and the resulting flow of batteries potentially entering the second-life market.

The suitability of retired EV batteries for subsequent applications is determined by their remaining state of health (SoH), usable capacity, degradation characteristics, and expected remaining useful life. Although a battery may no longer satisfy the performance requirements of its original automotive application, its residual performance may still support alternative applications with different power, energy, and cycling requirements. Gu et al. highlight the importance of degradation modelling, battery screening, safety assessment, and economic evaluation in determining the viability of second-life batteries. Similarly, Roslan et al. review the potential applications, degradation mechanisms, and capacity-estimation approaches associated with second-life battery energy-storage systems. These findings indicate that treating all retired batteries as a uniform resource can overestimate their usable capacity and overlook differences in their suitability for alternative applications.

Battery degradation continues during second-life operation, and its progression depends on operating conditions and application-specific duty cycles. Cycling frequency, depth of discharge, operating temperature, and calendar ageing can influence the remaining capacity and useful life of a battery. Furthermore, applications differ in their requirements for energy capacity, power capability, cycling frequency, and service reliability. A battery that becomes unsuitable for one application may remain useful for another with less demanding requirements. This creates the possibility of cascading battery utilisation, in which batteries transition between applications as their health and performance decline. Quantifying this process requires tracking both the evolution of battery condition and the remaining usable capacity throughout successive stages of second-life operation. State-of-health estimation is central to this characterisation. Srinivasan et al.[290] identify challenges associated with estimating the SoH of second-life lithium-ion batteries, including incomplete battery operating histories, variations in degradation, differences in battery chemistry, and the charging protocols applied during first-life operation. Such uncertainties influence the assessment of battery quality and the estimation of remaining useful life. Accordingly, a systematic assessment of second-life batteries should consider not only the aggregate energy capacity available but also its distribution across SoH ranges and the suitability of batteries for different applications.

Against this background, this chapter develops a data-driven framework to characterise the growth and future availability of second-life EV batteries in India. The analysis begins with historical EV adoption and projections by vehicle category, followed by estimation of the associated battery capacity and first-life retirement. A Weibull survival model is employed to estimate battery retirement patterns and the annual capacity potentially entering second-life use. The analysis subsequently models second-life battery degradation, estimates the distribution of SoH over time, and quantifies the capacity available across different SoH ranges. Finally, batteries are assessed in terms of

[288] X. Gu, H. Bai, X. Cui, J. Zhu, W. Zhuang, Z. Li, X. Hu, and Z. Song, "Challenges and opportunities for second-life batteries: Key technologies and economy," Renewable and Sustainable Energy Reviews, vol. 192, Art. no. 114191, Mar. 2024.

[289] M. F. Roslan, P. R. Satpathy, T. Prasankumar, V. K. Ramachandaramurthy, M. Mansor, and S. L. Walker, "Second-life battery energy storage system for energy sustainability: Recent advancements, key takeaways and future perspectives," Journal of Energy Storage, vol. 123, Art. no. 116808, Jul. 2025.

[290] S. Vignesh, H. S. Che, J. Selvaraj, K. S. Tey, J. W. Lee, H. Shareef, and R. Errouissi, "State of Health (SoH) estimation methods for second life lithium-ion battery—Review and challenges," Applied Energy, vol. 369, Art. no. 123542, Sep. 2024.

application-wise suitability, degradation, remaining useful life, and annual capacity availability. The principal objective is to establish a quantitative relationship between EV growth in India and the future supply of usable second-life battery capacity. The expected outputs include annual retired battery inflows, available capacity by SoH range, battery-quality distributions, estimates of remaining useful life, and application-wise capacity projections. By distinguishing newly retired capacity from the remaining stock of batteries undergoing second-life use, the framework aims to provide a consistent basis for assessing the scale, quality, and temporal evolution of India's potential second-life battery resource.

10.1. Methodology

The analysis begins with vehicle-registration data obtained from the VAHAN portal, which is used to characterise the growth of electric mobility in India. The data are organised by vehicle category and year to establish historical adoption trends. Following data processing and consistency checks, these trends provide the basis for projecting the future EV fleet. The vehicle categories considered in the analysis are linked to representative battery-pack capacities to estimate the total battery capacity associated with the EV fleet. The next stage estimates the annual retirement of EV batteries. A Weibull survival model is used to represent the distribution of battery service life and estimate the proportion of batteries reaching the retirement threshold in each year. The resulting annual retirement estimates provide the potential inflow of batteries into the second-life stage. This approach distinguishes the annual retirement flow from the cumulative quantity of batteries retired over the study period. The retired battery inflow is then characterised according to its initial SoH and subsequent degradation during second-life operation. Application-specific degradation assumptions are used to estimate the evolution of battery health, remaining usable capacity, and remaining useful life. Batteries are classified into different SoH ranges to quantify the distribution of battery quality and the capacity available at different stages of degradation.

Finally, the estimated second-life battery resource is allocated across the selected applications. Where cascading utilisation is considered, batteries are tracked as they transition between applications, carrying forward their remaining capacity rather than being counted as new battery inflows. The resulting outputs quantify annual application-wise capacity availability and its evolution over the projection period. Together, these steps establish a consistent framework for assessing the scale, quality, and potential utilisation of second-life EV batteries in India.

10.1.1 Data Source and Collection: VAHAN Dashboard

The vehicle registration data obtained from the VAHAN dashboard of the Ministry of Road Transport and Highways (MoRTH), Government of India, are used to analyse the historical growth of electric vehicles (EVs) in India. The analysis considers both the absolute number of EV registrations and the share of EVs in total vehicle registrations. These indicators provide complementary perspectives on the evolution of the Indian EV market and establish the basis for estimating the future availability of retired EV batteries for second-life applications. The VAHAN dashboard classifies registered vehicles according to fuel type and vehicle class. Table 70 summarises the fuel-type classifications available in the dataset, while Table 71 presents the vehicle-class abbreviations and their corresponding descriptions. These classifications are used to identify the relevant EV registrations and organise the data by vehicle category. In particular, the fuel-type classification helps distinguish electric vehicles from conventional internal-combustion vehicles and hybrid technologies, while the vehicle-class classification supports the grouping of registrations into relevant segments for battery-capacity estimation.

Table 70: Fuel-type classifications available in the VAHAN dataset

Fuel type	Fuel type	Fuel type
Bio-CNG/Bio-Gas	CNG Only	Di-Methyl Ether
Diesel	Diesel/Hybrid	Dual Diesel/Bio-CNG
Dual Diesel/CNG	Dual Diesel/LNG	Electric (BOV)

Ethanol (E100)	Flex-Fuel (Bio-Diesel)	Flex-Fuel (Ethanol)
Fuel Cell Hydrogen	HCNG	Hydrogen (ICE)
LNG	LPG Only	Methanol
Not Applicable	Petrol	Petrol (E20)
Petrol (E20)/CNG	Petrol (E20)/Hybrid	Petrol (E20)/Hybrid/CNG
Petrol (E20)/Hybrid/CNG — as separately listed in the source	Petrol (E20)/LPG	Petrol/CNG
Petrol/Hybrid	Petrol/Hybrid/CNG	Petrol/LPG
Petrol/Methanol	Plug-in Hybrid EV	Pure EV
Solar	Strong Hybrid EV	-

Note: The table reproduces the fuel-type labels visible in the supplied presentation. For the analysis, the specific electric-vehicle categories included in the dataset should be explicitly identified to avoid inadvertently including hybrid or other non-fully electric vehicles.

Table 71 Vehicle-class abbreviations used in the VAHAN dataset

Abbreviation	Vehicle class	Abbreviation	Vehicle class
2WIC	Two-Wheeler (Invalid Carriage)	HPV	Heavy Passenger Vehicle
2WN	Two-Wheeler (Non-Transport)	LGV	Light Goods Vehicle
2WT	Two-Wheeler (Transport)	LMV	Light Motor Vehicle
3WIC	Three-Wheeler (Invalid Carriage)	LPV	Light Passenger Vehicle
3WN	Three-Wheeler (Non-Transport)	MGV	Medium Goods Vehicle
3WT	Three-Wheeler (Transport)	MMV	Medium Motor Vehicle
4WIC	Four-Wheeler (Invalid Carriage)	MPV	Medium Passenger Vehicle
HGV	Heavy Goods Vehicle	OTH	Others
HMV	Heavy Motor Vehicle	—	—

10.1.2 Historical EV Registration Trends

The historical trend in monthly EV registrations is shown in Figure 63. Registrations remained relatively low during the earlier years, followed by a marked acceleration from around 2021. The more recent observations indicate substantially higher monthly registration volumes, although month-to-month fluctuations remain visible. This growth provides the historical basis for estimating the future EV fleet and the battery capacity associated with each vehicle category.

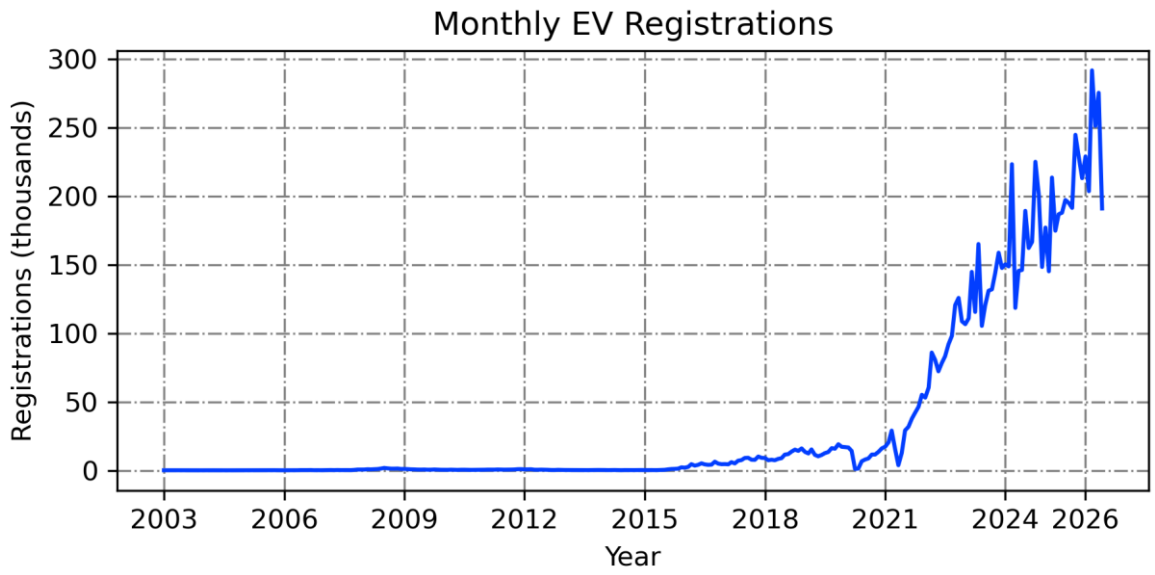


Figure 63: Monthly EV registrations in India based on VAHAN dashboard data.

Figure 64 presents the EV share of total vehicle registrations. The share increased considerably after 2021, reaching approximately 10–12% in some of the latest observations shown. This relative measure complements the absolute registration trend by illustrating the increasing contribution of EVs to the overall vehicle market.

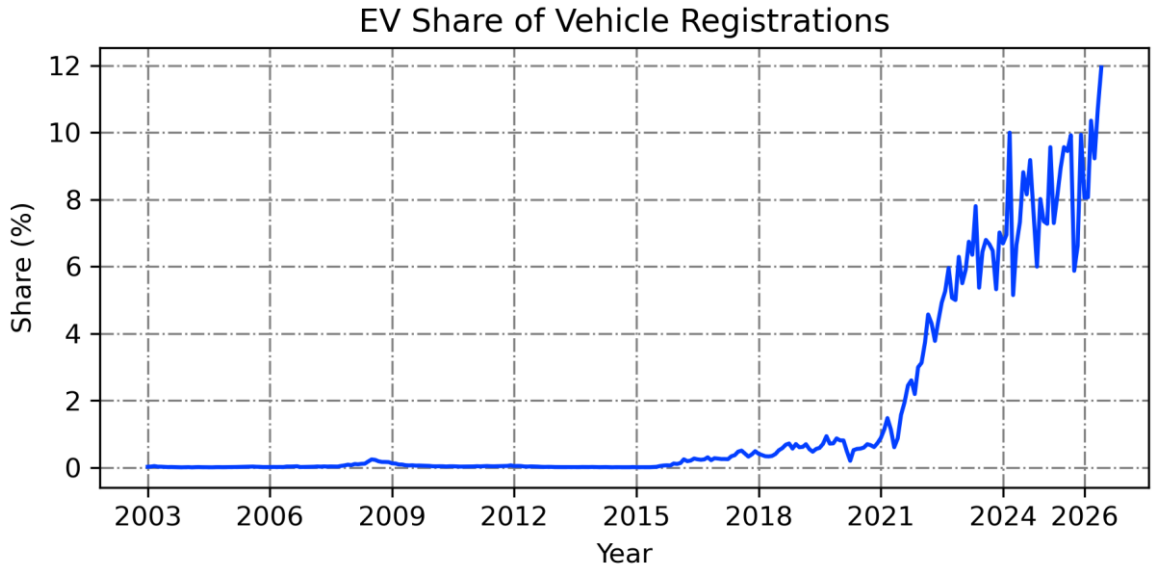


Figure 64 EV share of total vehicle registrations in India based on VAHAN dashboard data.

Following the analysis of overall EV registration trends in Figures 1 and 2, the next step is to examine the composition of registered vehicles and the evolution of fuel-market shares. These two aspects are important for estimating future

battery availability because the contribution of each vehicle category to the EV fleet, together with the growth of electric powertrains, determines the battery capacity potentially entering the second-life market. Figure 65 presents the composition of vehicle registrations across the vehicle classes identified in Table 71. The stacked area plot shows that the increase in registrations after 2021 is accompanied by a substantial expansion in the overall registration volume. The composition also indicates that vehicle categories contribute differently to total registrations. In particular, the 2WN category represents a substantial portion of the displayed registration volume, while other categories, including three-wheelers and light motor vehicles, contribute additional registrations. This variation highlights the need to retain vehicle-category distinctions rather than estimate battery availability using a single representative vehicle type.

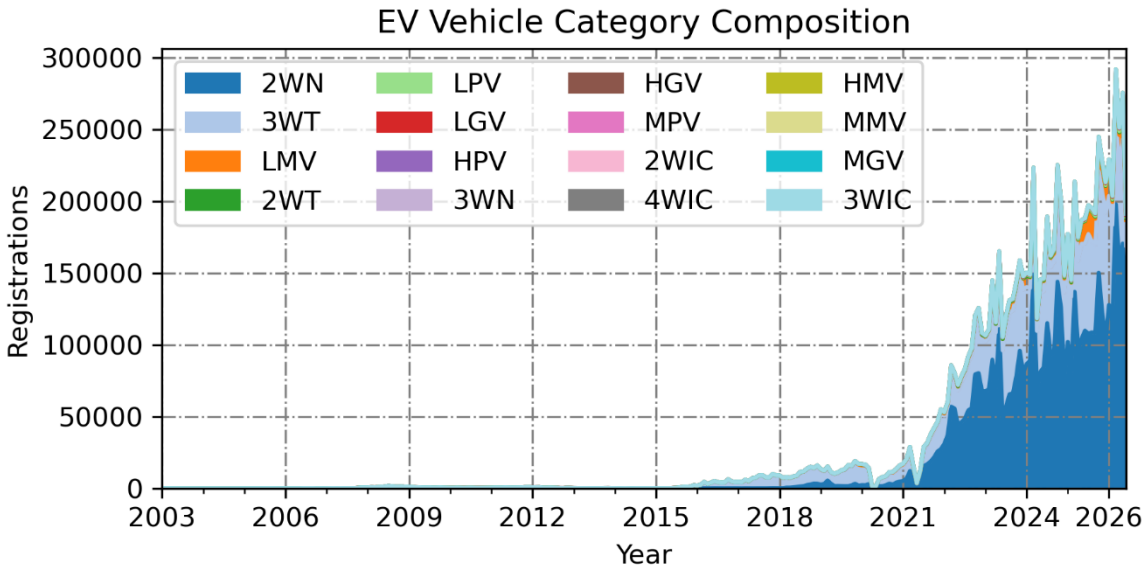


Figure 65 Composition of vehicle registrations across vehicle categories in India.

For the second-life battery analysis, the vehicle-category composition provides the basis for assigning category-specific battery-pack capacities. The estimated battery capacity associated with each category can then be combined with its registration history to estimate the total battery capacity entering the EV fleet. This is important because many registrations do not necessarily correspond to an equally large battery-energy capacity: the battery-pack size varies across vehicle categories.

Figure 66 shows the evolution of market shares for selected fuel types, including petrol, diesel, CNG, Pure EV, and Electric (BOV). Petrol and diesel account for the majority of the plotted fuel-market share over much of the historical period, while the share of electric categories increases in the more recent years. The rise in Pure EV and Electric (BOV) registrations is particularly relevant to the present study because these categories contribute to the population of vehicles whose batteries may eventually become available for second-life use.

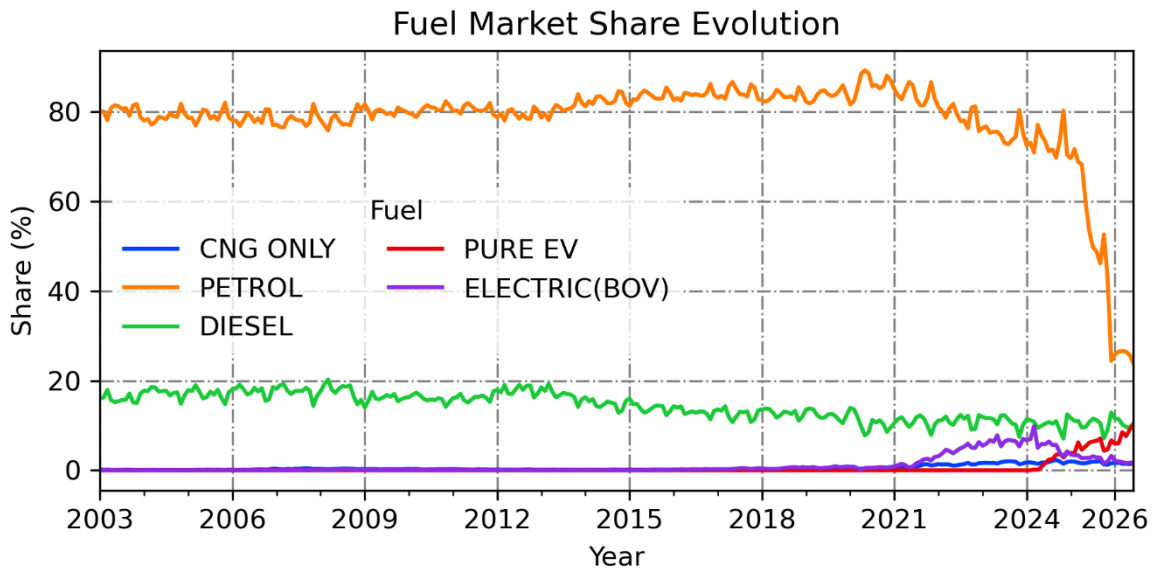


Figure 66 Historical evolution of fuel-type shares in vehicle registrations in India.

The fuel-market share trends also reinforce the importance of applying consistent vehicle-selection criteria. The categories labelled Pure EV and Electric (BOV) are shown separately in Figure 66; therefore, their treatment in the analysis should follow the fuel-type definitions used in the underlying VAHAN data. Hybrid and plug-in hybrid categories should likewise be included or excluded according to the study's stated scope, rather than being combined automatically with fully electric vehicles. Together, Figure 65 and Figure 64 provide the basis for the next modelling stage. The vehicle-category composition is used to estimate battery capacity by vehicle segment, while the fuel-market trends help characterise the changing contribution of electric vehicles to the registration dataset. These estimates are subsequently combined with assumptions about battery service life and a Weibull survival model to calculate annual battery retirement inflows. This step connects the historical growth of India's EV fleet to the quantity of battery capacity potentially available for second-life applications.

10.2. Estimation of EV Battery Capacity and First-Life Retirement

10.2.1 Battery-Pack Capacity Assumptions and Historical Deployment

This section establishes the quantity of EV battery capacity deployed in India and provides the basis for estimating the battery inflow available for second-life applications. The vehicle-category-specific battery capacities are combined with the historical EV registration data to estimate annual battery capacity additions and cumulative deployed capacity. These estimates are subsequently used in the battery-retirement model.

Table 72 Assumed battery-pack capacity for different electric vehicle classes

Vehicle class	Vehicle type	Assumed battery capacity (kWh)
2WIC	Two-wheeler (invalid carriage)	2
2WN	Two-wheeler (non-transport)	3
2WT	Two-wheeler (transport)	5
3WIC	Three-wheeler (invalid carriage)	5
3WN	Three-wheeler (non-transport)	7

Vehicle class	Vehicle type	Assumed battery capacity (kWh)
3WT	Three-wheeler (transport)	10
4WIC	Four-wheeler (invalid carriage)	20
LGV	Light goods vehicle	80
LMV	Light motor vehicle	35
LPV	Light passenger vehicle	50
MMV	Medium motor vehicle	100
MGV	Medium goods vehicle	120
HGV	Heavy goods vehicle	220
HMV	Heavy motor vehicle	250
HPV	Heavy passenger vehicle	300

Note: These are assumed representative battery-pack capacities used for the analysis, not measured capacities for individual registered vehicles.

The estimated EV fleet and associated battery deployment are analysed using the vehicle-registration data and the representative battery-pack capacities specified in Table 72. Figure 67 to Figure 70 present complementary indicators of EV growth and battery deployment, providing the basis for estimating the future flow of retired batteries into second-life applications. Figure 67 illustrates the cumulative EV battery energy deployed in India. The estimated cumulative capacity increases gradually during the earlier years, followed by a marked acceleration after 2021. By the latest observation shown, the cumulative deployed battery energy reaches approximately 80 GWh. This increase reflects the growing number of registered EVs, and the associated battery capacity estimated using the vehicle-category-specific assumptions. The cumulative series represents the total estimated battery capacity associated with vehicle additions over the study period; it should not be interpreted as the remaining operational battery stock because battery retirements are not deducted at this stage.

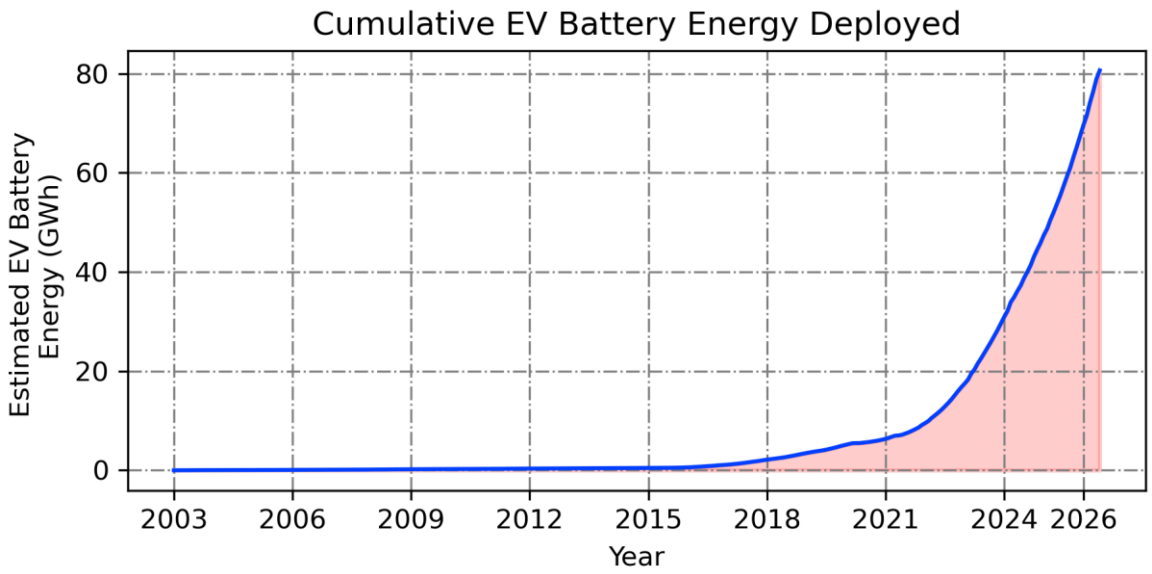


Figure 67 Cumulative EV battery energy deployed in India.

Figure 68 presents the annual EV battery capacity added to the fleet. Annual additions remain relatively small during the earlier years but increase substantially from 2021 onward. The figure indicates that annual additions reach approximately 22 GWh around 2025, followed by a lower value in the latest observation. This variation highlights the importance of distinguishing annual battery deployment from cumulative deployment. In particular, the latest annual value may be affected by incomplete-year registration data and should be interpreted accordingly.

Figure 69 presents the historical trend in estimated annual battery-capacity additions, expressed in megawatt-hours (MWh). The series shows a substantial increase in annual battery deployment after 2021, accompanied by considerable fluctuations in recent years. These fluctuations may reflect changes in registration volumes, vehicle-category composition, and the corresponding battery-capacity assumptions. The MWh representation provides a more detailed view of annual changes in battery deployment, while Figure 6 presents the same general measure in GWh.

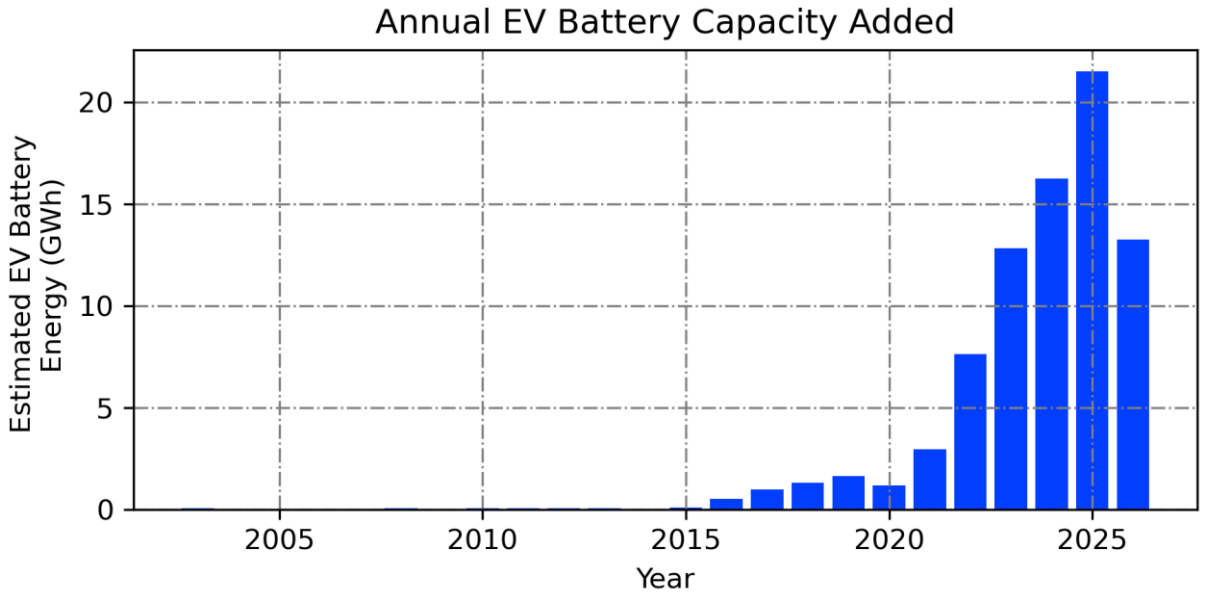


Figure 68 Historical trend in estimated EV battery capacity additions.

To further characterise the battery deployment profile, the estimated battery energy is disaggregated by vehicle class using the representative battery-pack capacities listed in Table 3. Figure 9 presents the annual battery capacity associated with different vehicle classes, while Figure 10 shows the contribution of each class as a percentage of the

total annual battery capacity added. As shown in Figure 69, the estimated battery capacity additions increase substantially in recent years, with the contributions of individual vehicle classes becoming more pronounced as EV adoption expands. The results indicate that battery deployment is not distributed uniformly across vehicle classes. Differences in registration volumes and assumed battery-pack capacities influence the contribution of each class to the total battery energy. Consequently, vehicle classes with relatively small battery packs may contribute substantially through high registration volumes, whereas classes with larger battery packs can contribute significant energy capacity even at lower registration volumes.

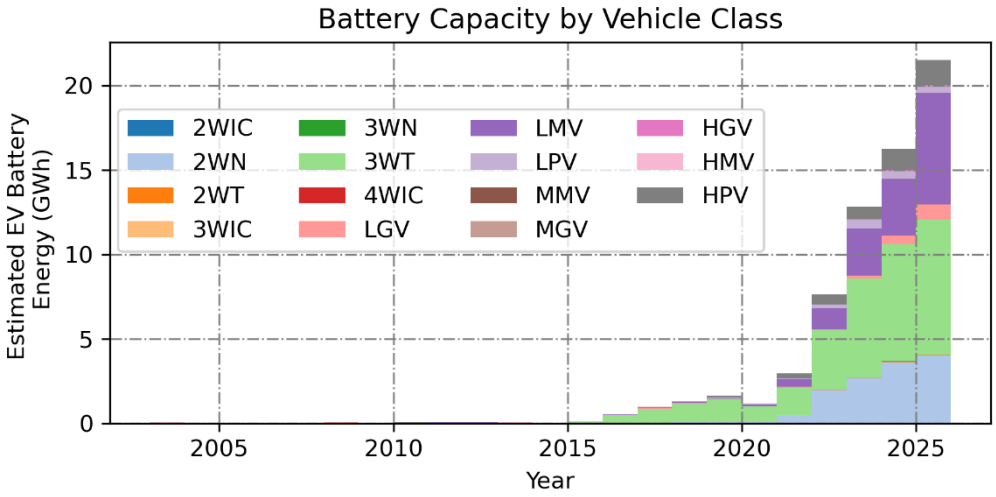


Figure 69 Estimated annual EV battery capacity by vehicle class in India.

Figure 70 illustrates the changing composition of annual battery-capacity additions. The relative contributions of vehicle classes vary over the study period, indicating that the battery-energy mix associated with EV adoption changes as the composition of registrations evolves. This distinction is important because the future second-life battery resource depends not only on the total number of EVs but also on the vehicle classes in which the batteries were originally deployed. Different vehicle classes may have substantially different battery capacities and service-life characteristics, affecting the magnitude and timing of their eventual retirement.

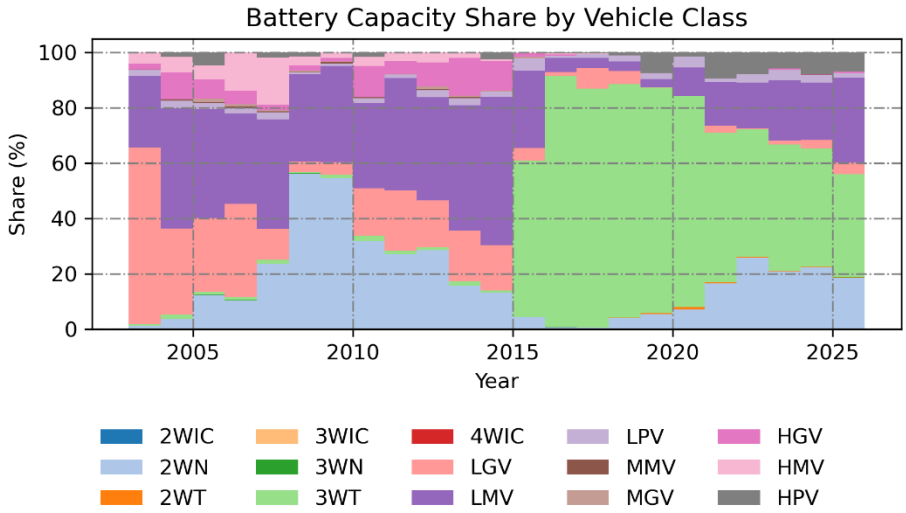


Figure 70 Share of annual EV battery capacity additions by vehicle class in India.

The class-wise battery-capacity estimates therefore provide a more detailed input to the retirement analysis than aggregate EV registrations alone. For each vehicle class, the annual battery capacity associated with new registrations can be treated as a separate cohort of batteries entering first-life service. Applying the survival model to these cohorts allows retirement to be estimated while retaining the differences in battery energy associated with each vehicle class.

The resulting annual retired capacity can then be aggregated across classes to quantify the potential inflow of batteries into second-life use.

10.3. Projection of EV Growth in India Using Policy-Informed Adoption Targets

10.3.1 Policy-Informed Adoption Targets

The historical registration trends and vehicle-category-specific battery capacities establish the baseline for estimating future EV battery deployment. To extend the analysis beyond the historical data, future EV registrations are projected using vehicle-class-specific adoption targets. This step is essential because the quantity of batteries potentially available for second-life applications depends on both the future scale of EV adoption and the distribution of registrations across vehicle categories. India's EV transition is supported by national policy initiatives and adoption scenarios published by NITI Aayog. The NITI Aayog and RMI analysis discusses differentiated EV adoption prospects across vehicle segments, while subsequent NITI Aayog studies examine projected EV penetration under different market and technology scenarios[291]. These studies demonstrate the importance of accounting for differences between two-wheelers, three-wheelers, passenger vehicles, and commercial vehicles when projecting future EV deployment.

In the present analysis, the adoption percentages shown in Table 73 are used as vehicle-class-specific modelling targets. These targets are applied to project the future EV registration trajectory for each class, rather than assuming a uniform adoption rate across all vehicle categories. The targets vary from 60% to 100%, reflecting the assumptions adopted for the different classes in this study. These percentages should be described as the study's policy-informed modelling assumptions, not as uniform, legally mandated national targets for every vehicle class. The distinction is important because published Indian policy and scenario documents use different definitions of EV penetration, including shares of new sales and shares of the total vehicle stock.

Table 73 Assumed EV adoption targets by vehicle class.

Vehicle class	Assumed adoption target (%)
3WIC	100
3WN	100
2WN	95
2WIC	95
3WT	95
HPV	95
2WT	90
4WIC	90
LMV	90
LPV	90
LGV	80
MMV	70
MGV	70
HGV	60
HMV	60

[291] NITI Aayog, Electric Vehicles in India: Unlocking a $200 Billion Opportunity. Government of India, Aug. 2025

The adoption targets are assigned to the vehicle classes identified in Table 71. The assumed targets are 95–100% for selected two-wheeler and three-wheeler classes, 90–95% for several light-vehicle classes, and 60–80% for selected goods and medium/heavy vehicle classes. These values provide the class-specific assumptions for the projection framework.

10.3.2 Forecast of EV Registrations and Battery Additions

The historical registration data are used to establish the baseline trajectory for each vehicle class. The assumed adoption targets are then incorporated into the projection to estimate future annual EV registrations. Figure 71 presents the resulting historical and forecast registration trajectories, with the dashed vertical line indicating the transition between the historical-data period and the forecast period. The projected registrations show an increasing EV fleet, with growth becoming more pronounced over the forecast horizon. The class-wise projections preserve differences in the assumed adoption targets and historical registration patterns. This approach provides a more suitable basis for estimating battery deployment than applying a single growth rate to the entire EV market.

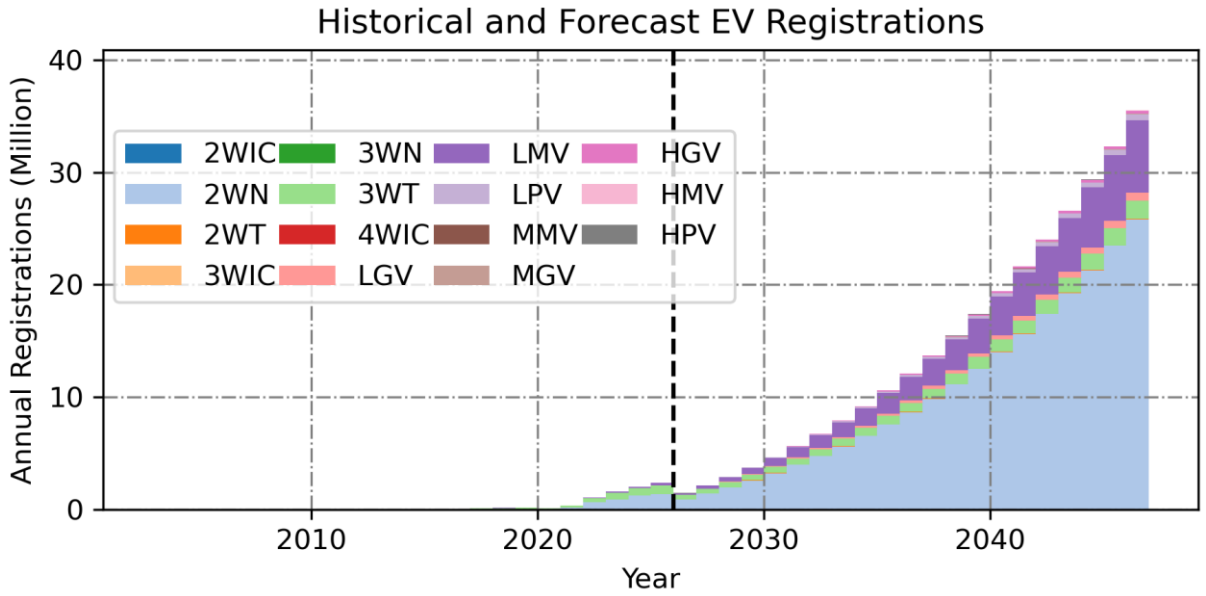


Figure 71 Historical and forecast EV registrations by vehicle class in India.

10.4. First-Life Battery Survival and Retirement Modelling

Following the projection of EV registrations and annual battery capacity additions, the next step is to estimate when batteries leave their first-life vehicle applications and become potential candidates for second-life use. In this study, retirement is modelled using a State of Health (SoH) threshold of 80%, rather than explicitly modelling the continuous degradation trajectory of each battery. The 80% SoH threshold is used as an operational criterion to distinguish batteries that remain in their first-life application from those that may be considered for repurposing. Crossing this threshold does not necessarily mean that a battery is unusable; it indicates that the battery may no longer meet the performance requirements of its original vehicle application while potentially retaining value for less demanding stationary storage applications. Actual suitability for second-life use would also depend on factors such as safety, power capability, and remaining useful life.

10.4.1 Weibull-Based Survival Modelling

A Weibull survival function is used to represent the probability that an EV battery remains above the specified SoH threshold after a given number of years in service. The vehicle classes are grouped according to their assumed characteristic service lives, as shown in Figure 72. The parameter η represents the characteristic life associated with

each group, while the survival function captures the declining probability of a battery remaining above 80% SoH as its service age increases. The survival probability is expressed as

$$S_c(t) = \exp\left[-\left(\frac{t}{\eta_c}\right)^{\beta}\right]$$

where $S_c(t)$ is the probability that a battery in vehicle class c remains above the 80% SoH threshold after t years, η_c is the characteristic life parameter, and β is the Weibull shape parameter. The probability of crossing the threshold during a given service-year interval can be estimated from the reduction in survival probability:

$$p_c(t) = S_c(t-1) - S_c(t).$$

This formulation enables the projected EV battery cohorts to be translated into annual estimates of batteries reaching the end of their first-life service under the selected SoH criterion.

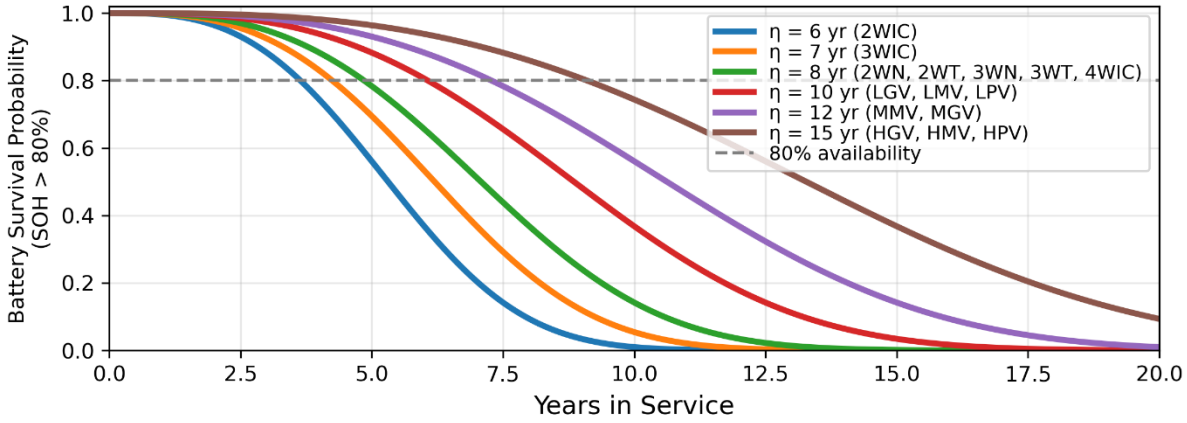


Figure 72 Weibull survival probability of EV batteries remaining above the 80% SoH threshold for different vehicle classes.

10.4.2 Annual Battery Additions and Retirements

The characteristic life values adopted in the model are 6 years for 2WIC, 7 years for 3WIC, 8 years for 2WN, 2WT, 3WN, 3WT and 4WIC, 10 years for LGV, LMV and LPV, 12 years for MMV and MGV, and 15 years for HGV, HMV and HPV. These values are modelling assumptions used to differentiate the service-life distributions across vehicle classes. The Weibull survival model is combined with the projected EV registrations and the assumed battery-pack capacities for each vehicle class to estimate annual battery additions and retirements over the study horizon. Annual battery additions represent the battery capacity associated with newly registered EVs, whereas annual retirements represent the capacity associated with battery cohorts reaching the specified retirement criterion of SoH ≤ 80%.

Figure 13 illustrates the projected annual battery additions and retirements from 2003 to 2047. Battery additions increase substantially as EV adoption accelerates, particularly after 2030. Annual retirements also increase over time as larger EV cohorts reach the end of their first-life service. The gap between additions and retirements reflects the continuing expansion of the EV fleet and the delayed retirement of batteries installed in earlier years.

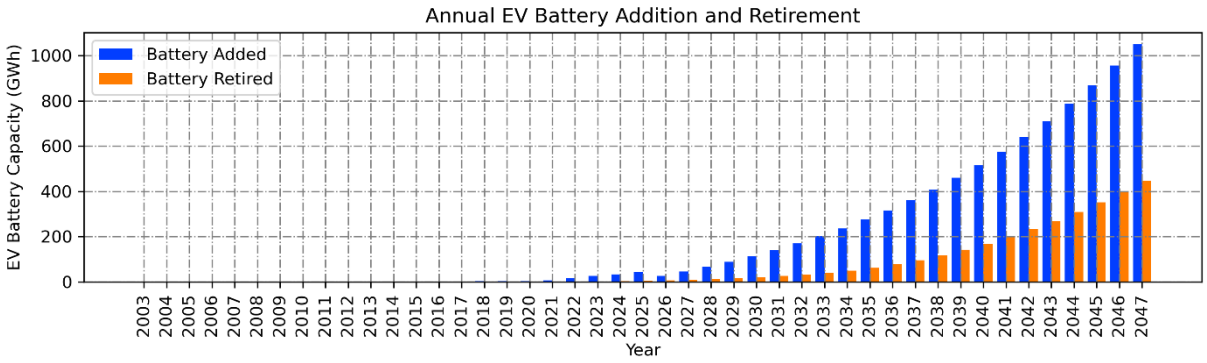


Figure 73 Annual EV battery capacity additions and retirements based on projected EV registrations and Weibull survival modelling.

Figure 73 and Figure 74 presents the annual and cumulative retirement results. The annual retirement trajectory indicates a growing flow of batteries reaching the 80% SoH threshold, while cumulative retired capacity increases sharply towards the end of the projection period. This trend suggests that the expansion of EV adoption will progressively create a substantial pool of batteries that could be assessed for second-life applications.

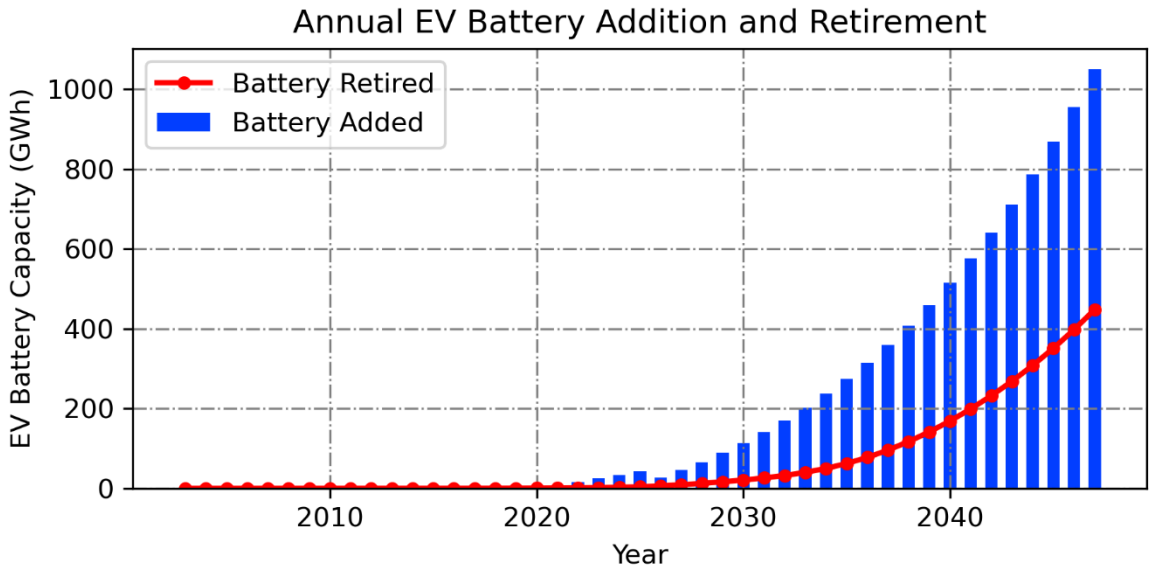


Figure 74 Annual EV battery additions and retirements

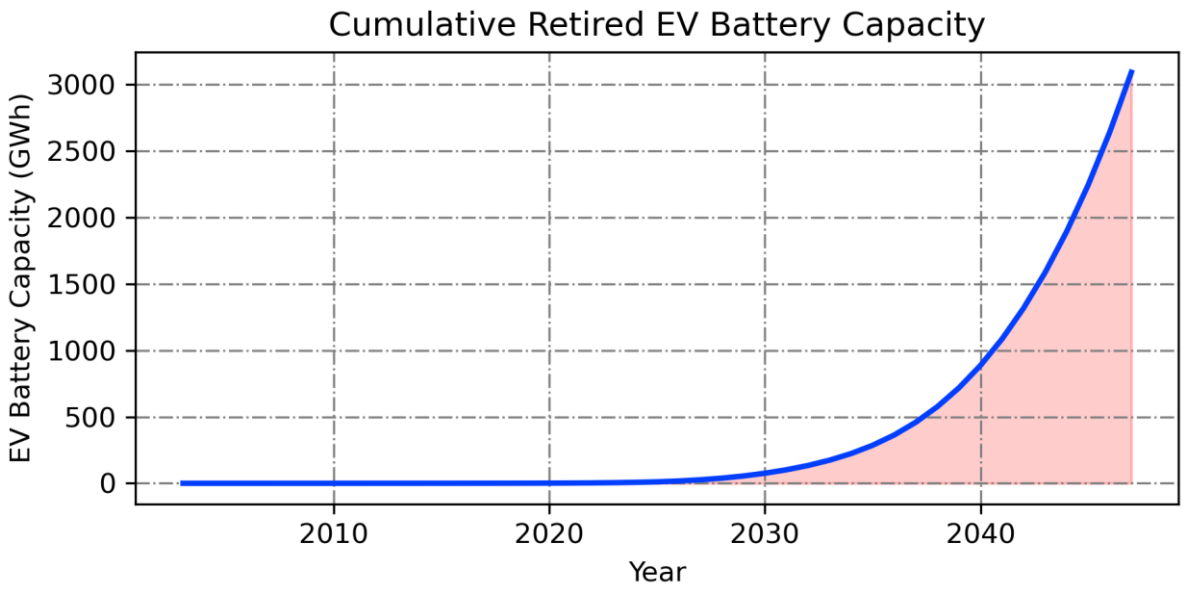


Figure 75 Cumulative retired EV battery capacity

The estimated retired capacity provides the basis for the subsequent second-life battery assessment. However, retired capacity should not be interpreted as fully usable second-life capacity. The estimates indicate the battery capacity reaching the modelled SoH threshold; further assessment is required to determine the fraction that is technically suitable for reuse, its remaining useful life, and the capacity available for specific second-life applications.

10.5. Second-Life Battery Utilisation: Usable Capacity, Service Life, and Application Value

The estimated retired EV battery capacity provides the potential resource for second-life energy storage. However, the total retired capacity cannot be directly treated as usable grid-storage capacity because batteries continue to lose capacity during second-life operation, and their useful service life depends on the operating requirements of the selected application. This section evaluates how much retired battery capacity can be utilised, how long it can remain in service, and how its deployment across different applications can create value. The analysis considers six second-life applications: frequency regulation, peak shaving, renewable firming, backup power, residential energy storage systems (ESS), and miscellaneous applications. These applications have different cycling requirements and operating profiles, represented by their assumed annual equivalent full cycles (EFCs). The analysis also considers calendar ageing, the initial State of Health (SoH) at the start of second-life use, and the minimum SoH threshold for the end of second-life operation.

10.5.1 Second-Life Battery Degradation and Service-Life Assumptions

The second-life model assumes that batteries enter the repurposing stage at an initial SoH of 80% and remain in service until their SoH reaches 30%. Calendar ageing and cycle-induced ageing are considered in estimating the decline in usable battery capacity. The adopted parameters are summarised in Table 74.

Table 74 Assumptions for second-life battery ageing and end-of-life assessment

Parameter	Value	Description
Initial SoH	80%	Battery SoH at the beginning of second-life use
End SoH	30%	End-of-life threshold for second-life operation
Calendar ageing factor	0.025	Annual calendar degradation factor

Calendar ageing exponent, β	1	Exponent used in the calendar ageing model
Cycle life at 80% SoH	2,500 EFC	Equivalent full cycles associated with a 20% capacity loss

The initial SoH represents the condition at which batteries are assumed to enter second-life applications after reaching the first-life retirement threshold. The end SoH of 30% defines the lower operating limit in the model. Thus, the assumed SoH window for second-life operation extends from 80% to 30%, corresponding to a potential reduction of 50 percentage points in nominal capacity relative to a new battery. The calendar ageing factor and exponent represent the assumed time-dependent component of degradation, while the cycle-life parameter characterises cycle-induced ageing. These parameters are used to estimate the decline in battery SoH during second-life operation and, consequently, the duration for which a battery can continue to provide its intended service. The resulting lifetime depends on both elapsed time and cumulative cycling. The service life of a second-life battery depends on how frequently it is charged and discharged. To represent these differences, each application is assigned an annual EFC value. One EFC corresponds to cumulative discharged energy equivalent to the battery's usable capacity; therefore, annual EFCs provide a consistent measure of cycling intensity across applications.

Table 75 Assumed annual cycling intensity and use cases for second-life battery applications

Application	EFC per year	Typical use
Frequency regulation	700	High-frequency charging and discharging for ancillary services
Peak shaving	350	Daily demand reduction and load shifting
Renewable firming	250	Smoothing variability from solar and wind generation
Backup power	50	Emergency backup and periodic testing
Residential ESS	180	Residential solar PV coupled with battery storage
Miscellaneous	100	Low-speed EVs, forklifts, telecom backup, campus mobility, and similar applications

10.5.2 Application-Specific Cycling Requirements

Frequency regulation is assigned the highest annual cycling intensity because it involves frequent charge–discharge operation to support ancillary services. Peak shaving and renewable firming have intermediate cycling requirements, reflecting their roles in reducing demand peaks and managing renewable generation variability. Residential ESS is assigned a moderate cycling intensity, while backup power has the lowest value because batteries are primarily used during outages and periodic testing. These application-specific EFC assumptions allow the model to differentiate second-life service life across use cases. Applications with higher annual cycling intensity are expected to accumulate cycle-induced ageing more rapidly, whereas lower-cycling applications may be more strongly influenced by calendar ageing. Consequently, the same retired battery cohort may have different remaining service lives depending on its assigned application.

10.5.3 Allocation of Second-Life Battery Capacity Across Applications

To estimate the distribution of retired EV batteries across potential second-life applications, the annual second-life battery inflow is allocated among six application categories: frequency regulation, peak shaving, renewable firming, backup power, residential energy storage systems (ESS), and miscellaneous applications. The allocation is based on the fixed percentages specified in Table 76, which sum to 100% of the estimated annual second-life battery inflow.

Table 76 Assumed allocation of second-life battery inflow across applications

Application	Allocation (%)
Frequency regulation	15
Peak shaving	20
Renewable firming	25
Backup power	15
Residential ESS	15
Miscellaneous	10
Total	100

The annual battery capacity allocated to each application is calculated by multiplying the total annual second-life battery inflow by the corresponding allocation fraction. As illustrated in Figure 76, the annual second-life battery inflow increases substantially towards the end of the projection period. Renewable firming receives the largest share at 25%, followed by peak shaving at 20%. Frequency regulation, backup power, and residential ESS each receive 15%, while miscellaneous applications account for the remaining 10%.

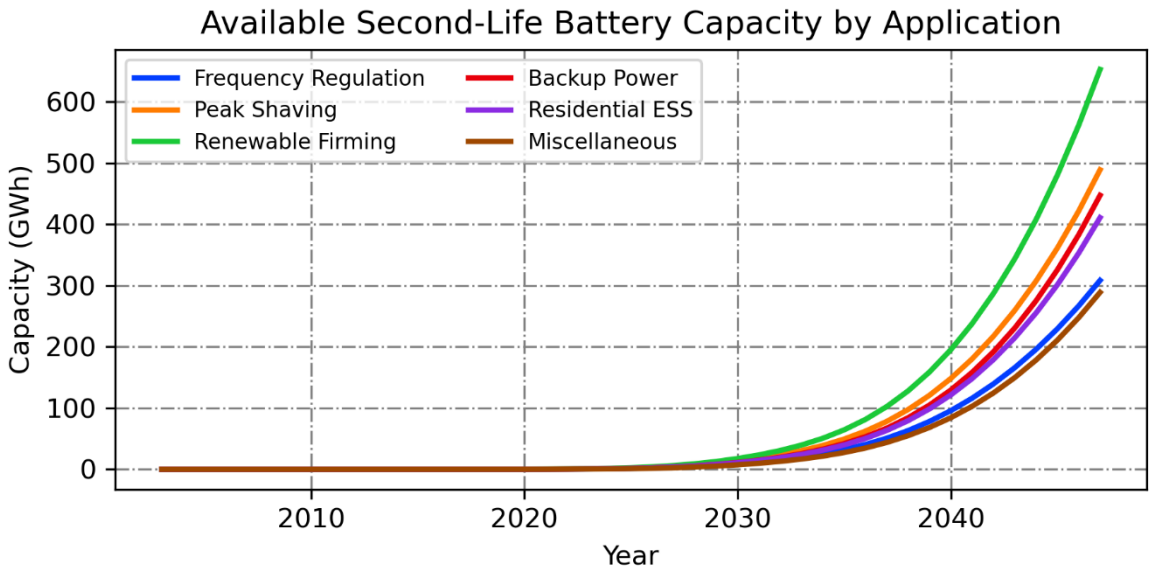


Figure 76 Annual second-life battery inflow allocated across the six applications according to the assumed allocation percentages.

Figure 77 presents the projected capacity allocated to each application individually. All six application categories exhibit substantial growth towards 2047, reflecting the increasing availability of batteries reaching the end of their first-life service. The absolute capacity allocated to each application follows its assigned share of the total annual

inflow. Consequently, renewable firming and peak shaving receive the largest capacity allocations, while miscellaneous applications receive the smallest.

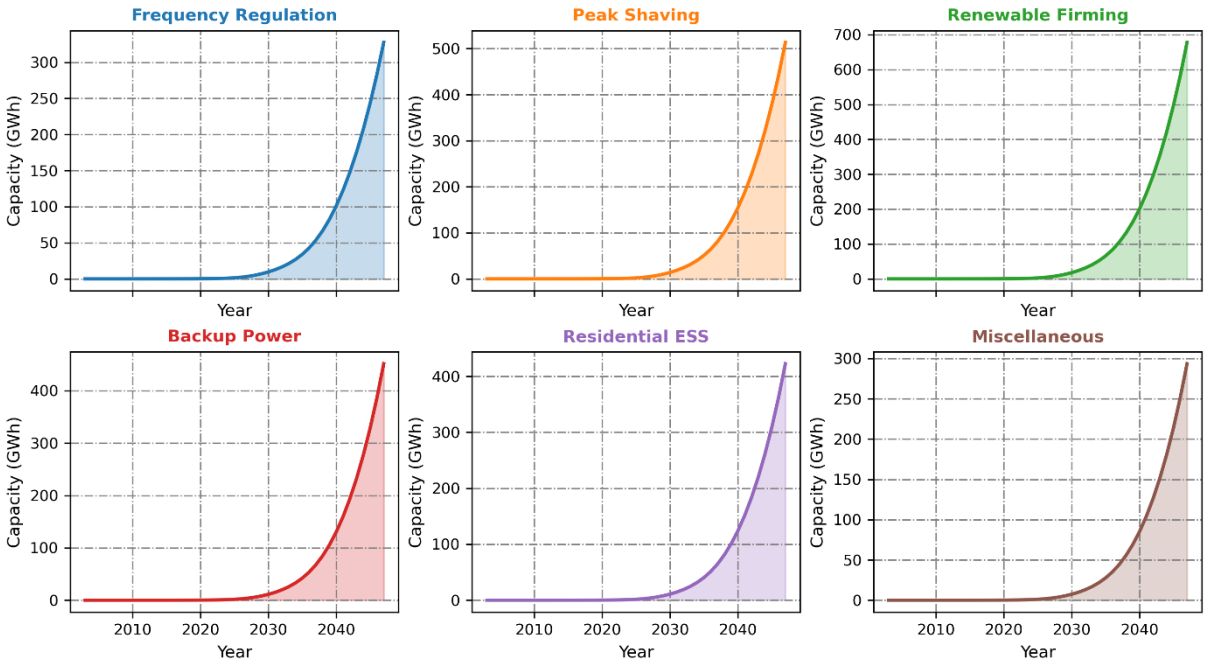


Figure 77 Projected second-life battery capacity allocated to individual applications.

10.5.4 Interpretation of Application-Wise Capacity Projections

The allocation percentages are modelling assumptions intended to distribute the projected second-life battery inflow across representative use cases. They do not imply that the entire allocated capacity will necessarily be deployed or economically viable in practice. Actual deployment would depend on battery condition, application-specific technical requirements, safety screening, system integration costs, and market demand.

10.6. Summary

This chapter developed a framework to estimate the potential availability and application-wise distribution of second-life EV batteries in India. Historical vehicle registration data from the VAHAN dashboard were used to characterise EV adoption and establish the basis for future registration projections. Vehicle-class-specific battery-pack capacity assumptions were then applied to estimate annual battery capacity additions. Future EV growth was projected using the study's policy-informed adoption assumptions, followed by Weibull survival modelling to estimate when first-life batteries reach the specified retirement criterion of SoH ≤ 80%.

The estimated retired battery capacity was subsequently evaluated using second-life ageing assumptions, including an initial SoH of 80%, an end-of-life threshold of 30%, calendar ageing parameters, and cycle-life assumptions. Six representative applications were considered, with different annual equivalent full-cycle requirements to capture their contrasting operating intensities. Finally, the annual second-life battery inflow was distributed among these applications using fixed allocation shares.

The resulting framework provides estimates of annual battery additions, first-life retirements, potential second-life battery inflows, and application-wise capacity allocation through 2047. These estimates establish a quantitative basis for assessing the potential contribution of retired EV batteries to stationary storage and other applications.

However, the projected retired capacity and allocated inflows represent technical potential under the study assumptions, rather than confirmed deployable capacity or realised economic value. Further assessment of battery suitability, application-specific performance, and economic feasibility would be required before translating these projections into practical deployment estimates.

Chapter 11.

Emerging Technologies and Smart Integration: Readiness and Deployment Outlook

This chapter advances the earlier descriptive discussion of future trends into a structured outlook on technology readiness and deployment. It assesses storage and enabling technologies across commercial, early-commercial, demonstration/pilot, and research-and-development stages; benchmarks international grid-forming requirements and practices and draws relevant implications for India; establishes key grid-forming performance metrics; defines and evaluates long-duration energy storage; examines hybrid storage configurations; and expands the treatment of digital twins, artificial intelligence and machine learning, virtual power plants, and distributed storage. The chapter further addresses communications, interoperability and cybersecurity requirements, considers climate-resilient design under Indian operating conditions, and concludes with a global technology and policy watchlist to track emerging developments relevant to future deployment.

11.1.A Readiness Framework

Two scales are used to classify maturity. The technology readiness level (TRL), from 1 (basic principles) to 9 (proven in operational environment), measures technical maturity. The commercial readiness index (CRI), developed by Australian Renewable Energy Agency (ARENA), from 1 (hypothetical commercial proposition) to 6 ("bankable" asset class), measures commercial maturity, including supply chains, financing, standards and regulatory acceptance[292]. A technology may be technically mature (e.g., TRL 9) yet remain commercially immature in the Indian context (e.g., CRI 2-3) because of constraints such as underdeveloped domestic supply chains, limited standardisation and certification frameworks, insufficient operational experience, or the absence of established procurement and revenue mechanisms. Accordingly, this report adopts the four deployment-readiness classes defined in Table 77 and applied in Data Compiled from Multiple Sources

Table 78. The classification reflects the assessment undertaken throughout this report, considering both the underlying technological maturity and the status, scale, and experience of ESS deployment in India.

Table 77: Deployment classes used in this chapter

Class	Typical TRL	Typical CRI	Meaning for Indian Decision-Makers
Commercial	9	5–6	Procure at scale through competitive tenders, standard contracts, and financing
Early commercial	8–9	3–4	First commercial projects; procure through targeted tenders or with support; build standards and supply chains
Demonstration / pilot	6–8	2–3	Fund demonstrations with performance monitoring; prepare standards; watch international deployment

[292]Australian Renewable Energy Agency (ARENA), Commercial Readiness Index for Renewable Energy Sectors, 2014.

Class	Typical TRL	Typical CRI	Meaning for Indian Decision-Makers
R&D	1–5	1	Support research; monitor breakthroughs

Data Compiled from Multiple Sources

Table 78: Readiness classification of storage and integration technologies (global and Indian)

Technology	TRL (global)	Global class	Indian class	Key uncertainty / trigger for reassessment
Pumped storage (fixed speed)	9	Commercial	Commercial	Construction pace; transmission
Pumped storage (variable speed)	9	Commercial	Early commercial	E&M supply; cost premium
Li-ion LFP BESS	9	Commercial	Commercial	Cell prices; safety; domestic manufacturing
Grid-forming BESS	8–9	Early commercial → commercial	Early commercial	Test protocols; OEM model quality; performance evidence
Sodium-ion BESS	8	Early commercial	R&D / pilot	Cost and cycle-life evidence at scale
Vanadium redox flow	8–9	Early commercial	Demonstration	Vanadium price; system cost
Iron / zinc flow	7–8	Demonstration → early commercial	R&D	Durability; bankability
Iron-air (multi-day)	7	Demonstration → first commercial	R&D	Field performance; cost
Adiabatic CAES	7–8	Early commercial (China)	R&D	Geology; RTE
Liquid-air (LAES)	7–8	Demonstration → first commercial	R&D	RTE; cost at scale
Gravity (solid mass)	6–7	Demonstration	R&D	Economics
Carnot / pumped thermal	5–7	Demonstration	R&D	RTE; cost
Industrial heat batteries	7–9	Early commercial	Pilot	Industrial uptake; tariffs
Ice / chilled-water TES	9	Commercial	Commercial (niche)	Incentives for load shifting
Hydrogen P2H2P	6–7 (system)	Demonstration	R&D / pilot	Electrolyser cost; storage geology; RTE

Technology	TRL (global)	Global class	Indian class	Key uncertainty / trigger for reassessment
Supercapacitor / flywheel hybrids	8–9	Early commercial	Pilot	Service value (FFR)
Synchronous condensers (new and converted)	9	Commercial	Early commercial	System-strength procurement
Digital twins for BESS	7–8	Early commercial	Pilot	Data access; validation
AI/ML dispatch and health analytics	7–9	Early commercial	Pilot	Explainability; cyber; data
Virtual power plants / DERMS	8–9	Commercial (US, EU, AU)	Pilot	DSO roles; aggregator rules
V2G	7–8	Demonstration	R&D	Standards; battery warranties

Data Compiled from Multiple Sources

11.2. Emerging technologies: Readiness & Indian applicability

Table 79 summarises the emerging storage technologies most relevant to India, their global technology readiness, and their specific applicability in India. Chapter 13 further develops the readiness framework in more detail.

Table 79: Emerging storage technologies: readiness and India-specific applicability

Technology	Global TRL	Indian status	India-specific applicability and conditions
Sodium-ion batteries	8	R&D; pilot manufacturing plans	Reduces lithium/graphite dependence; good heat tolerance; could use LFP-like manufacturing lines; pilot BESS (10–50 MWh) recommended by 2028
Vanadium redox flow	8–9	Early Commercial	6–10 h applications; low fire risk suits urban sites; vanadium import dependence — explore recovery from steel slag
Iron and zinc flow	7–8	None	Low-cost materials; demonstrations for 8–12 h
Iron-air	7	None	Multi-day adequacy for monsoon low-RE periods; land-intensive; demonstration after international results
Adiabatic CAES	7–8	None	Requires suitable caverns (hard rock, depleted fields); geological survey needed
Liquid-air (LAES)	7–8	None	Synergy with LNG terminals (waste cold) and industrial waste heat
Gravity (solid mass)	6–7	Proposals	Abandoned mines and hilly terrain; unproven economics

Technology	Global TRL	Indian status	India-specific applicability and conditions
Thermal (heat batteries, Carnot)	6–9	Early	Industrial clusters (textiles, food, chemicals); cooling-load shifting with ice/chilled water is mature
Hydrogen / ammonia storage	6–9 by component	NGHM pilots	Direct industrial use first; P2H2P for seasonal/strategic reserves after 2035
Supercapacitor / flywheel hybrids	8–9	Niche	FFR and power-quality hybrids with BESS

11.3. Grid-Forming Technology: International Practice And Implications for India

11.3.1 Australia

Australia's National Electricity Market (NEM) has been the global pioneer in grid-forming batteries. After the South Australian blackout of 2016, system-strength shortfalls in South Australia and western Victoria and the success of the Hornsdale Power Reserve (including its later "virtual machine mode" providing inertia-like response)[293], AEMO published a voluntary specification for GFM inverters in 2023 and a test framework in 2024[294], and ARENA funded eight GFM batteries totalling about 2 GW[295]. A new system-strength framework obliges transmission networks to procure system strength, for which GFM batteries are eligible. By 2026, about 74% of batteries in the NEM connection pipeline featured grid-forming inverters.[296]

11.3.2 Great Britain

Great Britain defined a minimum specification for "GB Grid Forming" capability in Grid Code modification GC0137 (2022), which is voluntary but standardised, and has procured stability services (inertia, short-circuit level, and dynamic voltage support) through successive Stability Pathfinders and a Stability Market.[297] Grid-forming batteries and synchronous condensers have both won contracts. The lesson is that defining the capability in the grid code and procuring it as a paid service can coexist.

11.3.3 Ireland

Ireland's all-island system operates with system non-synchronous penetration of up to 75%, a RoCoF standard of 1 Hz/s, and a minimum number of synchronous units online; it has introduced Low Carbon Inertia Services to procure inertia from synchronous condensers and potentially GFM converters, alongside the DS3 system-services suite, including FFR.[298] Ireland demonstrates that SNSP limits can be relaxed progressively as stability services are procured.

11.3.4 Continental Europe

ENTSO-E's Phase II technical report (November 2025) set out grid-forming requirements to be incorporated in the revised Network Code on Requirements for Generators (NC RfG 2.0), which will require GFM capability for new power

[293] Aurecon, Hornsdale Power Reserve: Year 1 Technical and Market Impact Case Study (Aurecon, 2018).

[294] Australian Energy Market Operator, Voluntary Specification for Grid-Forming Inverters: Core Requirements Test Framework.

[295] Australian Renewable Energy Agency (ARENA), 'Large Scale Battery Storage Funding Round', Australian Renewable Energy Agency, December 2022.

[296] George Heynes, 'Grid-Forming Inverters Feature in 74% of Australia's 33.2 GW NEM Battery Storage Pipeline', Energy Storage News, 2026.

[297] National Grid Electricity System Operator, GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (Formerly Virtual Synchronous Machine/VSM Capability).

[298] EirGrid and SONI, 'DS3 Programme: Operational Constraints Updates and Low Carbon Inertia Services Procurement'.

park modules and storage above 1 MW once adopted and implemented by member states.[299] The Iberian blackout of 28 April 2025, which resulted from cascading overvoltage events, has reinforced the European focus on dynamic voltage control and on requiring CBRs to operate in voltage-control mode.[300]

11.3.5 North America

NERC published GFM functional specifications for BESS in 2023,[301] IEEE 2800-2022 sets interconnection requirements for CBRs, including ride-through and negative-sequence current.[302] The Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium published GFM specifications;[303] and ERCOT's NOGRR 272, effective 1 Dec. 2025, introduced "advanced grid support" (GFM-type) requirements for new CBR-ESS resources, complemented by an incentive programme for GFM capability.[304] Hawaii's island grids have operated GFM BESS for several years.

11.3.6 India

India's energy storage capacity expanded rapidly in 2026. Grid-India's discussion paper recommended GFM capability for new BESS above 50 MW, particularly in weak-grid areas, phased pilots and harmonisation with international testing frameworks;[305] the CEA's July 2026 advisory requires 100% GFM inverters for upcoming BESS, with black-start and 24×7 AGC capability for BESS of 50 MW and above;[306] and the August 2026 draft connectivity regulations propose GFM capability for at least 15% of inverters in new solar and wind plants from July 2027.[307] Table 80 compares the key points in these approaches.

Table 80: Grid-forming approaches: international benchmark and implications for India

Dimension	Australia	Great Britain / Ireland	Continental Europe / North America	India (2026)
Instrument	Voluntary spec + test framework; system-strength obligations; ARENA funding	Grid-code capability (GC0137); stability procurement (GB); LCIS and SNSP (Ireland)	NC RfG 2.0 mandate (>1 MW, pending); NERC/UNIFI specs; ERCOT NOGRR 272 mandate for new ESRs	CEA advisory: 100% GFM BESS; draft 15% GFM in RE; Grid-India paper
Mandatory or voluntary	Voluntary capability; paid services	Voluntary capability; paid services	Mandatory (EU pending; ERCOT for ESRs)	Advisory → mandatory (draft regulations)
Remuneration	System-strength and inertia payments	Stability contracts	Mostly unpaid capability; ERCOT incentive programme	Not yet defined

[299] ENTSO-E, Grid Forming Capability of Power Park Modules: Phase II Technical Report (European Network of Transmission System Operators for Electricity, 2025).

[300] ICS Investigation Expert Panel, Grid Incident in Spain and Portugal on 28 April 2025.

[301] North American Electric Reliability Corporation, Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems.

[302] 'IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems'.

[303] UNIFI Consortium, UNIFI Specifications for Grid-Forming Inverter-Based Resources—Version 2.

[304] Electric Reliability Council of Texas, 'NOGRR272: Advanced Grid Support Requirements for Inverter-Based ESRs'; Energy-Storage.News, 'ERCOT Incentivises Grid-Forming BESS with US$25 Million Programme', 2026.

[305] Grid Controller of India Limited, Discussion Paper on Grid-Forming Technology and Its Possible Applications in the Indian Grid (Grid Controller of India Limited, 2026).

[306] Gupta, 'CEA Mandates 100% Grid-Forming Inverters for Upcoming BESS Projects in India'.

[307] Central Electricity Authority, 'Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026'.

Dimension	Australia	Great Britain / Ireland	Continental Europe / North America	India (2026)
Test/compliance	AEMO test framework	Compliance processes	ENTSO-E implementation guidance; NERC	To be developed
Lesson for India	Pair mandates with paid services and test frameworks	Define capability precisely; procure where needed	Mandate for new assets is feasible; cost impact is modest for BESS	Convert advisory into testable standard; define cost recovery; build EMT model library

Implications for India: Five key priorities emerge from the international benchmarking:

i. The CEA advisory should be progressively translated into a formal and testable technical standard, supported by clearly defined and measurable performance requirements.
ii. A comprehensive compliance and validation framework should be established, encompassing type testing, HIL testing, EMT model validation and field commissioning tests, supported by accredited testing facilities in India.
iii. An appropriate commercial mechanism for recovering the incremental cost of GFM capability should be developed, either through its explicit recognition in contracted BESS tariffs or through procurement of system-strength and related grid-support services.
iv. A national repository of validated OEM EMT models should be established and maintained by Grid-India and CTUIL to support system-strength assessment, connection studies and operational planning.
v. GFM-based resources should not be considered in isolation; their deployment should be co-optimised with synchronous condensers and transmission-system reinforcement as part of coordinated system-strength planning, particularly in weak-grid and high-CBR regions such as Khavda and Rajasthan.

11.4. Grid-Forming Performance Metrics and Testability

GFM requirements must be defined through clear, measurable and verifiable performance criteria. Table 81 presents the proposed GFM performance metrics, indicative requirements and associated test and validation methods.

Table 81: Grid-forming performance metrics and test methods

Capability	Metric / Requirement	Indicative Value	Test Method
Voltage-source behaviour	Effective source impedance; dynamic response to grid-voltage magnitude and phase-angle disturbances	Response initiation within 5 ms and completion within 30 ms for specified voltage and phase-angle disturbances (CEA)	EMT, HIL voltage/phase-angle step tests
Droop control (P–f, Q–V)	Droop characteristics, steady-state accuracy, deadband, and power-sharing response	Configurable droop coefficients, e.g., 2–10%, subject to applicable grid-code requirements	Frequency and voltage perturbation tests in EMT and HIL
Synthetic inertia	Equivalent inertia constant, H_eq (s), on the specified MVA base; active-power response to RoCoF	Declared and configurable H_eq, e.g., 2–8 s, subject to available power and energy headroom	RoCoF injection and frequency-ramp tests in EMT and HIL

Current limiting and overload capability	Maximum current, overload duration, current-limiting behaviour, and post-limit recovery	At least 1.5 p.u. for 200 ms (CEA), subject to specified operating conditions	Fault and current-limit tests in EMT and PHIL
Fault ride-through (LVRT/HVRT)	Voltage ride-through characteristics, reactive-current response, and post-fault recovery	Compliance with applicable CEA LVRT/HVRT requirements	Balanced fault tests, EMT, HIL and field validation
Unbalanced fault performance	Negative-sequence current response, phase-current limits, and stability during asymmetrical faults	Controlled positive- and negative-sequence response within converter current limits	SLG, LL and LLG fault tests in EMT and HIL
Phase-angle ride-through	Maximum phase-angle jump without tripping or loss of synchronization; active-power response	±60° phase-angle jump (CEA)	Positive and negative phase-angle step tests in EMT and HIL
RoCoF withstand	Maximum positive and negative RoCoF tolerated without instability or disconnection	E.g., ±2–4 Hz/s, with specified measurement window and duration	Positive and negative frequency-ramp tests in EMT and HIL
Low-system-strength operation	Stable operation under weak-grid conditions with varying grid impedance	SCR ≤ 2 (CEA)	EMT and HIL studies with varying SCR and grid X/R ratio
Oscillation damping	Damping of converter-control and network oscillations over the specified frequency range	0.1–20 Hz (CEA)	Small-signal perturbation, ring-down and dynamic stability tests in EMT and HIL
Loss of synchronous generation	Ability to maintain stable voltage and frequency following disconnection of the last synchronous generator	Stable operation without loss of synchronization, sustained oscillations, or unacceptable voltage/frequency deviations	EMT and HIL tests involving sudden synchronous generator disconnection
Multiple GFM converter coordination	Synchronization, active/reactive power sharing, and control interactions among multiple GFM units	Stable parallel operation and appropriate power sharing without sustained oscillations	Multi-inverter EMT, HIL and PHIL studies
Grid-connected to islanded transition	Ability to establish and maintain island voltage and frequency following intentional grid separation	Stable transition without converter tripping or unacceptable voltage/frequency deviations	Grid-disconnection and islanding tests in EMT and HIL
Islanding and resynchronization	Stable islanded operation and controlled reconnection to the main grid	Stable operation and successful resynchronization within specified voltage, frequency, and phase-angle limits	EMT, HIL and field synchronization tests
Black-start capability	Establishment of voltage and frequency in a de-energized network; staged load pickup and system restoration	Black-start capability for applicable BESS projects ≥ 50 MW (CEA); successful restoration within specified operating limits	EMT, PHIL and field black-start demonstration

Active/reactive power dispatch tracking	P/Q reference tracking, ramp-rate capability, settling time, and PPC coordination	Accurate tracking of dispatch commands within specified response times and operating limits	PPC-integrated EMT, HIL and field tests
Harmonic behaviour	Harmonic emissions, converter impedance, and network resonance characteristics	Compliance with IEEE 519 and applicable grid-code limits; no unacceptable resonance amplification	Harmonic measurements and impedance-frequency scanning in EMT, HIL and field tests
Frequency-domain characterization	Converter output impedance/admittance, P–f and Q–V frequency responses, and interaction with grid impedance	Stable frequency-dependent characteristics within declared operating conditions and bandwidth	Frequency-response measurements, impedance scans, EMT and HIL
Model fidelity	Validation of RMS and EMT models against measured converter and plant responses	Agreement within defined error bands for relevant operating conditions and disturbances	Benchmarking against HIL, PHIL and field measurements

11.5. Long-Duration Energy Storage: Definitions and Metrics Beyond Duration

LDES is defined inconsistently across different grid codes and standards, ranging from at least 8 hours (LDES Council; Ofgem), at least 10 hours (US DOE), at least 12 hours ("deep" storage in AEMO's ISP) or, in Chinese practice, at least 4 hours.[308] Duration alone, however, is an inadequate descriptor. What distinguishes LDES technologies economically is the combination of:

- **Cycling frequency and storage period**: Daily cycling (~300+ cycles/yr), weekly (~50), or seasonal (a few cycles per year), which determines how many times the energy-related capital cost is amortised.
- **Round-trip efficiency**: Parameter that matters greatly for daily cycling but much less for rare, multi-day discharges.
- **Self-discharge**: Parameter that matters for long storage periods.
- **Power-related cost (US$/kW) versus energy-related cost (US$/kWh)**: LDES technologies typically have high power cost but low energy cost, the reverse of short-duration batteries.

Sepulveda et al. showed that, for LDES to substantially reduce the cost of decarbonised electricity by displacing firm generation, its energy-capacity cost would need to be of the order of US$20/kWh or less, with efficiency and power cost mattering less than energy cost.[309] For India, LDES is needed mainly for multi-day low-RE periods (for example, extended monsoon cloud cover) and for adequacy as coal retires after 2035-40; PSP with large reservoirs is the natural backbone, supplemented by flow batteries, CAES/LAES, iron-air and thermal storage as they mature.

11.6. Hybrid Storage Systems

Hybrid storage combines two or more technologies, or storage with other grid devices, so that each operates where it is most efficient (Table 82, Figure 78).

[308] LDES Council and McKinsey & Company, Net-Zero Power: Long Duration Energy Storage for a Renewable Grid (Long Duration Energy Storage Council, 2021); Australian Energy Market Operator, 2024 Integrated System Plan (ISP); Energy-Storage.News, 'UK's Ofgem Goes Big on LDES Cap-and-Floor Window 1; 18-Hour Lithium-Ion Among Winners'.

[309] Sepulveda et al., 'The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems'.

Table 82: Hybrid storage systems: configurations and applicability to India

Hybrid	Rationale	Control / design considerations	Indian applicability
BESS + PSP	BESS provides fast response, covers PSP mode-change times and smooths pumping; PSP provides bulk energy and inertia	Coordinated dispatch; shared connection	High: PSP complexes in AP, MP, Maharashtra, Karnataka
BESS + flywheel / supercapacitor	Power device absorbs high-frequency cycling (regulation, FFR), extending battery life	Frequency-split control; sizing of the power device	Medium: FFR and regulation at weak nodes
BESS + synchronous condenser	Condenser provides inertia and fault current (5–7 pu); BESS provides energy and fast active power	Coordinated voltage control; protection studies	High: Khavda, western Rajasthan
BESS + STATCOM	STATCOM provides dynamic reactive power; BESS provides active power and GFM	Voltage-control coordination	High: RE pooling stations
BESS + GFL RE plant	Co-located GFM BESS stabilises GFL PV/wind at the same POI	Plant-controller coordination; GFM share	Very high: co-location mandate (draft 2026)
BESS + thermal storage	Electric heaters or heat pumps absorb surplus; heat supplied to industry; BESS for power services	Sector-coupling contracts	Medium: industrial clusters
BESS + electrolyser	BESS smooths electrolyser input; electrolyser absorbs sustained surplus	Electrolyser minimum load and ramp	Medium–high: NGHM hubs
PSP + floating solar	Solar on PSP reservoirs; shared connection	Reservoir operations; floating PV design	Medium — reservoirs of PSPs

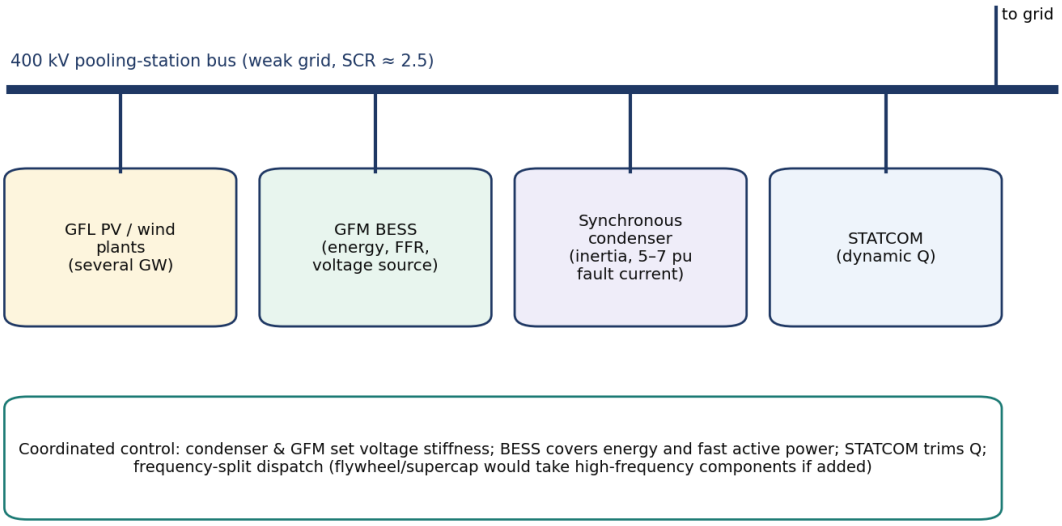


Figure 78: Example hybrid architecture: GFM BESS, synchronous condenser and STATCOM at a weak RE pooling station, with a frequency-split control scheme

11.7. Digital Twins for Storage

A digital twin is a continuously updated virtual representation of a physical asset that combines physics-based and data-driven models with live operational data to estimate states, predict behaviour and support decisions. For BESS, digital twins will be able to support several functions as listed (Table 13.6):

- **State estimation**: Accurate SOC and SOH estimation at cell, rack and system levels, combining BMS measurements with electrochemical-thermal models (particularly important for LFP's flat voltage curve).
- **Degradation prediction**: Forecasting capacity fade and resistance growth under planned duty cycles, informing warranties, augmentation and bidding.
- **Predictive maintenance**: Detecting incipient faults in cells, cooling systems, PCS components and transformers before failure.
- **Thermal and safety monitoring**: Detecting anomalies (self-discharge, micro-shorts, abnormal temperature rise, off-gas precursors) that may precede thermal runaway.
- **Lifetime optimisation**: Co-optimising dispatch and degradation (Section 5.5) to maximise lifetime value.
- **Grid-integration studies**: Maintaining EMT/RMS models consistent with installed firmware and settings.

Table 83: Digital-twin functions for BESS: data, models and value

Function	Data required	Model type	Value
SOC/SOH estimation	Cell voltage, current, temperature (≈1 s); capacity tests	Equivalent-circuit + Kalman filtering; electrochemical models	Accurate dispatchable energy; contract compliance
Degradation prediction	Duty cycles; temperature history; lab ageing data	Semi-empirical (Eq. (2.3)); physics-informed ML	Augmentation planning, bidding, and warranty management
Predictive maintenance	PCS, HVAC, transformer condition data	Anomaly detection; reliability models	Higher availability; lower O&M cost

Function	Data required	Model type	Value
Thermal/safety monitoring	Cell temperature gradients; off-gas sensors; impedance	ML anomaly detection; thermal models	Early warning of thermal runaway
Lifetime optimisation	Prices, service schedules, and degradation model	Optimisation (MPC, stochastic)	Higher lifetime value
Grid model management	Firmware versions, settings, and field test data	EMT/RMS models	Accurate studies; compliance

Implementation in India would require clearly defined contractual provisions enabling procurers and system operators to access BMS and PCS data at appropriate temporal resolution, supported by standardised data formats and interoperability requirements, robust cybersecurity and data-governance safeguards, and periodic validation of digital-twin predictions against field-based capacity and performance tests.

11.8. Artificial Intelligence and Machine Learning

AI/ML techniques are increasingly becoming integral to storage operations (Table 13.7). Their most valuable applications could potentially be as follows:[310]

- **Forecasting with uncertainty**: Probabilistic (quantile or scenario) forecasts of solar, wind, load and prices, which allow storage schedules to hedge against uncertainty rather than rely on single-point forecasts.
- **Dispatch optimisation**: Model-predictive control and, increasingly, reinforcement learning to co-optimise energy, reserves and degradation in real time.
- **Battery-health estimation**: Data-driven estimation of SOH and remaining useful life (RUL); for example, studies have shown that cycle life could be predicted from early-cycle data with high accuracy.[311]
- **Predictive maintenance and anomaly detection**: Identifying abnormal cells, failing cooling components or PCS faults.
- **Grid-level applications**: Inertia and system-strength estimation, oscillation detection from PMU data, and fast security assessment.

Table 84: AI/ML applications for storage and their governance requirements

Application	Techniques	Benefit	Governance requirements
Probabilistic RE/load/price forecasting	Gradient boosting, deep learning, quantile regression, ensembles	Better scheduling and reserve sizing	Benchmarking; forecast-error reporting
Storage dispatch and bidding	MPC, stochastic optimisation, reinforcement learning	Higher value; degradation-aware operation	Explainability; operating limits; market-conduct rules
SOH/RUL estimation	Physics-informed ML; Gaussian processes; neural networks	Warranty and augmentation decisions	Validation against capacity tests

[310] Saad Aslam et al., 'Machine Learning Applications in Energy Systems: Current Trends, Challenges, and Research Directions', Energy Informatics 8, no. 1 (2025): 62, https://doi.org/10.1186/s42162-025-00524-6.

[311] Kristen A. Severson et al., 'Data-Driven Prediction of Battery Cycle Life Before Capacity Degradation', Nature Energy 4 (2019): 383–91, https://doi.org/10.1038/s41560-019-0356-8.

Application	Techniques	Benefit	Governance requirements
Anomaly detection and safety	Unsupervised learning on cell data	Early fault/thermal-runaway warning	False-alarm management; escalation protocols
Grid stability analytics	ML on PMU data; inertia estimation	Situational awareness	Integration with control-room tools

AI/ML also introduce risks, including limited interpretability of automated decisions, susceptibility to erroneous or manipulated data, and new cybersecurity attack surfaces. Accordingly, safety-critical protection and control functions should not rely solely on ML-based decisions; rather, AI/ML should be used for advisory, predictive, or optimisation functions within defined operating boundaries, with deterministic control and protection systems retaining authority over safety-critical actions.

11.9. Virtual Power Plants and Distributed Storage

Distributed storage, including residential and C&I batteries, EV batteries, and thermal storage, can be aggregated into virtual power plants (VPPs) that provide grid services comparable to those of utility-scale assets. VPPs are commercial in the United States, Europe and Australia; however, in India, they are at the pilot stage. Realising their potential would require the following (Table 13.8):

- **Aggregation rules** allow aggregators to participate in energy and ancillary-service markets (the CERC Ancillary Services Regulations, 2022 allow demand response and storage to provide ancillary services, but detailed aggregator frameworks are still evolving)[312].
- **Distributed energy resource management systems (DERMS)** at DISCOMs to monitor and dispatch DERs while respecting distribution-network limits.
- **Telemetry** of adequate resolution and latency, with cost-effective metering.
- **Baseline methodologies** for measuring demand response and storage performance.
- **Distribution-constraint management** allows coordination between DSO (DISCOM) and TSO (SLDC/RLDC) so that VPP dispatch does not overload feeders.
- **EV and V2G** integration and coordinated charging (V1G) is an immediate opportunity using time-of-day tariffs. Vehicle-to-grid (V2G) requires bidirectional chargers, communication standards (e.g., ISO 15118-20), interconnection rules, and battery warranty arrangements, and is at the demonstration stage.

Table 85: Enablers for VPPs and distributed storage in India

Enabler	Requirement	Current status (India)	Recommended action
Market access	Aggregators in DAM/RTM/AS	DR and ESS allowed in AS in principle	Aggregator registration, minimum bid sizes, settlement rules
DERMS	DISCOM visibility and control of DERs	Limited; smart-meter rollout under way	DERMS pilots in high-rooftop DISCOMs
Telemetry and metering	1–15 min data; secure communications	Smart meters (15–30 min); limited DER telemetry	Standards for DER telemetry (IEC 61850-7-420/IEEE 2030.5)

[312] Central Electricity Regulatory Commission, Central Electricity Regulatory Commission (Ancillary Services) Regulations, 2022.

Enabler	Requirement	Current status (India)	Recommended action
Baselines	Methods for DR and BTM storage	Not established	CERC/Forum of Regulators guidelines
Distribution constraints	DSO–TSO coordination	Informal	Dynamic operating envelopes; hosting-capacity maps
EV integration	Managed charging; V2G standards	ToD tariffs; BIS charging standards; V2G at R&D	Managed-charging programmes; V2G pilots with fleets

11.10. Communications, interoperability and cybersecurity

11.10.1 Control architecture and communications

A utility-scale BESS has a layered control architecture (Figure 13.6): the BMS (cell to system level), the PCS controllers, the power-plant controller (PPC) regulating the POI, the EMS (scheduling and market interface), the plant SCADA, and interfaces to the SLDC/RLDC (typically IEC 60870-5-104 in India) and to OEM remote-monitoring platforms. IEC 61850 is increasingly used in substations and plants (including GOOSE messaging for fast protection and control), and IEC 61850-7-420 is used for DER information models.[313] Latency requirements vary by function (Table 13.9): fast-frequency and voltage functions must be implemented locally in the PCS/PPC, whereas AGC and scheduling can tolerate delays of seconds.

[313] International Electrotechnical Commission, IEC 61850: Communication Networks and Systems for Power Utility Automation, International Standard IEC 61850 (International Electrotechnical Commission, n.d.).

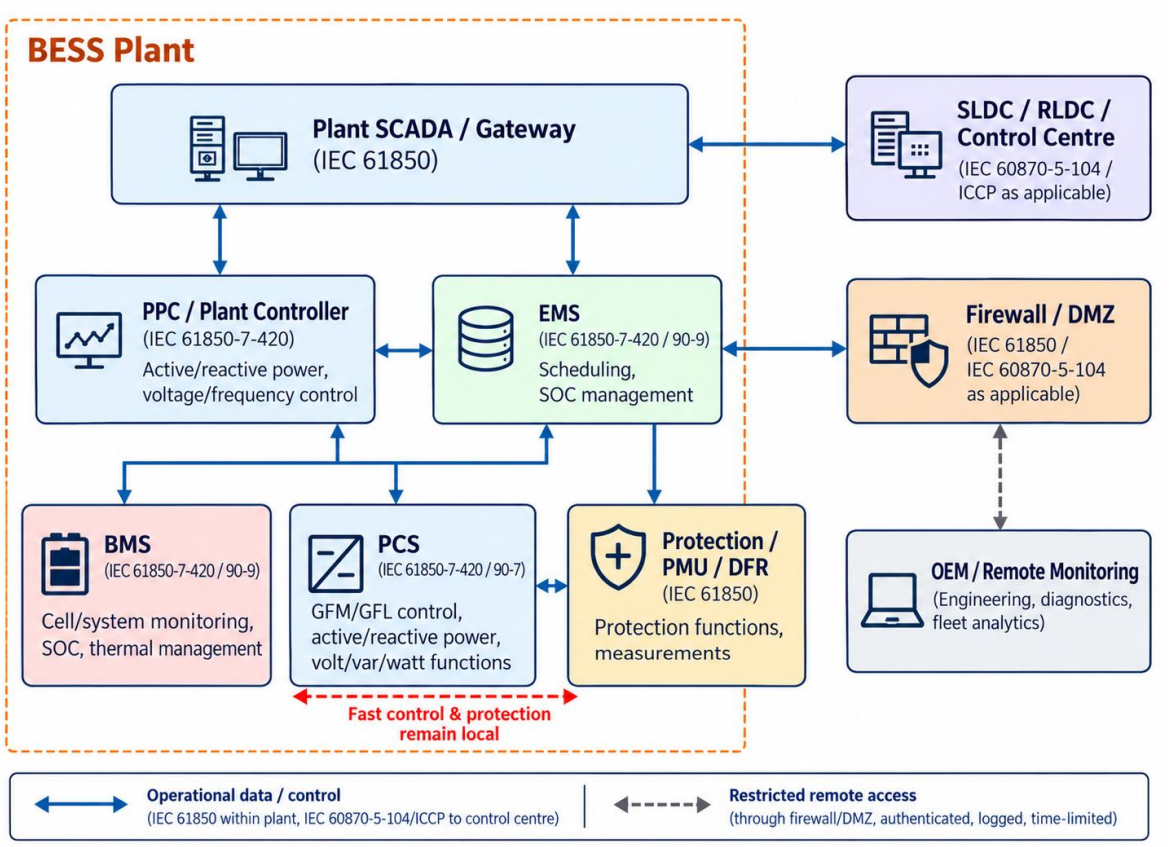


Figure 79: Communication and control architecture of a utility-scale BESS (Source: Author's schematic informed by IEC 61850, IEC 60870-5-104, IEC 62351 and IEC 62443)

Table 86: Control functions, latency requirements and implementation location

Function	Required Latency (Typical range)	Implementation	Communication
GFM response, FFR, fault ride-through	< 5–30 ms	Local in PCS	None (autonomous)
Primary frequency response (droop)	< 0.5–1 s	PCS/PPC local	None or plant LAN
Voltage control at POI	50 ms – 1 s	PPC	Plant LAN (IEC 61850)
AGC / SRAS setpoints	2–4 s cycle	PPC via SCADA	IEC 60870-5-104 to SLDC/RLDC
Remedial action schemes (virtual line)	< 100–200 ms	Local + fast comms	GOOSE / dedicated channels
Scheduling and market bids	Minutes	EMS	Secure IT links
OEM remote monitoring	Minutes	Cloud / remote	Secure, one-way where possible

11.10.2 Cybersecurity

Storage assets are cyber-physical systems whose compromise could cause local damage (overcharging, thermal events) or, at fleet scale, system-wide disturbances (coordinated power swings). Key risks include remote-access pathways used by OEMs, cloud-based EMS and monitoring, supply-chain compromise of firmware, and weak segmentation between IT and OT networks. Relevant frameworks include IEC 62351 (power-system communication security), IEC 62443 (industrial control systems) and NERC CIP.[314] In India, the regulatory discussion should reference the latest CEA Cyber Security Regulations published in August 2026,[315] together with applicable CERT-In directions (2022) and sector-specific requirements.[316] The Ministry of Power's July 2020 order mandates security testing of imported equipment used in India's power supply system and requires prior government permission for imports originating from specified prior-reference countries. Subsequently, the August 2025 amendment to the BESS VGF guidelines mandated indigenously developed Energy Management System (EMS) application software for projects supported under the scheme.[317]

Recommended practices include: defence-in-depth network segmentation (per IEC 62443 zones and conduits); local, autonomous implementation of all safety- and stability-critical functions (no dependence on cloud connectivity); strictly controlled, logged and time-limited remote access; firmware integrity verification and software bills of materials (SBOMs); testing of imported PCS/BMS/EMS in accredited Indian laboratories; clear data-ownership rules (operational data owned by the asset owner, with mandatory sharing of specified data with system operators and procurers); and incident-response plans coordinated with CERT-In and the sectoral CERT.

11.11. Climate-Resilient Design for Indian Conditions

India's climate imposes design conditions that differ markedly from the temperate conditions under which many storage products are rated (Table 87). Western Rajasthan has recorded temperatures above 50°C in recent years, and multi-week periods above 45°C are common across the north-west in summer. Coastal sites face high humidity, salt-laden air, and frequent cyclones. The Thar desert and many solar parks face severe dust storms, and floods and monsoon inundation affect low-lying substations in places across the country.

Table 87: Climate stress factors in India and design responses for storage

Stress Factor	Effect on storage	Design and specification responses
High ambient temperature (45–50 °C)	Accelerated degradation; PCS and transformer derating; higher HVAC load (auxiliary consumption 3–5% in summer)	Liquid cooling; specify performance at 50 °C; PCS derating curves; shading; night pre-cooling; include auxiliaries in RTE guarantee
Humidity and condensation	Corrosion; insulation failure; condensation in containers	Humidity control; conformal coating; IP54–IP55+ enclosures

[314] International Electrotechnical Commission, IEC 62351: Power Systems Management and Associated Information Exchange – Data and Communications Security, International Standard IEC 62351 (International Electrotechnical Commission, n.d.), 62443; International Electrotechnical Commission, IEC 62443: Security for Industrial Automation and Control Systems, International Standard IEC 62443 (International Electrotechnical Commission, n.d.).

[315] Central Electricity Authority, 'Draft Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2026'.

[316] Indian Computer Emergency Response Team (CERT-In), Directions under Sub-Section (6) of Section 70B of the Information Technology Act, 2000 Relating to Information Security Practices, Procedure, Prevention, Response and Reporting of Cyber Incidents for Safe & Trusted Internet, Directions under Section 70B(6) of the Information Technology Act, 2000 No. 20(3)/2022-CERT-In (Ministry of Electronics and Information Technology, Government of India, 2022).

[317] Ministry of Power, Government of India, "Testing of all equipment, components and parts imported for use in the power supply system and network in the country to check for any kind of embedded malware/trojans/cyber threat and for adherence to Indian Standards," Order No. 25-17/6/2018-PG, Jul. 2, 2020; Ministry of Power, Government of India, "Amendment in Operational Guidelines for Viability Gap Funding Scheme for Development of Battery Energy Storage System Supported Through Power System Development Fund (PSDF)," Letter F. No. 48-15/7/2025-NRE Section, Aug. 4, 2025.

Stress Factor	Effect on storage	Design and specification responses
Dust and sand	Filter clogging, reduced cooling, and abrasion	Sealed liquid-cooled designs; filter maintenance regimes; dust-resistant PCS
Coastal corrosion	Enclosure and busbar corrosion	Marine-grade coatings; stainless fittings; ISO 12944 protection
Monsoon flooding	Water ingress; electrical failure	Raised plinths above flood levels (design flood 1-in-100 years plus climate margin); drainage; site selection
Cyclones and high winds	Structural damage; debris	Wind-load design per IS 875 (Part 3); anchoring; debris protection
Seismicity	Rack and container damage	Seismic design per IS 1893 for the zone
Lightning	Surges	Lightning protection and surge arresters
Heatwave–demand coincidence	High demand while assets are derated	Derating-aware capacity accreditation; thermal headroom
Water scarcity (PSP, cooling)	Limits water-based cooling and PSP filling	Dry cooling; closed-loop PSP with secure water allocation

Chapter 11: Key Takeaways

- Only LFP BESS, PSP, and a few niche technologies have been commercialised so far in India; sodium-ion, flow batteries, CAES/LAES, iron-air, gravity and P2H2P would require structured demonstration before large-scale procurement could be materialised.
- International experience shows that GFM mandates work best when paired with precise performance definitions, test frameworks and paid stability services.
- LDES should be defined by cycling frequency, storage period, RTE and the split between power and energy cost and not duration alone. An energy-capacity cost of around US$20/kWh is the long-term benchmark.
- Hybrid configurations (GFM BESS + synchronous condenser/STATCOM at weak nodes; BESS + PSP; BESS + electrolyser) can deliver services more efficiently than single technologies.
- Digital twins and AI/ML add value for SOH estimation, safety and dispatch, but safety-critical functions must remain deterministic and local.
- Cybersecurity, data ownership and climate-resilient design (50 °C, dust, humidity, floods, cyclones) must be explicit in Indian specifications.

Chapter 12.

Recommendations for Energy Storage in Indian Power Sector

This chapter summarises the principal evidence-led conclusions, presents a decision framework for considerations, and concludes with stakeholder-specific and thematic recommendations. The recommendations distinguish, where relevant, among existing requirements, extensions of current policy direction, and additional measures suggested by the assessment conducted in this study.

12.1. Decision Framework for Energy Storage

The central recommendation of this report is that storage decisions in India, from national planning to individual procurements, may follow a common, seven-step decision framework (Table 88). Drawing on the service-oriented approach developed in (6.1), this report consolidates the main planning considerations into a multi-step decision framework, which is intended to serve as a structured screening and decision aid. It links the required service to technology attributes, location, alternatives, procurement specifications and post-commissioning verification, while allowing the detailed methodology to vary with the planning authority and application.

Table 88: Seven-step national decision framework

Step	Key Questions	Tools and Data	Output	Key stakeholders
1. Identify the grid requirement	Which needs: adequacy, energy, flexibility, stability, resilience? Where and when?	LT-NRAP, SLDC data, curtailment-by-cause, event reports, modelling, system studies	Problem statement with location, sizing and timescale	CEA, Grid-India/CTUIL, STUs/SLDCs
2. Quantify service and timescale	What service, which metric, how much, how often?	Net-load metrics, ramp and reserve analysis, ELCC, RoCoF/nadir and other relevant system studies	Service specification (MW, MWh, response, cycles, availability, ramp rate, duty cycle)	CEA, Grid-India/CTUIL, CERC/SERCs/ ESS developers
3. Determine MW, MWh and location	How much capacity and where?	Optimal Sizing method (Section 5.3); siting	Size, location requirement	SECI, ESS developers, CEA, Grid-India/CTUIL,

		methodology (Section 12.11)		CERC/SERCs/ ESS developers
4. Screen technologies and alternatives	Storage vs alternatives (transmission, DR, flexible thermal, sync condensers)? Which storage technology?	Technology matrix (2.2); master service-to-technology matrix (6.2); alternatives table	Short-list of potential solutions	CEA, utilities, developers
5. Assess stability, safety and environment	Does the solution work in weak grids? Is it safe and environmentally acceptable?	RMS/EMT/power quality studies; climate-hazard analysis	Technical and safety acceptance	Grid-India, CTUIL, CEA, SLDCs, STUs, DISCOMs
6. Evaluate lifecycle economics	What is the cost per unit of service over life, including charging, losses, degradation, augmentation and end of life?	LCOS for the duty cycle; NPV of stacked value; risk analysis	Economic ranking; reference tariff	ESS developer, CERC/SERC
7. Procure and verify performance	Procurement mode/tender type, technology agnostic, and performance evaluation criteria?	Attribute-based tender; commissioning tests; performance monitoring	Contract with verifiable attributes; performance reports	ESS developer, SLDC/RLDC, CEA

12.2. Integrated roadmap 2026–2047

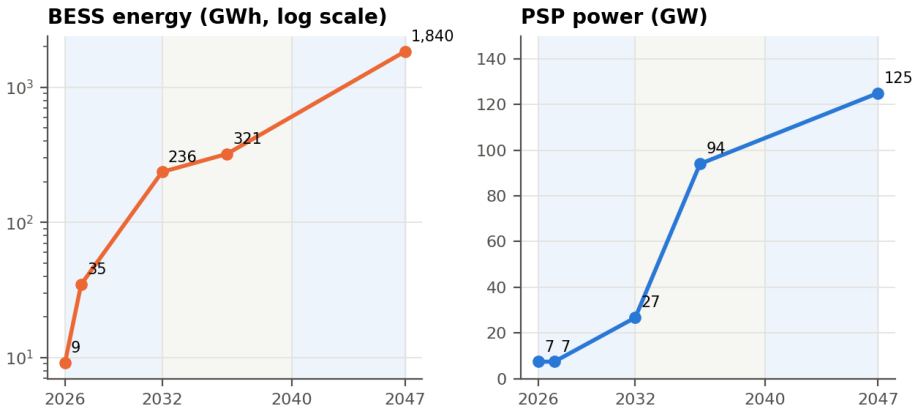
Table 89 and Figure 12.10 present an integrated roadmap for storage in India across three horizons: near-term (to 2030/3), medium-term (2032–2040), and long-term (2040–2047), covering deployment, technology, manufacturing, recycling, grid-forming capability, standards, markets, R&D, and workforce. The roadmap is consistent with the NEP, the LT-NRAP, the CEA PSP roadmap and the 2047 storage estimate, and translates the recommendations of Chapter 14 into milestones.

Table 89: Integrated storage roadmap for India, 2026–2047

Dimension	Near term (2026 to 2030/32)	Medium term (2032–2040)	Long term (2040–2047)
BESS deployment	≥ 47 GW / 236 GWh by 2031-32; commission the ≈80 GWh under construction by 2028; shift to 4–6 h	≈80 GW / 321 GWh by 2035-36 (LT-NRAP); ≥ 150 GW by 2040	≈300–460 GW / 1,840 GWh by 2047
PSP	≈27 GW by 2031-32 (NEP); 54 GW of new PSP planned by 2031-32 (CEA); all 100 GW-roadmap projects at DPR by 2030	≈100 GW by 2035-36 (roadmap); variable-speed share ≥ 30% of new units	100–150 GW; mine-void and seawater PSP where viable
Long-duration storage (LDES)	Demonstrations (flow, Na-ion, CAES/LAES, thermal): 1–5 GWh; LDES procurement pilot	Competitive LDES procurement (tens of GWh; 10–100 h)	LDES tens of GW; multi-day adequacy assured
Hydrogen / sector coupling	Flexible-electrolyser requirements in NGHM; managed EV charging; cooling-storage programmes	Tens of GW of flexible electrolysers; ammonia storage; industrial heat batteries	Seasonal H_2/NH_3 reserves; TWh-scale sector coupling
Grid-forming capability	100% GFM on new BESS (from 2026); ≥ 15% GFM in new RE (from 2027); GFM test protocols and EMT model library	System-strength framework with procurement; GFM retrofits at weak nodes	GFM as default for IBRs; system strength planned like adequacy
Standards and safety	UL 9540A-type testing mandatory; BIS adoption of IEC 62933; GFM performance standard; cybersecurity regulations notified	Periodic revision; incident database; fire-service capability nationwide	Mature regime aligned with international practice
Markets and regulation	FFR product; performance-based SRAS; storage charging treatment; stacking rules; resource-adequacy procurement	Capacity mechanism or central adequacy procurement with ELCC; locational signals; LDES procurement	Fully technology-neutral, attribute-based markets
Manufacturing	≥ 50 GWh/yr cell capacity (LFP; Na-ion pilots); indigenous PCS/BMS/EMS; ALMM for cells/BESS	≥ 150 GWh/yr cells; cathode/anode materials; flow-battery and PSP E&M capacity ≥ 10 GW/yr	Global export hub for storage systems
Recycling and circularity	EPR enforcement; recycling capacity for early EOL; battery passports	Large-scale LFP recycling; second-life standards	Closed-loop materials; high recycled content
R&D	GFM/weak-grid, degradation in hot climates, Na-ion, flow, digital twins	LDES, hybrid storage, H_2 integration	Next-generation chemistries; seasonal storage
Workforce	Training for BESS O&M, commissioning, fire response, and tunnelling	Scale-up of specialised workforce (EMT modelling, GFM tuning, PSP construction)	Mature skills ecosystem

Prepared by this report, quantitative milestones consistent with NEP 2023, LT-NRAP 2026, the CEA PSP roadmap and the MNRE 2047 estimate.[318]

[318] Central Electricity Authority, National Electricity Plan, Volume I: Generation; Central Electricity Authority, Long Term National Resource Adequacy Plan (2026–27 to 2035–36).



Shading: near term (to 2032) · medium term (2032–40) · long term (2040–47). 2026 = actual; 2027/2032 NEP; 2036 LT-NRAP; 2047 CEA/MNRE (BESS) and indicative (PSP).

Figure 12.10: Integrated storage roadmap for India, 2026–2047: deployment trajectories and key milestones (Source: Indicative roadmap using data obtained from multiple sources)

12.3. Stakeholder Specific Recommendations

The recommendations are organised based on the stakeholder assumed to be primarily responsible, with the time horizon (*N = near term, to 2030/32*; *M = medium term, 2032–2040*; *L = long term, 2040–2047*), a measurable milestone and the finding(s) to which each recommendation responds.

12.3.1 Ministry of New and Renewable Energy, Ministry of Power, and CEA

Table 90: Recommendations for MoP, MNRE and CEA

#	Recommendation	Horizon
1	Adopt stepwise decision framework for storage planning and its potential use for VGF-supported and centrally procured storage	N
2	Translate national storage requirements into state-wise and zone-wise requirements (MW, MWh, duration, services) in the annual LT-NRAP update and other planning schemes	N
3	Consideration of moving from duration-based capacity credit to ELCC-based accreditation of storage in resource-adequacy planning; add multi-day stress-event analysis	N–M
4	Consideration for future VGF phases: link disbursement to verified performance (e.g., x% after one year of demonstrated availability), support for 4–8 h and GFM based storage in case of BESS, support for other alternative technically established storage technologies, and target high-value locations	N
5	Explore Establishing an LDES procurement programme (e.g., pilot 1–5 GWh by 2030; competitive procurement of 10–100 h storage from 2032) with revenue support (e.g., cap-and-floor)	N–M
6	PSP-oriented programme with integrated transmission planning for all roadmap projects, E&M manufacturing expansion (including reversible units made domestically), tunnelling expertise and faster clearances	N
7	Requirement of flexible operation capability (minimum load, ramp) for electrolysers supported under the NGHM and other Government schemes, and co-optimise hydrogen hubs with RE and storage	N
8	Strengthen cell manufacturing: accelerate PLI delivery, consider a stationary-storage cell and other competitive storage technology PLI, and introduce an ALMM for cells/BESS	N
9	Possibility of exploring Publishing monthly/quarterly RE curtailment-by-cause data,	N

10	Cybersecurity regulations for BESS EMS/PCS/BMS and associated components	N
11	Adequate regulatory mechanism for data collection, monitoring and data storage for BESS plants (high resolution 20 ms PMU data, 1 ms PCS data, EMS data and DR data	

12.3.2 CERC and SERCs

Table 91: Recommendations for CERC and SERCs

#	Recommendation	Horizon
1	Frame regulations to enable ESS participation in various existing ancillary services and other grid support services covering distribution level (below 3 kV) connected storage	N
1	Introduce a fast frequency response (FFR) ancillary service, sized for common-mode CBR loss calculated based on recurrent (monthly basis) studies/estimates	N
2	Move SRAS to performance-based remuneration and market-based procurement	N
3	Define stability services (inertia, system strength, voltage support) and a mechanism for their procurement or cost recovery preferably through market based or hybrid (regulatory + market) mechanism	N–M
4	Establish regulations/guidelines for revenue stacking: priority, without double charges/taxes, SOC/headroom declaration, metering requirement and verification	N
5	Harmonise treatment of storage charging energy: without double network charges, consistent state practices	N
7	Consider a central resource-adequacy mechanism (or state-level adequacy obligations with ELCC-based accreditation) to focus on long-term storage investment as price spreads compress further	M
8	Standardise availability, energy, RTE and response-time performance incentives and penalties in storage contracts	N
9	Adopt standard curtailment reason codes and compensation rules, with States adopting consistent procedures	N

12.3.3 Grid Operators (NLDC/RLDCs and SLDCs) and RPCs

Table 92: Recommendations for Grid-India, RLDCs and SLDCs

#	Recommendation	Horizon
1	Implement SOC-aware scheduling and reserve allocation for storage, including SOC declarations and verification	N
2	Co-optimise energy and reserves in SCED/RTM, including ESS headroom	N–M
3	Develop restoration plans considering GFM BESS, PSPs and other emerging sources/grid elements as black-start resources	N
6	Publish standardised net-load and flexibility metrics (ramps, minimum net load, non-synchronous penetration levels) regularly (weekly/monthly) basis	N

12.3.4 CTUIL and STUs

Table 93: Recommendations for CTUIL and STUs

#	Recommendation	Horizon
1	Identify priority nodes for storage by service and its availability to public	N
2	Consideration of storage as a transmission asset or "virtual line" alongside reinforcement, using explicit deferral criteria	N
3	Adequate modelling of ESS and its consideration in transmission planning	N
4	Enforce SCR and other sophisticated system strength assessments with a uniform methodology and EMT studies for all connections in weak zones Measures to strengthen grid, particularly in weak regions from transmission side (grid reinforcement, new grid elements) while considering potential support of ESS in grid strengthening	N
5	Integrate PSP transmission into the national transmission plan and assess the impacts and potential challenges (≈98 GW of PSP projects needing transmission)	N

12.3.5 DISCOMs

Table 94: Recommendations for DISCOMs

#	Recommendation	Horizon
1	Include storage in DISCOM resource-adequacy plans using ELCC and non-solar-hour requirements	N
2	Deployment of distribution-level BESS for feeder and DT congestion management, enhanced rooftop-PV hosting capacity and reliability in high-value locations	N
3	Explore implementation of Distributed Energy Resource Management System (DERMS) and managed EV charging to shift load to solar hours	N–M
4	Contract storage with flexible cycling rights (annual throughput) to cover both winter morning and evening peaks	N

12.3.6 Developers, OEMs and System Integrators

Table 95: Recommendations for developers, OEMs and system integrators

#	Recommendation	Horizon
1	Design specific for Indian climates: performance guaranteed at Indian climatic zones, auxiliaries included in RTE, dust- and humidity-resistant enclosures	N
2	Validated EMT and RMS models tied to firmware versions; support HIL testing of GFM controls	N
4	Offer usable energy guarantees at the POI for the full contract, with future augmentation plans	N
5	Localise PCS, BMS and EMS development and manufacturing; increased focus on domestic cell and stack manufacturing	N–M

12.3.7 Academia and R&D institutions

Table 96: Recommendations for academia and R&D institutions

#	Recommendation	Horizon
2	Create open datasets and models for Indian net load, degradation in hot climates and stability assessment in weak grids	N
3	Lead the priority R&D agenda in emerging including high risk high gain ESS technology with industry co-funding	N–L
4	Develop curricula and training programmes for ESS related courses	N

12.4. Thematic Recommendations

12.4.1 Technology-neutral, attribute-based implementation of ESS

ESS implementation and operational engagement are expected to specify and separately value the attributes that deliver system value, rather than the power capacity alone. Table 97 sets out a preliminary template for this purpose, which could be extended to consider key performance attributes. Technology neutrality means that any resource, ranging from BESS, PSP, LDES, and flexible demand to thermal storage, has the attributes to compete, with evaluation based on the service's lifecycle cost.

Table 97: Attribute-based procurement template of ESS

Attribute	How is it specified	How is it valued/verified
Rated power (MW, charge and discharge)	At POI, at ambient temperature appropriate/required for Indian climatic conditions	Capacity test; availability-weighted payment
Usable energy (MWh) and duration	At POI, each contract year	Annual capacity test; energy shortfall penalties
Availability	≥ 95% monthly, power and energy	EMS/SCADA-based computation; payment linked
Round-trip efficiency	AC-AC at POI, including auxiliaries	Monthly metering; efficiency adjustment to payments
Degradation and augmentation	Guaranteed usable energy trajectory; augmentation obligation	Capacity tests; CEA 90/80/70% retention
Storage Cycling	Cycles/day and annual throughput	EMS logs; regular audits
Grid-support capability	Reactive P–Q/P-V curve requirement; GFM functions; black start	Compliance tests; stability-service payments
Location in the grid	Node or zone	Locational value in evaluation; if it helps in strengthening the grid

12.4.2 Resource adequacy

The required resource adequacy planning is expected to involve the following points:

i. Apply the MoP reliability standards (LOLP ≤ 0.2%, NENS ≤ 0.05%)[319] separately to solar and non-solar hours.
ii. Accredit storage using ELCC, recognising declining marginal value as penetration grows, and the net peak broadens.
iii. Analyse multi-day low-RE stress events using historical weather years.
iv. Require DISCOMs to demonstrate adequacy, including storage, with a national backstop mechanism.
v. Publish key adequacy assumptions, reserve margins and storage-accreditation values to improve transparency.

12.4.3 Locational planning

Storage should be planned where it delivers the highest value, using a suitable siting methodology at weak RE pooling stations (system strength and curtailment), at the load-centre end of congested corridors (adequacy and congestion), and at distribution nodes with high rooftop PV or constrained networks. Network-deferral value should be quantified in transmission planning, and VGF and ISTS treatment should reward high-value locations.

12.4.4 Regulation and Markets

Areas that may warrant further regulatory and market assessment include revenue-stacking rules, FFR products, performance-based ancillary services (e.g. SRAS), procurement of stability services, treatment of charging energy and network charges, storage capacity value in adequacy mechanisms, and longer-term arrangements for LDES where system studies demonstrate a need.

12.4.5 Safety and Resilience

Mandatory measures for ensuring safety and resilience with growing ESS facilities should include: UL 9540A-type large-scale fire testing and propagation data; NFPA 855-equivalent installation rules (separation, explosion control, detection, suppression); site-specific emergency response plans and training for fire services; cybersecurity requirements for EMS/PCS/BMS and remote access; climate-resilient design standards; augmentation and end-of-life plans at the time of procurement; and EPR-based recycling under the Battery Waste Management Rules, 2022.

The importance of site-specific electrical and fire-safety design was highlighted by a recent incident at ACME Solar's Suryodaya BESS facility in Pokhran, Rajasthan. In July 2026, a localised fire affected the power-conversion system, and the subsequent root-cause analysis identified an electrical short circuit in the AC cables between the transformer and the PCS as the initiating event.[320] While the event was not attributed to battery thermal runaway, it nevertheless highlights the need for robust cable and auxiliary-system design, electrical protection, fire detection and suppression systems, physical segregation of high-voltage equipment from accessible objects, and emergency-response provisions for utility-scale BESS deployed under India's demanding ambient conditions.

12.5. Concluding Remarks

India's rapid growth in RE generation is increasing the importance of flexibility, stability and non-solar adequacy in power-system planning. The analysis conducted in this review shows that the system has now entered a phase in which flexibility, stability, and non-solar adequacy, rather than installed capacity, determine the extent to which RE can be utilised, its cost, and the reliability associated with it. Energy storage is central to this new phase, but only if it is planned by service and location, specified by the attributes that matter, connected with verified grid-forming and ride-through capability, operated with SOC-aware and degradation-aware dispatch, remunerated for the services it provides, built safely for Indian conditions, and supplied increasingly from domestic manufacturing. The decision framework and recommendations presented here are therefore intended as inputs for further planning, regulatory assessment and project-level evaluation.

[319] Ministry of Power, Guidelines for Resource Adequacy Planning Framework for India (reliability criteria of LOLP ≤ 0.2% and NENS ≤ 0.05%), 28 Jun. 2023.

[320] Junaid Shah, 'The Difference Between a Battery Fire and a PCS Failure in a BESS', *Saur Energy International*, 27 July 2026.

Annexure

Review of GST, HSN Codes, and Customs Duties for Battery Imports in India

Some of the publicly available sources are included at the end of this document.

Understanding the Harmonized System of Nomenclature (HSN) codes, Basic Customs Duty (BCD), Social Welfare Surcharge (SWS), and Integrated GST (IGST) for each battery type is crucial for commercial imports of batteries. This report provides a structured overview of the customs duties and GST rates applicable to various battery chemistries, from traditional lead-acid to advanced lithium-ion, covering individual cells, battery packs, and batteries with Battery Management Systems (BMS).

HSN (Harmonized System of Nomenclature) is a 6-digit code standardized by the World Customs Organization (WCO), used in India (with up to 8 digits) to classify goods for GST and import/export duties. HSN codes help in determining the applicable GST rate for each product, ensuring accurate tax compliance. It ensures consistency in tariffs, compliance, and eligibility for concessions or exemptions. Misclassification can lead to penalties or missed benefits.

HSN Codes for Battery Chemistries and Forms

Batteries and battery components are classified under **Chapter 85** of the Indian Trade Classification (ITC) (Harmonized System) - 2017. The main heading for rechargeable batteries (referred as "electric accumulators") is **HSN 8507: ELECTRIC ACCUMULATORS, INCLUDING SEPARATORS THEREFOR, WHETHER OR NOT RECTANGULAR (INCLUDING SQUARE)**, while primary (non-rechargeable) batteries fall under **HSN 8506: PRIMARY CELLS AND PRIMARY BATTERIES**. Below is a list of relevant HSN codes for different battery chemistries and components.

Heading No.	ITC HSN Code(s)	Description	Unit
8506	**PRIMARY CELLS AND PRIMARY BATTERIES**		
	8506 10 00	Manganese dioxide	NOS
	8506 30 00	Mercuric Oxide	NOS
	8506 40 00	Silver Oxide	NOS
	8506 50 00	Lithium	NOS
	8506 60 00	Air-Zinc	NOS
	8506 80 10	Button Cells	NOS
	8506 80 90	Other	NOS
	8506 90 00	Parts	KGS
8507	**ELECTRIC ACCUMULATORS, INCLUDING SEPARATORS THEREFOR, WHETHER OR NOT RECTANGULAR (INCLUDING SQUARE)**		
	8507 10 00	**Lead-acid of a kind used for starting piston engines**	NOS
	8507 20 00	**Other lead-acid accumulators**	NOS
	8507 30 00	**Nickel-Cadmium (Ni-Cd)**	NOS
	8507 40 00	**Nickel-Iron (Ni-Fe)**	NOS
	8507 50 00	**Nickel-metal hydride (Ni-MH)**	NOS

	8507 60 00	**Lithium-ion**	NOS
	8507 80 00	**Other accumulators**	NOS
	8507 90 10	**Accumulator cases made of hard rubber and separators**	KGS
	8507 90 90	**Other**	KGS
8548	**WASTE AND SCRAP OF PRIMARY CELLS, PRIMARY BATTERIES AND ELECTRIC ACCUMULATORS; SPENT PRIMARY CELLS, SPENT PRIMARY BATTERIES AND SPENT ELECTRIC ACCUMULATORS; ELECTRICAL PARTS OF MACHINERY OR APPARATUS, NOT SPECIFIED OR INCLUDED ELSEWHERE IN THIS CHAPTER**		
8549	**CONTAINING PRIMARY CELLS, PRIMARY BATTERIES, ELECTRIC ACCUMULATORS, MERCURY-SWITCHES, GLASS FROM CATHODE-RAY TUBES OR OTHER ACTIVATED GLASS, OR ELECTRICAL OR ELECTRONIC COMPONENTS CONTAINING CADMIUM, MERCURY, LEAD OR POLYCHLORINATED BIPHENYLS (PCBS)**		

NOS: Numbers

Significance of Code Digits:

- First 2 digits (e.g. 85): Chapter covering electrical machinery
- Next 2 (e.g. 06 or 07): Heading; primary vs. electric accumulators
- Last 2-4 specify chemistry/type for precise taxation

Lithium-Ion Batteries – **HSN 85076000**: Covers all lithium-ion chemistry accumulators (including lithium-polymer and emerging solid-state lithium batteries). Individual Li-ion cells and assembled battery packs (with or without Battery Management System) are classified here as *electric accumulators*.

Other Accumulators – **HSN 85078000**: This is applicable to all rechargeable batteries not elsewhere specified. It would include emerging chemistries like sodium-ion batteries, flow batteries (vanadium redox, etc.), lithium-sulphur, and any new chemistry not explicitly listed under heading 8507.

Battery Parts – **HSN 850790**: Parts of batteries, such as battery cases, separators, and BMS circuits, when imported separately. For example, hard rubber cases and separators are 85079010, and other parts (including battery management PCBs or other components) fall under 85079090

Note: A battery pack with BMS is still classified as a battery/accumulator under HSN 8507. The inclusion of monitoring or control circuitry does not change the classification from an "accumulator" as long as its primary function is energy storage. Only if such electronic modules are imported standalone would they be classified as parts (e.g. a battery's PCB under 85079090).

Basic Customs Duty on Battery Imports

Basic Customs Duty (BCD) is the primary import duty levied on goods. Battery imports into India attract BCD that varies by the type of battery chemistry and form, aimed at balancing revenue needs with the protection of the domestic industry and the promotion of local manufacturing.

Heading No.	ITC HSN Code(s)	Description	Unit	BCD Rate
8506	**PRIMARY CELLS AND PRIMARY BATTERIES**			
	8506 10 00	Manganese dioxide	NOS	15%

	8506 30 00	Mercuric Oxide	NOS	15%
	8506 40 00	Silver Oxide	NOS	15%
	8506 50 00	Lithium	NOS	15%
	8506 60 00	Air-Zinc	NOS	15%
	8506 80 10	Button Cells	NOS	15%
	8506 80 90	Other	NOS	15%
	8506 90 00	Parts	KGS	10%
8507	**ELECTRIC ACCUMULATORS, INCLUDING SEPARATORS THEREFOR, WHETHER OR NOT RECTANGULAR (INCLUDING SQUARE)**			
	8507 10 00	**Lead-acid, of a kind used for starting piston engines**	NOS	**15%**
	8507 20 00	**Other lead-acid accumulators**	NOS	**15%**
	8507 30 00	**Nickel-Cadmium (Ni-Cd)**	NOS	**15%**
	8507 40 00	**Nickel-Iron (Ni-Fe)**	NOS	**15%**
	8507 50 00	**Nickel-metal hydride (Ni-MH)**	NOS	**15%**
	8507 60 00	**Lithium-ion**	NOS	**20%**
	8507 80 00	**Other accumulators**	NOS	**15%**
	8507 90 10	**Accumulator cases made of hard rubber and separators**	KGS	**10%**
	8507 90 90	**Other**	KGS	**10%**
8548	**WASTE AND SCRAP OF PRIMARY CELLS, PRIMARY BATTERIES AND ELECTRIC ACCUMULATORS; SPENT PRIMARY CELLS, SPENT PRIMARY BATTERIES AND SPENT ELECTRIC ACCUMULATORS; ELECTRICAL PARTS OF MACHINERY OR APPARATUS, NOT SPECIFIED OR INCLUDED ELSEWHERE IN THIS CHAPTER**		NOS	**10%**
8549	**ELECTRICAL AND ELECTRONIC WASTE AND SCRAP CONTAINING PRIMARY CELLS, PRIMARY BATTERIES, ELECTRIC ACCUMULATORS, MERCURY-SWITCHES, GLASS FROM CATHODE-RAY TUBES OR OTHER ACTIVATED GLASS, OR ELECTRICAL OR ELECTRONIC COMPONENTS CONTAINING CADMIUM, MERCURY, LEAD OR POLYCHLORINATED BIPHENYLS (PCBS)**		KGS	**10%**
	8549 13 00,	**Lithium-Ion battery waste and scrap**	KGS	**0%**

	8549 14 00, 8549 19 00			

Social Welfare Surcharge (SWS) is levied on the BCD for most imports under section 12 of the Customs Act, 1962. The SWS rate is 10% on the aggregate of duties, taxes and cesses which are levied and collected for the majority of products (including batteries). For instance, if a lithium-ion battery pack incurs INR 100 in BCD, an additional INR 10 SWS would be applicable.

Integrated GST (IGST) in Battery Imports

In addition to BCD, imported goods in India attract Integrated GST (IGST) at the point of import, equivalent to the GST that would apply on the domestic supply of the goods. IGST on imports is levied on the sum of the import value + customs duties, and it is typically fully adjustable against output GST for businesses. The IGST rates for batteries vary by type/usage of the battery, as set by the GST Council.

Heading No.	ITC HSN Code(s)	Description	Unit	IGST Rate
8506	**PRIMARY CELLS AND PRIMARY BATTERIES**			
	8506 10 00	Manganese dioxide	NOS	18%
	8506 30 00	Mercuric Oxide	NOS	18%
	8506 40 00	Silver Oxide	NOS	18%
	8506 50 00	Lithium	NOS	18%
	8506 60 00	Air-Zinc	NOS	18%
	8506 80 10	Button Cells	NOS	18%
	8506 80 90	Other	NOS	18%
	8506 90 00	Parts	KGS	18%
8507	**ELECTRIC ACCUMULATORS, INCLUDING SEPARATORS THEREFOR, WHETHER OR NOT RECTANGULAR (INCLUDING SQUARE)**			
	8507 10 00	**Lead-acid, of a kind used for starting piston engines**	NOS	**28%**
	8507 20 00	**Other lead-acid accumulators**	NOS	**28%**
	8507 30 00	**Nickel-Cadmium (Ni-Cd)**	NOS	**28%**
	8507 40 00	**Nickel-Iron (Ni-Fe)**	NOS	**28%**
	8507 50 00	**Nickel-metal hydride (Ni-MH)**	NOS	**28%**
	8507 60 00	**Lithium-ion**	NOS	**18%**

	8507 80 00	**Other accumulators**	NOS	**28%**
	8507 90 10	**Accumulator cases made of hard rubber and separators**	KGS	**28%**
	8507 90 90	**Other**	KGS	**28%**
8548	**WASTE AND SCRAP OF PRIMARY CELLS, PRIMARY BATTERIES AND ELECTRIC ACCUMULATORS; SPENT PRIMARY CELLS, SPENT PRIMARY BATTERIES AND SPENT ELECTRIC ACCUMULATORS; ELECTRICAL PARTS OF MACHINERY OR APPARATUS, NOT SPECIFIED OR INCLUDED ELSEWHERE IN THIS CHAPTER**		NOS	**18%**
8549	**ELECTRICAL AND ELECTRONIC WASTE AND SCRAP CONTAINING PRIMARY CELLS, PRIMARY BATTERIES, ELECTRIC ACCUMULATORS, MERCURY-SWITCHES, GLASS FROM CATHODE-RAY TUBES OR OTHER ACTIVATED GLASS, OR ELECTRICAL OR ELECTRONIC COMPONENTS CONTAINING CADMIUM, MERCURY, LEAD OR POLYCHLORINATED BIPHENYLS (PCBS)**		KGS	**18%**

GST Reforms 2025:

Earlier, lithium-ion batteries attracted 18% GST, and other batteries attracted 28% GST. Henceforth, all batteries under heading 8507 (HSN Code) will be uniformly taxed at 18% GST. The updated IGST rates for batteries vary by type/usage of the battery as per the Recommendations of the 56th Meeting of the GST Council as follows:

Heading No.	ITC HSN Code(s)	Description	Unit	Old IGST Rate	New IGST Rate
8507	**ELECTRIC ACCUMULATORS, INCLUDING SEPARATORS THEREFOR, WHETHER OR NOT RECTANGULAR (INCLUDING SQUARE)**				
	8507 10 00	**Lead-acid, of a kind used for starting piston engines**	NOS	**28%**	**18%**
	8507 20 00	**Other lead-acid accumulators**	NOS	**28%**	**18%**
	8507 30 00	**Nickel-Cadmium (Ni-Cd)**	NOS	**28%**	**18%**
	8507 40 00	**Nickel-Iron (Ni-Fe)**	NOS	**28%**	**18%**
	8507 50 00	**Nickel-metal hydride (Ni-MH)**	NOS	**28%**	**18%**
	8507 60 00	**Lithium-ion**	NOS	**18%**	**18%**
	8507 80 00	**Other accumulators**	NOS	**28%**	**18%**
	8507 90 10	**Accumulator cases made of hard rubber and separators**	KGS	**28%**	**18%**

	8507 90 90	**Other**	KGS	**28%**	**18%**

Import Duty Calculation Example for HSN Code 85076000 (Lithium-Ion Batteries)

Component	**Formula**	**Calculated Amount (INR)**
Cost, Insurance, and Freight (CIF) Value		1,00,000
Landing Charges (LC) (1% of CIF Value)	LC rate x CIF Value	1,000
Assessable Value (AV)	CIF Value + LC	1,01,000
Basic Custom Duty (BCD) (20% for Li-Ion)	BCD rate x AV	20,200
Social Welfare Surcharge (SWS) (10% of BCD)	SWS rate x BCD	2,020
IGST (18% for Li-ion)	IGST rate x (AV+BCD+SWS)	22,179.60
Total Duty Payable	**BCD + SWS + IGST**	**44,399.60**

Exemptions, Concessions and Policies in the Renewable Energy and Grid-Scale Energy Storage Sector

Large battery energy storage systems for renewable integration and grid support (using lithium-ion or other chemistries) also stand to benefit from certain tax policies:

- **GST on Storage Batteries:** As mentioned, lithium-ion batteries (which dominate grid-scale ESS projects) are at 18% GST, while other battery types (lead, flow, etc.) are 28%. Industry groups such as India Energy Storage Alliance (IESA) have been urging that all batteries be taxed uniformly at 5% or 18% instead of penalising non-Li-ion chemistries. The rationale is to promote energy storage adoption for renewable energy, regardless of chemistry. Thus far, the concession has only been given to Li-ion batteries at 18% GST.
- **Customs Duty on ESS Imports:** Sector-specific customs exemptions solely for RE storage have not been issued until now. However, indirect benefits exist. For example, the critical minerals duty exemptions in Budgets 2024-25 and 2025-26 make importing lithium, cobalt, etc., more cost-effective than before. This is expected to eventually reduce the cost of Li-ion batteries (whether for EV or grid storage).
- **Recycling and Second-Life Batteries:** The customs duty on imported waste and scrap of batteries has been eliminated recently, i.e., BCD on Li-ion battery waste/scrap was cut from 5% to 0% in Budget 2025. Also, waste/scrap of lead-acid batteries, cobalt waste, etc., are now at 0% BCD. Hence, companies can import spent batteries or battery scrap without any duty charges, facilitating recycling and recovery of materials, supporting a circular economy.

Viability Gap Funding to Support BESS Development in India

The Ministry of Power has approved an expanded Viability Gap Funding (VGF) scheme for 30 GWh of Battery Energy Storage Systems (BESS) on June 10, 2025. This builds upon the previous 2023 scheme that had supported 13.2 GWh, reflecting growing policy momentum to accelerate energy storage infrastructure. Of the newly announced 30 GWh BESS capacity, 25 GWh has been allocated across 15 Indian states, while 5 GWh is designated for National Thermal Power Corporation (NTPC). The INR 5,400 crore scheme is projected to mobilise investments worth approximately INR 33,000 crore, supporting India's

near-term BESS targets through 2028. Among the states, Rajasthan, Gujarat, and Maharashtra received the highest allocations at 4,000 MWh each, followed by Karnataka and Andhra Pradesh with 1,500 MWh each.

Under the original VGF scheme notified in September 2023, a budgetary provision of INR 3,760 crore was made for 4 GWh of BESS, later scaled to 13.2 GWh as battery costs declined. Initially estimated at INR 96 lakh/MWh, the VGF outlay was revised to INR 46 lakh/MWh or 30% of the capital cost, whichever is lower, on account of falling battery prices. The latest scheme further reduces this to INR 18 lakh/MWh, indicating greater cost efficiency and improved commercial viability of BESS solutions.

To access this funding, all eligible states and NTPC must submit their project proposals to the National Load Dispatch Centre within 30 days. These projects must be commissioned within 18 months from the battery energy storage purchase agreement (BESPA) or the power purchase agreement (PPA) signing date.

Parameters	**VGF Tranche - I (2023)**	**VGF Tranche - II (2025)**
BESS support	4 GWh (later increased to 13.2 GWh)	30 GWh
Budgetary allocation	INR 3,760 Cr	INR 5,400 Crore
Timeline	2023-2026	2025-2028
VGF amount	INR 96 lakh per MWh (later reduced to INR 46 lakh per MWh) or 30% of capital cost, whichever is lower	INR 18 lakh per MWh
Funding Source	Central grant	Power System Development Fund (PSDF)
Components	• Market component: 2.2 GWh • State component: 6 GWh • CPSUs: 5 GWh	• State Component: 25 GWh • NTPC: 5 GWh
Disbursement of VGF	• On financial closure: 10% • On COD: 45% • Completion of 1st year from COD: 15% • Completion of 2nd year from COD: 15% • Completion of 3rd year from COD: 15%	• On financial closure: 20% • On COD: 50% • Completion of 1st year from COD: 30%
Contract Period	10-12 years	12-15 years
Commissioning Period	24 months from the date of signing of BESPA	18 months from the date of signing of BESPA/PPA
Storage Duration	-	2 hours and 1.5 cycles per day (preferably)

Allocation of BESS Capacity Under the VGF Tranche–II Scheme:

S.N.	**State / Entity**	**BESS Capacity Allocation (MWh)**
1	Rajasthan	4000
2	Gujarat	4000

3	Maharashtra	4000
4	Tamil Nadu	1500
5	Karnataka	2000
6	Andhra Pradesh	2000
7	Madhya Pradesh	1500
8	Telangana	1500
9	Uttar Pradesh	1500
10	Haryana	500
11	Kerala	500
12	Punjab	500
13	Chhattisgarh	500
14	Odisha	500
15	Uttarakhand	500
16	NTPC	5000
	TOTAL	**30,000**

Input Tax Credit Availability on Battery

Input Tax Credit (ITC) is available on batteries in India, subject to certain conditions. Businesses can claim ITC on the GST paid on batteries purchased for use in their business operations. ITC cannot be claimed on batteries used for the manufacture of exempt goods or goods used for personal consumption. Additionally, the batteries must be purchased from a GST-registered supplier and must be accompanied by a proper invoice with the GST registration number of the supplier. ITC is the tax a business pays on its purchases, which it can claim back to lower the tax it owes when it sells products or services.

Regulatory Incentives and Exemptions for BESS Integrated with Renewable Energy

Inter-State Transmission Charge Waiver

The Ministry of Power (MoP) has extended a 100% waiver of inter-state transmission system (ISTS) charges for power transmitted from eligible renewable-plus-storage projects. Initially, RE projects were granted ISTS charge exemption for a specified period. In June 2025, the policy was expanded to include **BESS and pumped storage projects commissioned on or before June 30, 2028**. This waiver will be granted if the power from such BESS projects is consumed outside the state where these systems are commissioned. For any co-located BESS (battery storage at the same ISTS substation as a solar/wind plant) commissioned by that date, no ISTS fees will be levied on charging or discharging the battery for interstate use. For BESS projects that are not co-located, the ISTS charges waiver will be as per the extant orders issued by the Ministry of Power and the Central Electricity Regulatory Commission (CERC) regulations.

Possible Tax Incentives (GST and Customs Duties)

As of 2025, Lithium-ion batteries are taxed at 18% GST, while most other battery chemistries (lead-acid, sodium, flow batteries, etc.) face 28% GST. Industry groups like India Energy Storage Alliance (IESA) have strongly urged a unified 5% GST for all advanced batteries to align with the EV rate and reduce costs. In mid-2025, a government panel recommended slashing GST on batteries (and green hydrogen equipment) from 18% down to 5%, recognising that a lower tax would make storage more affordable and spur uptake. the recommendations of the panel will be placed before the GST Council at the next meeting that is scheduled for July 2025. The Council will make the final call on the tax rates.

Possible Customs Duty Exemptions:

***Battery Cells and Materials**:* Recognising that India currently imports most lithium-ion cells, the basic customs duty (BCD) on Li-ion cells for electric vehicles is at a low rate (around 5%), and in some cases, it is even waived. The Union Budget 2023-24 exempted import duties on specified capital goods and machinery for manufacturing lithium-ion cells (for EV batteries) until March 31, 2024. This exemption lowers the cost of setting up cell production lines.

Further, to secure raw materials, the Budget 2024-25 fully abolished import duties on 25 critical minerals, including Lithium, Cobalt, Nickel, etc., which are vital for battery production. These minerals previously had a 2.5-10% import duty, which has been totally exempted, making imports of lithium carbonate, cobalt, etc. cheaper for cell manufacturers. This is noted to help secure the availability of critical minerals for clean energy industries. These duty cuts on raw materials and minerals aim to reduce input costs by 5-7% for domestic battery manufacturers, ultimately lowering battery prices.

Imports for Use in Projects: For current RE projects with co-located BESS, a blanket project-import duty exemption is not present, especially since local solar/wind equipment manufacturing is encouraged. Going forward, as local battery cell gigafactories start production (from 2025 onward), the government has indicated it may increase duties on imported cells to safeguard the domestic industry.

State-Level Policies

Most state incentives for storage are indirect (riding on RE incentives like must-run status, duty exemptions, waiver of certain fees, etc.), since the central government is leading with explicit schemes (VGF, GST/duty reductions, PLI, etc.). For instance, Maharashtra and Tamil Nadu exempt RE (solar/wind) from state electricity duty and surcharges for 10-15 years. If a BESS is integrated behind-the-meter with a solar PV plant, the consumption of solar energy (even during non-sunshine hours via the battery) still enjoys those exemptions.

Production-linked incentives (PLI) Schemes for Battery Manufacturing in India

Production-linked incentives (PLI) schemes aim to give companies incentives on incremental sales from products manufactured in domestic units. It invites foreign companies to set up units in India; however, it also aims to encourage local companies to set up or expand existing manufacturing units.

National Programme on Advanced Chemistry Cell (ACC) Battery storage was approved by the Union Cabinet on 12.05.2021 with a budgetary outlay of **INR 18,100 crores**. This scheme will strengthen the ecosystem for Electric Mobility and Battery Storage in the country. The scheme envisages enhancing India's manufacturing capabilities of Advanced Chemistry Cell (ACC) by setting up Giga-scale ACC and battery manufacturing facilities in India with emphasis on maximum domestic value addition. This scheme will promote the Make in India initiative.

The scheme envisages the setting up of a cumulative ACC manufacturing capacity of 50 GWh for ACCs and an additional cumulative capacity of 5 GWh for Niche ACC Technologies. The manufacturing facility, as proposed by the beneficiary firm, would have to be commissioned within a period of 2 years. The subsidy will be disbursed thereafter over a period of 5 years. The beneficiary has to ensure achieving a domestic value addition of at-least 25% and incur the mandatory investment (INR 225 crore/GWh) within 2 Years (at the Mother Unit Level) and raise it to 60% domestic value addition within 5 Years, either at Mother Unit, in-case of an Integrated Unit, or at the Project Level, in-case of "Hub & Spoke" structure. The scheme has an initial 2 years of Gestation Period from the Appointed Date (AD) (01.01.2023 to 31.12.2024) and a five-year post-gestation period (01.01.2025 to 31.12.2029) is the Performance period.

Three beneficiary firms have been allocated a total capacity of 30 GWh, i.e. 20 GWh is now available for fresh allocation. These are:

Company	Allocated Capacity	Key Focus Areas
Reliance New Energy Ltd (a Reliance Industries subsidiary)	**20 GWh**	Integrated Giga-factory: Li-ion, Na-ion, solid-state batteries
Ola Electric Mobility Pvt Ltd	**20 GWh** (awarded 20, but executing 5 GWh in Phase 1)	EV battery cells, large-scale storage
Rajesh Exports Ltd (through subsidiary, ACC Energy Storage)	**5 GWh**	Li-ion cell manufacturing, export-oriented

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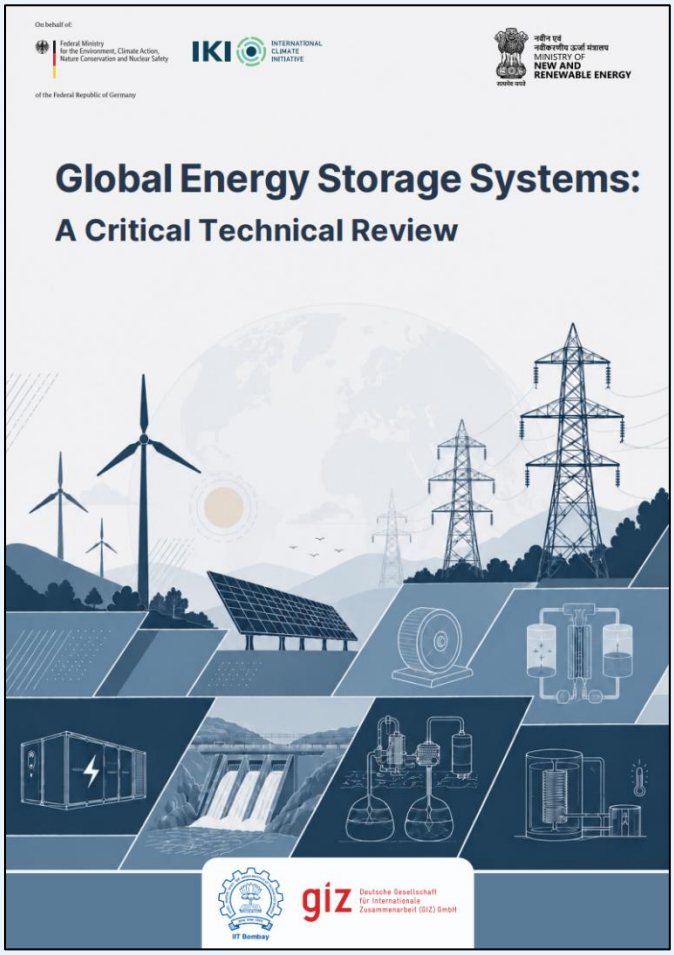
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