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Catalysing Energy Storage in India

From Procurement to Reliable Power

Report / March 2026

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All India Discoms Association (AIDA) is a not for profit collaboration platform representing a wide spectrum of electricity distribution entities of India. Our members are state government owned Distribution Companies, private sector Discoms, Electricity Departments of Union Territories and Franchisees.

AIDA serves as the unified voice of all electricity distribution entities in the country serving 345 million electricity consumers. Our core objectives include fostering collaboration among members, advocating for progressive policy and regulatory reforms, and driving holistic development across the power distribution sector.

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List of Abbreviations

AC	Alternating current
AC DR	Air conditioner demand response
A-CAES	Adiabatic compressed air energy storage
ACC	Annuitised capacity cost
ARENA	Australian Renewable Energy Agency
BESPA	Battery energy storage purchase agreement
BESS	Battery energy storage systems
BMS	Battery management system
BOO	Build-own-operate
BOOT	Build-own-operate-and-transfer
BoS	Balance-of-system
BTM	Behind-the-meter
BU	Billion units
C&I	Commercial and industrial
CAES	Compressed air energy storage
CAGR	Compound annual growth rate
CAISO	California Independent System Operator
CEA	Central electricity authority
CEM	Capacity expansion modelling
CERC	Central Electricity Regulatory Commission
CONE	Cost of new entry
CUF	Capacity utilisation factor
DAM	Day ahead market
DC	Direct current
D-CAES	Diabatic compressed air energy storage
DER	Distributed energy resource
DERMS	Distributed energy resource management system
DFR	Demand Fulfillment Ratio
DISCOM	Distribution company
DLS	Distribution located storage
DoD	Depth of Discharge
DOE	Department of energy
DR	Demand response
DRE	Decentralised renewable energy

DSM	Deviation settlement mechanism
EMS	Energy management system
EPC	Engineering, procurement, and construction
ESCO	Energy service company
ESS	Energy storage systems
EV	Electric vehicles
FDRE	Firm and dispatchable renewable energy
FERC	Federal Electricity Regulatory Commission
FoR	Forum of Regulators
FRP	Flexible ramping product
GES	Gravitational energy storage
GoI	Government of India
GUVNL	Gujarat Urja Vikas Nigam Limited
GW	gigawatt
GWh	gigawatt-hour
HP-DAM	High-price day-ahead market
HVAC	Heating, ventilation, and air conditioning
IEX	Indian Energy Exchange
IPP	Independent power producer
ISO	Independent system operator
kVA	kilovolt-amperes
kW	kilowatt
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelised cost of electricity
LCOS	Levelised cost of storage
LDES	Long duration energy storage
LFP	Lithium iron phosphate
LiB	Lithium-ion battery
LoA	Letter of award
MAB	Metal-sir battery
MIT	Massachusetts Institute of Technology
MoP	Ministry of Power, Government of India
MNRE	Ministry of New and Renewable Energy, Government of India
MW	megawatt
MWh	megawatt-hour
Na-S	Sodium-sulphur
NBI	Neighbourhood Battery Initiative
NIT	Notice inviting tender
NLDC	National Load Dispatch Centre

NREL	National Renewable Energy Laboratory
NRPC	Northern Region Power Committee
NTPC	National Thermal Power Corporation
O&M	Operations and maintenance
PCS	Power conversion system
PLI	Production-linked incentive
PPA	Power purchase agreement
PRAS	Primary reserve ancillary service
PRM	Planning reserve margin
PSP	Pumped storage projects
PV	Photovoltaic
R&D	Research and development
RA	Resource adequacy
RE	Renewable energy
RFP	Request for proposal
RFS	Request for selection
RRL	Ramp-rate limitation
RTC	Round-the-clock
RTE	Round-trip efficiency
RTM	Real time market
RTO	Regional transmission operator
SCADA	Supervisory control and data acquisition
SECI	Solar Energy Corporation of India
SERC	State electricity regulatory commission
SiB	Sodium-ion battery
SLDC	State load dispatch centre
SoC	State-of-Charge
SRAS	Secondary reserve ancillary service
T+D	Transmission and distribution
ToD	Time of day
ToU	Time of use
TRAS	Tertiary reserve ancillary service
TSC	Total system cost
UC	Unit commitment
UL	Underwriters Laboratories
US	United States
VGF	Viability gap funding
VPP	Virtual power plant
VRE	Variable renewable energy

Foreword

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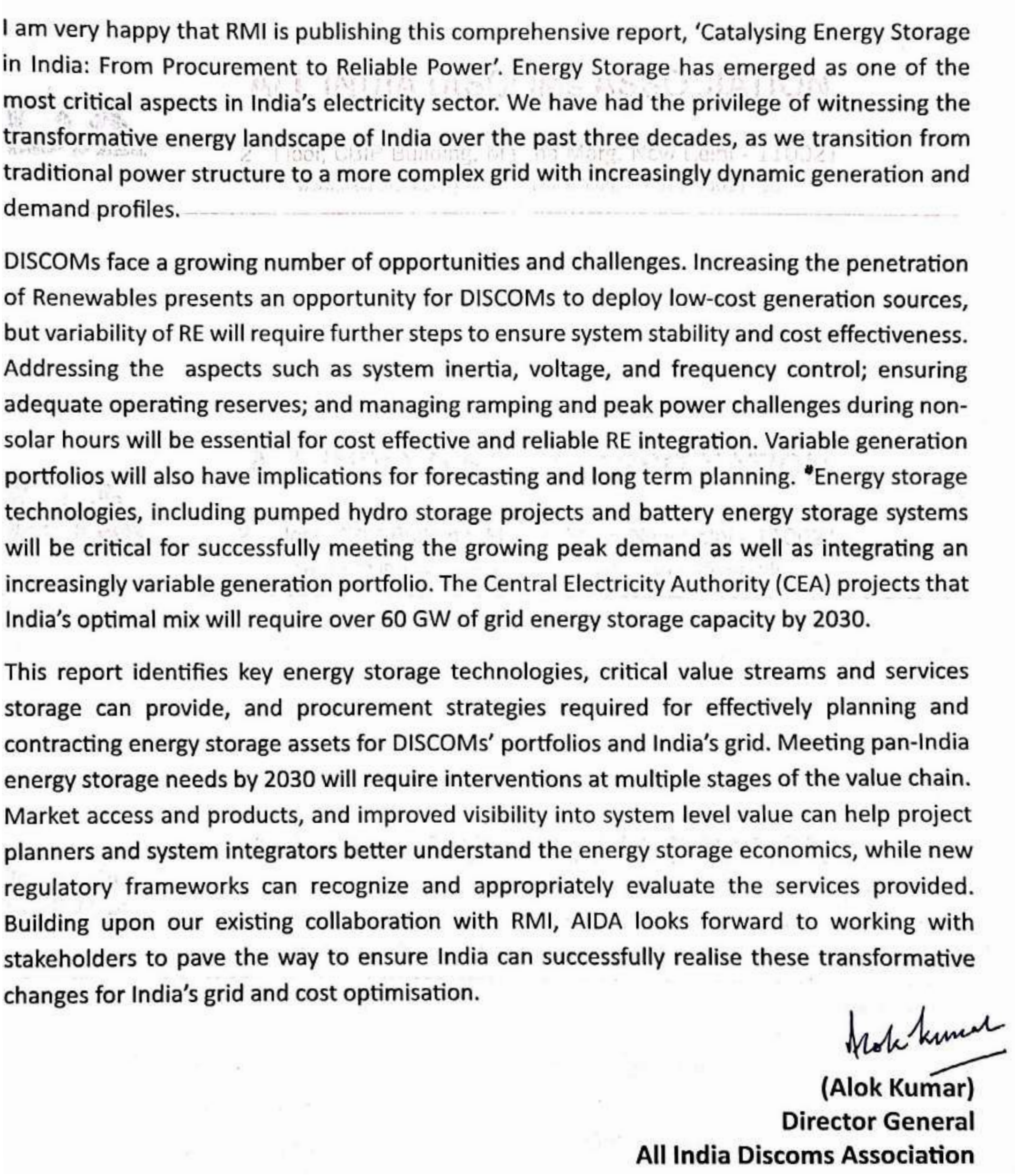


I am very happy that RMI is publishing this comprehensive report, 'Catalysing Energy Storage in India: From Procurement to Reliable Power'. Energy Storage has emerged as one of the most critical aspects in India's electricity sector. We have had the privilege of witnessing the transformative energy landscape of India over the past three decades, as we transition from traditional power structure to a more complex grid with increasingly dynamic generation and demand profiles.

DISCOMs face a growing number of opportunities and challenges. Increasing the penetration of Renewables presents an opportunity for DISCOMs to deploy low-cost generation sources, but variability of RE will require further steps to ensure system stability and cost effectiveness. Addressing the aspects such as system inertia, voltage, and frequency control; ensuring adequate operating reserves; and managing ramping and peak power challenges during non-solar hours will be essential for cost effective and reliable RE integration. Variable generation portfolios will also have implications for forecasting and long term planning. Energy storage technologies, including pumped hydro storage projects and battery energy storage systems will be critical for successfully meeting the growing peak demand as well as integrating an increasingly variable generation portfolio. The Central Electricity Authority (CEA) projects that India's optimal mix will require over 60 GW of grid energy storage capacity by 2030.

This report identifies key energy storage technologies, critical value streams and services storage can provide, and procurement strategies required for effectively planning and contracting energy storage assets for DISCOMs' portfolios and India's grid. Meeting pan-India energy storage needs by 2030 will require interventions at multiple stages of the value chain. Market access and products, and improved visibility into system level value can help project planners and system integrators better understand the energy storage economics, while new regulatory frameworks can recognize and appropriately evaluate the services provided. Building upon our existing collaboration with RMI, AIDA looks forward to working with stakeholders to pave the way to ensure India can successfully realise these transformative changes for India's grid and cost optimisation.

(Alok Kumar)
Director General
All India Discoms Association

Executive Summary

Building out sufficient energy storage will be essential for India's grid to successfully integrate increasing generation from variable renewable resources and meet the future load demand. Peak demand growth exceeding historic projections is one key factor driving challenges for India's electricity sector. India has also seen radical changes in its installed capacity mix, having already achieved the ambitious 2030 renewable energy deployment target of 50% cumulative electric power installed capacity from non-fossil fuel-based energy sources by summer 2025.[1]

Despite robust success with deployment, India's renewable sector is facing challenges in scaling growth. Since 2023, there has been a notable rise in post-bidding challenges of utility-scale renewable energy tenders, including under-subscription, delays in power purchase agreement (PPA) signings, and cancellations.[2] While solar power continues to become more competitive, the need to meet daily evening peak demand is pushing electricity distribution companies (DISCOMs) to procure from hybrid systems or stand-alone battery energy storage systems (BESS) or explore other options such as firm and dispatchable renewable energy (FDRE) and round-the-clock (RTC) agreements.[3]

To attain and sustain a reliable, cost-effective power grid, the Central Electricity Authority's (CEA) *National Electricity Plan (Generation)* projects that India's optimal energy mix will require over 60 GW of grid energy storage capacity by 2030. CEA's optimal mix projection encompasses multiple technologies, including 19 GW (128 GWh) of pumped storage projects (PSPs) and 42 GW (208 GWh) of BESS, the two leading storage technologies for the Indian grid by 2030.[4] As of July 2025, India has tendered 58 GWh of battery storage capacity, which is in various stages of development, but only about 0.5 GWh is currently operational. By streamlining procurement and operations, India can rapidly convert this tendering momentum into operational assets and scale up storage capacity manifold to meet its 2030 goals.

Storage technologies overview

The performance and cost-effectiveness of energy storage technologies vary by use case, with each technology suited to specific grid services depending on parameters like discharge duration, round-trip efficiency (RTE), and energy density. While energy density is less relevant for large-scale grid-connected projects, it becomes a critical constraint in urban distribution networks or behind-the-meter (BTM) settings.

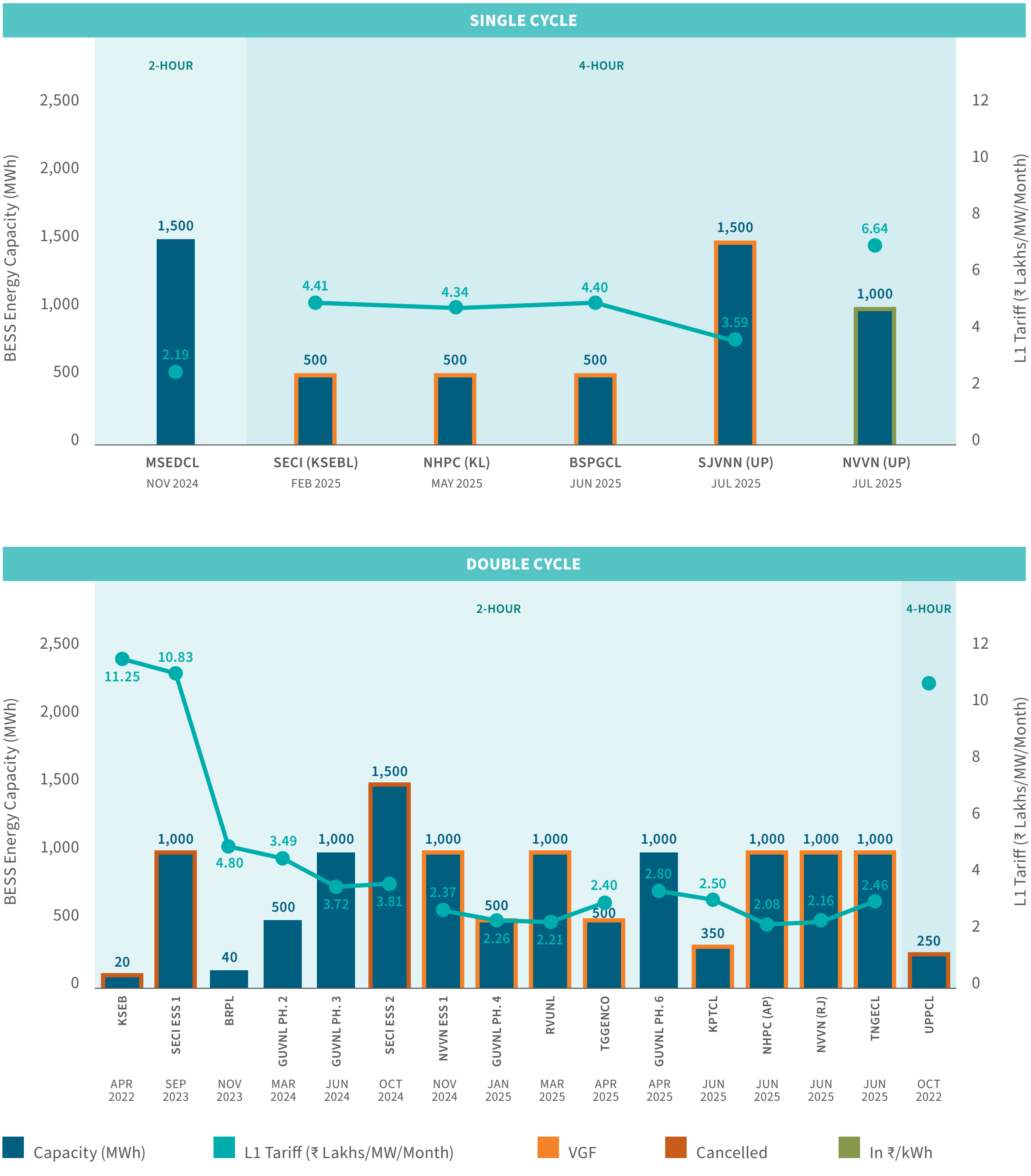
Lithium-ion batteries (LiBs), particularly lithium iron phosphate (LFP), currently dominate the Indian market due to their high RTE (~86%), modularity, and rapidly declining costs. However, there remains a strong interest in a variety of alternative storage technologies, including sodium-ion batteries, flow batteries, and mechanical storage solutions such as PSPs. PSP remains a cost-effective long-duration storage solution (8–10 hours) in the Indian context, though it is often constrained by long development timelines and site-specific requirements.

Selecting the appropriate storage technology will depend not only on performance metrics but also on life-cycle economics and supply chain considerations. For example, battery cells account for only approximately 35% of the total project cost, with balance-of-system (BoS), controls, and integration costs playing a significant role.[5] India has a cost advantage in BoS and engineering, procurement, and construction (EPC) compared to global markets, but the complexity of sourcing, standardisation, and logistics for key components remains a challenge.[6] The Indian power sector has an opportunity to scale up Li-ion BESS deployment in the short term while actively supporting domestic manufacturing and accelerating early pilots of alternative storage chemistries to build longer-term resilience and reduce costs. Strengthening domestic manufacturing through schemes like the Production-Linked Incentive (PLI) Scheme, while diversifying raw-material sourcing and investing in battery recycling, will be essential to ensure the secure and scalable deployment of storage technologies aligned with India's 2030 goals and beyond.

Storage procurment strategies

Declining battery costs and increasing project flexibility have made BESS a critical enabler for integrating variable renewable energy (VRE) and meeting peak demand. Globally, the Li-ion pack weighted average price dropped 20% to US$115/kWh (approximately ₹10,154/kWh) in 2024, the steepest annual decline since 2017.[7] Stand-alone BESS prices in India fell from around ₹10.83 lakh/MW/month in spring 2022 to ₹2.02 lakh/MW/month for two hours of storage and ₹3.59 lakh/MW/month for four hours of storage by summer 2025. Further reductions have been realised through a viability gap funding (VGF) subsidy for capital costs, culminating in a 75% cost decline (see **Exhibit ES1**).[8]

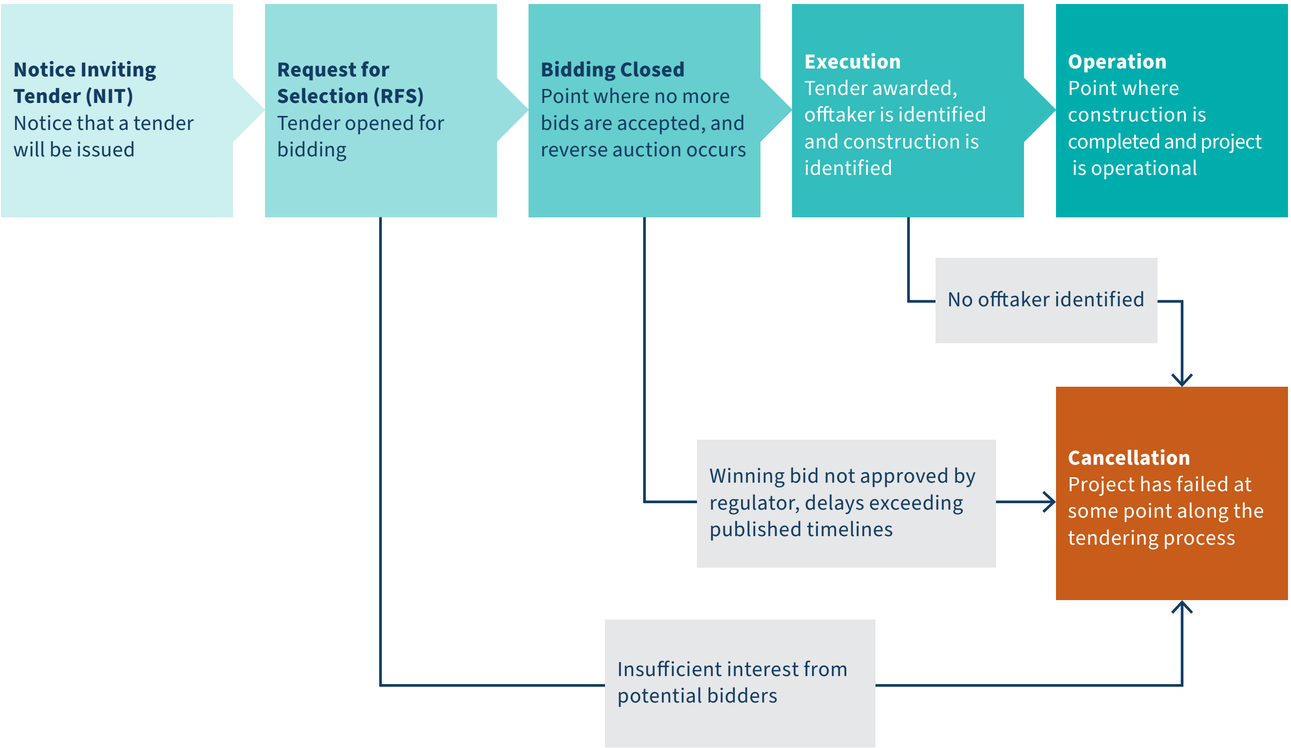
Exhibit ES1 Stand-alone BESS tariff trends, 2022–2025



RMI Graphic. **Source:** Adapted from "1H 2025 Energy Storage Update — India," Debmalya Sen, last modified July 2025, **https://www.linkedin.com/posts/debmalya-sen_1-h-2025-energy-storage-update-india-activity-7348873268998586368-i7ix**.

As costs decline, BESS is increasingly becoming an economic option for DISCOMs to serve end users. DISCOMs' needs for renewable energy and storage vary significantly based on factors such as demand growth, system peaks, portfolio mix, and regional characteristics. Their ability to procure BESS is further shaped by system readiness, institutional capacity, and access to finance. Given this diversity, a one-size-fits-all approach to storage procurement is not feasible. Instead, the inherent flexibility of BESS allows for a wide range of ownership, business, and contracting models that can be tailored to meet specific system needs. Globally and in India, utilities have adopted multiple procurement structures, including public–private partnerships with varying allocations of planning, financing, operational, and risk responsibilities. For DISCOMs, selecting an appropriate model requires careful planning within India's competitive public procurement framework to ensure transparency and cost-effectiveness (see **Exhibit ES2**).[9]

Exhibit ES2 Tendering process in India



Notice Inviting Tender (NIT)
Notice that a tender will be issued

Request for Selection (RFS)
Tender opened for bidding

Bidding Closed
Point where no more bids are accepted, and reverse auction occurs

Execution
Tender awarded, offtaker is identified and construction is identified

Operation
Point where construction is completed and project is operational

No offtaker identified

Winning bid not approved by regulator, delays exceeding published timelines

Cancellation
Project has failed at some point along the tendering process

Insufficient interest from potential bidders

RMI Graphic. **Source:** RMI Analysis

As more energy storage-linked projects go through the tendering process and reach the execution and operational phases, key learnings and best practices will emerge to reduce cancellation risk. Already, stakeholders in India have seen greater success in the tendering process. In 2022 and 2023, 10 out of 12 energy storage-linked tenders were cancelled. In 2024, tender cancellations fell significantly, with only two tenders being cancelled out of 35 issued.[10] There are two key trends: the number of energy storage-linked tenders issued annually is growing, while the number of cancellations is declining. There were no energy storage tender cancellations in the first half of 2025.[11] These trends indicate growing stakeholder familiarity and success with the tendering process.

DISCOMs have several ownership and contracting options when procuring BESS, ranging from direct asset ownership to third-party models such as PPAs with entities like the Solar Energy Corporation of India (SECI). While stand-alone BESS contracting offers flexibility, operational control, and value-stacking opportunities, it can also shift more performance and resource risks to the purchasing DISCOM. To meet growing demand and integrate VRE, DISCOMs are increasingly turning to innovative PPA configurations, including PV + BESS, FDRE, and RTC models.

Hybrid projects combining renewable energy generation and BESS are becoming increasingly popular. By combining generation and storage assets, DISCOMs and project developers can reduce infrastructure, material, land, and operation costs, while also potentially taking advantage of existing interconnection. Given the variable nature of VRE resources, the transmission capacity used to deliver the power may be underutilised for large portions of the year. A BESS asset co-located with VRE can reduce the transmission capacity needed to integrate these resources and increase the utilisation of the remaining capacity while also reducing curtailment of VRE generation.[12]

Within India, the PV + BESS model has gained growing attention, with 4,400 MW of PV capacity and 6,400 MWh of BESS capacity tendered in 2024 and discovered tariffs ranging from ₹3.09 to ₹3.52 per kWh with two to four hours of storage duration. Co-locating solar PV and storage allows DISCOMs to increase operational flexibility by moving generation from the middle of the day to evening hours. RMI's analysis shows that stand-alone solar costs approximately ₹3.1 per unit today. As battery storage is added, delivered energy costs rise nominally (see **Exhibit ES3**). For a 100 MW solar PV + 50 MW/100 MWh BESS system, the cost of energy is ₹4.0 per unit.[i] As DISCOMs increasingly explore solar PV + BESS systems, there is an opportunity to store low-cost renewable energy (RE) and use it to meet the growing evening peak demand.

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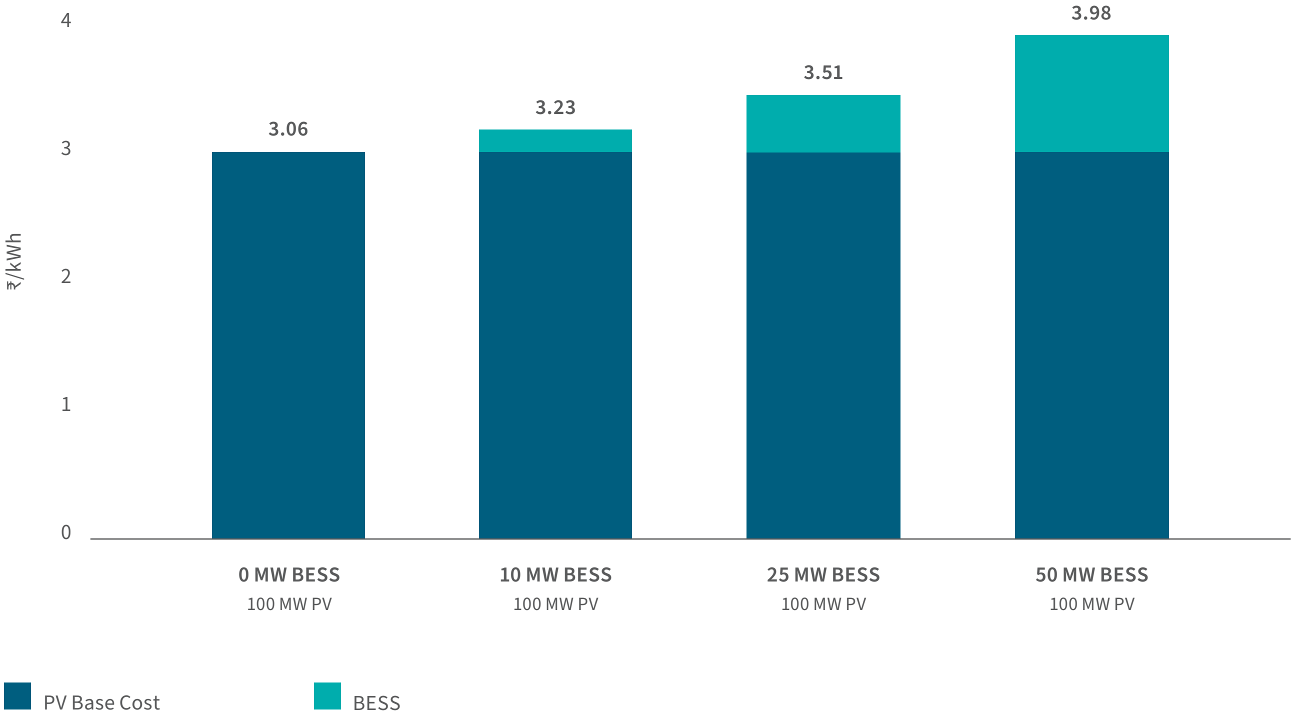
[i] Estimates are conservative and do not reflect the more recent, sharply declining prices observed in recent tenders. Refer to **Appendix E** for additional information.

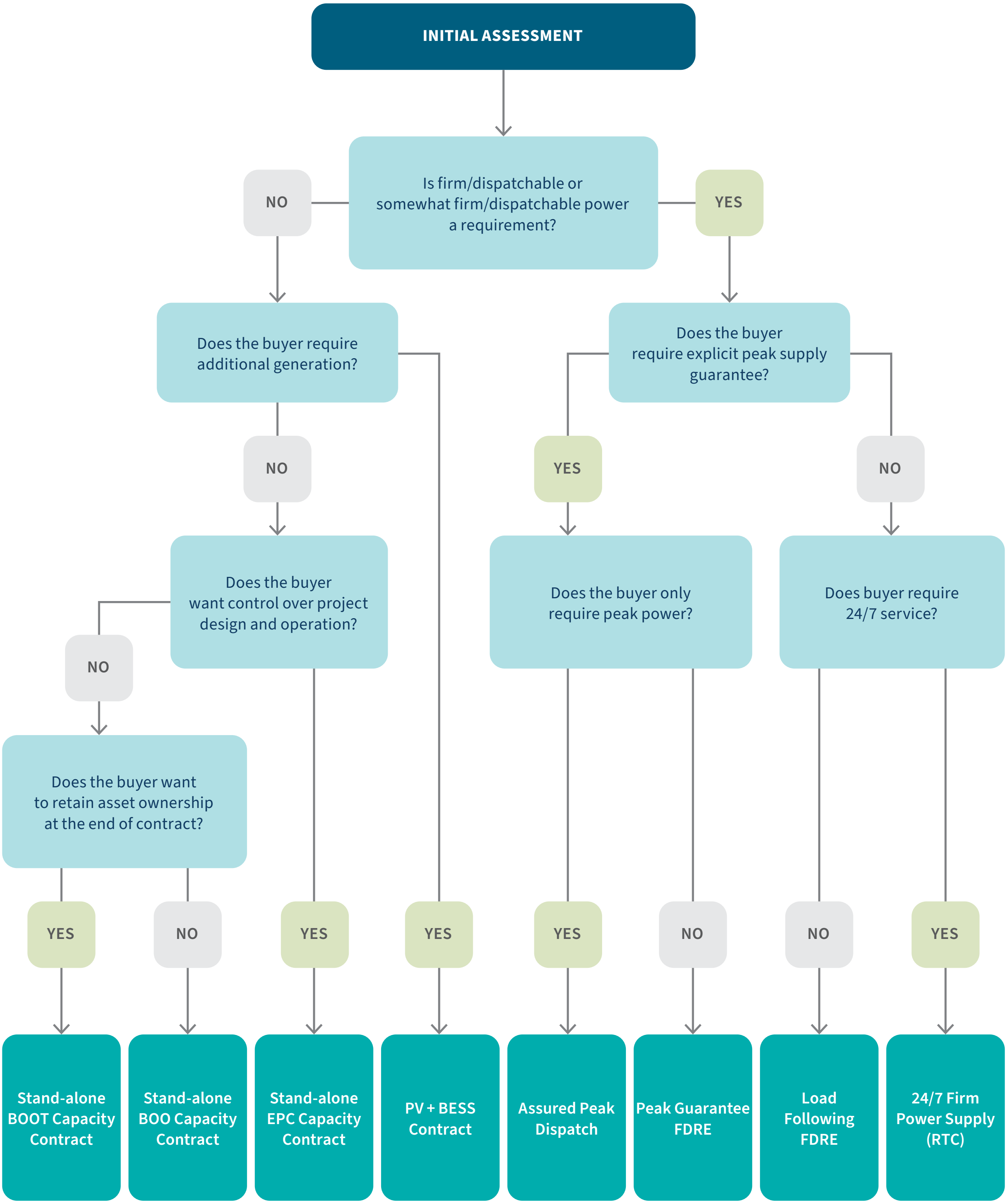
Exhibit ES3 Estimated cost impact adding BESS to solar PV generation projects



Note: See **Appendix E**: Methodology for calculating solar PV + BESS delivered energy costs.
RMI Graphic. **Source:** RMI Analysis

Selecting the right procurement pathway depends on a combination of need assessment, economic viability, risk appetite, and contract complexity. Stand-alone storage projects provide high levels of flexibility for DISCOMs, particularly those with a need for additional power capacity, but may involve higher risk and responsibility for the DISCOM to manage project development and operation. Simpler PV + BESS PPAs are suitable for near-term reliability needs, while FDRE contract models address longer-term dispatchability challenges, but require long-term load profile projections that may be challenging for DISCOMs with dynamic and evolving demand. However, such contracts may be especially appealing for large-scale commercial and industrial (C&I) consumers with more consistent and predictable electricity demand. For identification of key decisions that influence the suitability of the procurement model, see **Exhibit ES4**.

Exhibit ES4 Energy storage procurement options decision tree



Note: BOOT = build-own-operate-and transfer; BOO = build-own-operate.
RMI Graphic. **Source:** RMI Analysis

Battery energy storage system applications and value

BESS assets offer considerable flexibility in siting and sizing, allowing deployment across the electricity system — from co-location with solar photovoltaic (PV) to transmission, distribution, and BTM applications — each delivering system-level benefits such as load shifting, peak shaving, and capacity deferral.

Stand-alone BESS systems sited at the transmission or distribution network can shift the timing of power flows in the transmission and distribution network, as well as provide a range of critical functions, reducing load on key transmission corridors, substations, and transformers. This can help avoid costly equipment failures and extend the life of existing assets. These assets can also provide a range of other services, including ensuring the system remains balanced and shifting load through arbitrage. Mature markets with various products to meet system needs can create valuable avenues for stand-alone BESS participation. Indian markets are evolving fast, with the recent implementation of the market-based ancillary services to create a short-term market for BESS and progress on the resource adequacy (RA) framework guidelines and potential eligibility for BESS for capacity credits to provide long-term signals. However, these short-term and long-term market initiatives have yet to fully mature and achieve a streamlined implementation.

The BTM BESS installed at C&I or residential sites is regaining relevance due to rising utility tariffs (often exceeding ₹7/kWh), increasing demand (projected to be 8.2% compound annual growth rate [CAGR] for C&I consumers), and growing reliability concerns, especially with nighttime peak loads and electric vehicle (EV) charging.[13] BTM storage can offer backup power, improve power quality, manage demand charges, and enable participation in aggregated services like virtual power plants (VPPs). Aggregation of distributed energy resources (DERs), including rooftop solar, demand response (DR), and BTM BESS, can enable customers to access utility-scale value streams while supporting grid flexibility and resilience.

Pathways for accelerated storage deployment

The Government of India (GoI) has taken several policy initiatives laying the groundwork for an enabling environment for energy storage. These policies have included defining energy storage systems (ESS) and extending key RE generator benefits to energy storage assets, subsidies, and market development. The sharp decline in BESS costs over the past two years has contributed to a rise in the number of tenders issued. However, operational BESS capacity in India currently remains below 1 GWh, with a significant pipeline of new projects progressing from procurement to operations. Successfully commissioning and integrating these new BESS assets into DISCOM operations will be critical over the next few years to accelerate storage deployment in India.

As the market transitions from planning to execution, attention must now shift to improving tender design, streamlining regulatory approvals, and enhancing institutional capacity to operate and manage BESS assets effectively. Ensuring that storage resources are reliably integrated into system planning and daily operations will determine how quickly India can scale up deployment and realise the full value of storage across the grid.

The next step in accelerating deployment is to integrate BESS into power sector operations through action across four key pillars: procurement, market development, regulatory reform, and institutional capacity building. Immediate priorities include refining tender designs and minimising the cancellation of tenders with firmer commitment from DISCOMs in the procurement of hybrid or stand-alone BESS. In the medium term, expanding BESS participation in ancillary service markets, aligning capacity planning, and establishing clear capacity credit methodologies under the RA Framework will be key to unlocking the full value of storage. At the same time, modernising data systems, adopting standardised valuation tools, and building institutional knowledge through training and safety standards will ensure reliable, scalable, and efficient deployment and position DISCOMs to meet the increasing demand cost-effectively and reliably. Recommendations for accelerating energy storage deployment in India are summarised in **Exhibit ES5** below.

Exhibit ES5 Energy storage recommendations

Pillar	Focus Area	Near-Term Recommendations	Medium-Term Recommendations
Procurement	Tender Design	Refine tender guidelines for BESS and hybrid projects	Align local and central planning
Market Development	Monetising Value Streams	Clarify BESS capacity rules for RA and the pathway for ancillary service participation	Consider additional appropriate market products
Regulatory Reforms	Accelerate Project Regulatory Review and Approval	Guide DISCOMs and state regulators on BESS value streams and evaluation methodology; derisk project cancellations	Deploy technological and software interventions to improve system optimisation and BESS integration
Institutional Knowledge Building	Ensure State and Central Participants are prepared to integrate BESS	Needs assessment for addressing state-level entities' BESS knowledge gaps	Establish BESS Knowledge Hub

RMI Graphic. **Source:** RMI Analysis

Accelerating procurement

Near-Term Recommendations

Provide additional guidance for BESS or hybrid project request for proposal (RFP) and tender design.

While existing guidelines set a useful standard for bidding on energy storage projects, additional guidance for RFP design would help procuring entities and developers appropriately plan for bids and projects and avoid conflicts in design and operation.

Medium-Term Recommendations

Align capacity and network planning.

As the RA framework is implemented, a process should be developed to align local capacity and national and regional grid network planning. Concurrently, a transparent tariff and the system implication planning should be undertaken.

Market development

Near-Term Recommendations

Provide additional RA framework implementation clarity.

This includes insight for DISCOMs on RA implementation and enforcement, and strategies for least cost integrated resources planning. Institutional knowledge building for DISCOM and the State Electricity Regulatory Commission's (SERC) staff should be initiated to create internal capabilities to plan, evaluate, and execute RA assessments. BESS assets should also be explicitly recognised as able to serve as a capacity resource under the RA framework. The guidelines on the RA Framework by the Ministry of Power, Government of India (MoP), released in June 2023, are a starting point. Building upon it, additional clarity is needed for DISCOMs on RA implementation and enforcement.

Amend and adopt methodology for calculating capacity credits under the RA Framework.

Successful implementation of capacity credit and coincident peak requirements hinges on clear, transparent requirements and careful deliberation of key parameters. This draft discussion should be codified with amendments, including additional clarity on how battery storage capacity credits are calculated.

The capacity credit methodology for storage devices, for example, should consider state-of-charge (SoC) awareness, with full capacity credit if the asset contains sufficient SoC to provide power at rated power capacity during peak demand hours. FDRE and hybrid resources should be considered for capacity credit eligibility after evaluating system and stakeholder benefits.

Shift ancillary services procurement to market mechanisms.
Of the three ancillary service products in India's electricity system, only tertiary reserve ancillary services (TRAS) are currently procured through a market-based mechanism. Both secondary reserve ancillary services (SRAS) and primary reserve ancillary services (PRAS) should be exchanged on the market, and BESS must be enabled to compete for all categories.

Publicly report clearing prices for all market products and other ancillary services.
Publicly available data on the clearing of ancillary services prices will provide market signals to project planners and developers on an asset's economic viability and will enable the discovery of the marginal cost for meeting peak power and ancillary services.

Revisit commitment charges.
Resources participating in ancillary services markets receive a commitment charge for the hours that they are cleared to supply/withdraw energy, regardless of whether energy is dispatched. Raising the cap on commitment charges will incentivise participation in ancillary markets, as BESS can get more value from being available to provide ancillary services for many hours of the day.

Medium-Term Recommendations

Introduce additional market products.
Services such as fast frequency response, voltage support, black start, and capacity can be economically provided through market products and aid in both immediate and longer-term project planning.

Addressing load shedding.
Some buyers are reluctant to participate in the power exchanges, especially during periods of higher prices, preferring to shed load. Compensation should be in line with regulations to incentivize behavior that ensures power reliability.

Regulatory reforms

Near-Term Recommendations

Adopt a clear methodology for state regulators and DISCOMs to assess BESS service value.

The value for BESS services will vary heavily depending on local conditions and needs. However, the lack of agreed-upon evaluation methods creates project approval risk. The Central Electricity Regulatory Commission (CERC) and state-level regulators should undertake a workshop to develop clear, agreed-upon methodologies to calculate a project's value across multiple services.

Achieve uniform technological readiness across all state-level entities.

Governance mechanisms should be adopted by DISCOMs and other stakeholders to provide an accurate status of current communications systems, and a scheme should be developed to modernise all communications systems.

Develop standardised data disclosure forms and mandate data reporting in regulations.

State-level data on load profiles, generation, deployment, and substation and feeder performance will be critical for project planning and finding critical metrics such as the value of "lost load" and curtailment frequency.

Medium-Term Recommendations

Deploy software interventions that enable optimal operation of BESS.

Once legacy communications systems are identified, upgraded, and automated, a roadmap should be created to prepare for the integration of software to improve system intelligence. This will require revised grid modernisation programmes and studies of area control errors and frequency deviations.

Create a publicly accessible data repository to collect and archive state-level data.

Once standardised reporting forms are developed and reporting is mandated, a central repository should be created where data reported by state-level entities will be readily accessible.

Institutional knowledge building

Near-Term Recommendations

Develop institutional knowledge and capability-building programmes for state-level entities.

SERCs, state load dispatch centres (SLDCs), and DISCOMs will require additional training and support to close knowledge gaps around BESS project planning, grid services, operation, and contribution to RA. RA planning and the role BESS plays should be aligned with SERCs' regulatory evaluation process. State-level entities should be aware of BESS's capability to provide not just energy, but capacity and non-wired alternative services.

Medium-Term Recommendations

Establish a centralised BESS Knowledge Hub.

A publicly accessible means to compile findings from BESS pilots across the power system should be created to allow for learnings and best practices to be shared with all stakeholders.

Through implementation of these recommendations, BESS assets in India will have greater access to markets that enable them to provide full value to the power system, while being a part of a holistic and economic planning process of the power sector and DISCOMs. As India shifts from improving electricity access to improving the quality of electricity service and reliability, new regulatory frameworks and business models need to be developed and implemented to support these needs. DISCOMs have a unique opportunity to play a role in integrating BESS in their portfolios. These actions are the next steps to improving the conditions for deploying innovative technology solutions, helping India become a global leader for energy storage, successfully integrate renewables with growing demand, and provide a model of energy transition to the world.

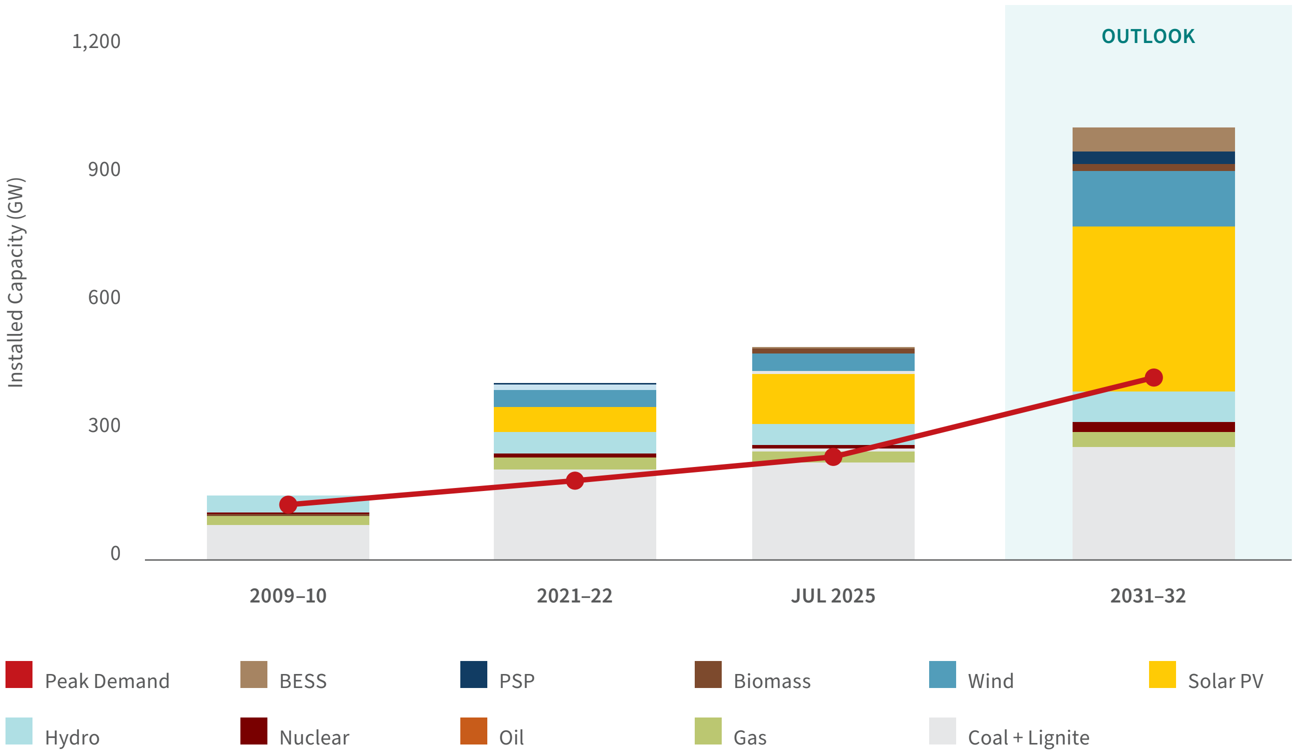
Introduction

India's power sector continues to face pressure from rapid growth in peak electricity demand. A crisis occurred in summer 2024, when peak demand exceeded 250 GW by May 30, and the CEA estimated a 14 GW shortage.[14] The peak demand shortage in 2024 was the largest such shortfall in 14 years and required the government to take drastic steps to minimise load shedding, including shifting planned maintenance of power plants and reviving thermal plants under extended outages.[15] In addition, distribution networks are under strain due to peak demand growth, including transformer failures that lead to outages. In the first two and a half months of 2024, 578 transformers failed in Kerala due to overheating and excessive load.[16] Additional failures and infrastructure stress compound costs, exacerbating existing challenges posed by global transformer shortages, where the procurement time has more than doubled from 50 weeks in 2021 to two years in 2024.[17]

Peak demand growth exceeding historic projections is one key factor driving challenges for India's electricity sector. India has also set ambitious renewable energy deployment targets, including having 50% cumulative electric power installed capacity from non-fossil fuel-based energy sources by 2030.[18] By the end of July 2025, India's total non-fossil fuel-based energy capacity reached 246.2 GW; 31.8 GW of solar capacity and 5.06 GW of wind capacity were added from July 2024 to July 2025 (see **Exhibit 1**).[19, ii]

[ii] For additional detailed system capacity projections across 2030 studies, see **Appendix A**.

Exhibit 1 Installed capacity by FY 2031–32 projected



Note: Projections are based on CEA's *Base Scenario of the Optimal Generation Mix 2030* study. It finds the optimal generation capacity mix to meet the projected regional peak electricity demand and electrical energy requirements, considering possible technology options, intermittency associated with VRE sources, and constraints (fuel availability, technical operational constraints, financial considerations, etc.).

RMI Graphic. **Source**: *Report on Optimal Generation Mix 2030 Version 2.0,* Government of India, Ministry of Power, Central Electricity Authority, 2023, **https://cea.nic.in/wp-content/uploads/irp/2023/05/Optimal_mix_report__2029_30_Version_2.0__For_Uploading.pdf**; *All India Installed Capacity (in MW) of Power Stations (As on 31.07.2025) (UTILITIES),* Government of India, Ministry of Power, Central Electricity Authority, 2025, **https://cea.nic.in/wp-content/uploads/installed/2025/07/IC_July_2025_allocation_wise_approved.pdf**.

Despite robust success with deployment, India's renewable sector is facing challenges in scaling growth. Since 2023, there has been a notable rise in post-bidding challenges of utility-scale renewable energy tenders, including undersubscription, delays in power agreement signings, and cancellations.[20] While solar and wind continue to become more competitive, the need to meet daily peak demand is shifting sector demand to hybrid or capital-intensive projects such as FDRE, RTC tenders, or storage projects such as BESS or pumped storage projects (PSPs).[21, iii]

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iii. Pumped storage projects is the preferred term in India but may also be referred to as hydro-pumped storage projects or pumped hydro storage in other geographies. For this report, pumped storage projects will be utilised.

Building out sufficient energy storage will be essential for India's grid needs to successfully integrate increasing generation from VRE resources and to meet future demand. ESS can provide multiple services to power networks, most importantly, saving excess renewable energy during periods of high generation and releasing it when needed.[22] ESS can address intermittent and variable generation challenges by providing grid stability and flexibility services such as contingency reserves, inertia support, power reliability, renewables firming and smoothing, managing system congestion, and peaking capacity.[23]

To maintain a reliable and economical power grid, CEA's *National Electricity Plan* projects that India's optimal mix will require more than 60 GW of grid energy storage capacity by 2030. CEA's optimal mix projection encompasses multiple technologies, including PSP and BESS, two leading storage technologies for the Indian grid by 2030 (see **Exhibit 1**, page 24).[24] PSP and BESS are examples of complementary technologies that can improve grid reliability and performance, with the determination of the appropriate energy storage technologies dependant on the use case. Factors for determining the appropriate technology to meet the targeted use case include duration of grid application required, required response time, cycle frequency required, physical site and size necessities, deployment timeframe, and competitiveness of power capacity and energy capacity costs.[25, iv]

The Government of India (GoI) has enacted several impactful policies, laying the groundwork for an enabling environment for energy storage. These policies include defining ESS, extending key RE generator benefits to ESS assets, subsidies, market development, and procurement targets. The National Framework for Promoting Energy Storage Systems, released by the MoP in August 2023, details these policies and is a step towards creating a comprehensive national roadmap for accelerating storage development in the coming years. In February 2025, CEA issued an advisory for renewable energy implementing agencies and state utilities to incorporate a minimum of two-hour co-located ESS equivalent to 10% of installed solar project capacity in future solar tenders.[26]

This report explores the opportunities for accelerating energy storage deployments within India, with an emphasis on addressing near-term to mid-term barriers for grid-scale battery storage project development. It aims to provide policymakers, regulators, and industry stakeholders with a comprehensive understanding of storage technologies, current trends on battery storage costs and procurements, understanding the full value of battery storage assets, and actionable solutions to unlock the full potential of storage in India's power sector.

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iv. Power capacity cost is defined as rupee per installed megawatt (₹/MW); energy capacity cost is defined as rupee per generation (₹/MWh).

The report is organised as follows:

- **Landscape of Energy Storage Technologies** includes an overview of the energy storage landscape, including reviewing key performance and financial metrics for energy storage technologies applicable for meeting stationary storage needs, an introduction to key energy storage technologies, and a comparative framework for assessing suitability for technologies to meet end uses.

- **Battery Storage Cost and Procurement** provides an overview of BESS project cost trends and ownership and contracting models, and reviews projects and outcomes that have been explored to date in India.

- **Battery Storage Applications and Value** provides an overview of battery value streams, including generator-sited, network-sited, and behind-the-meter, and an assessment of monetisability status in India as part of current tenders.

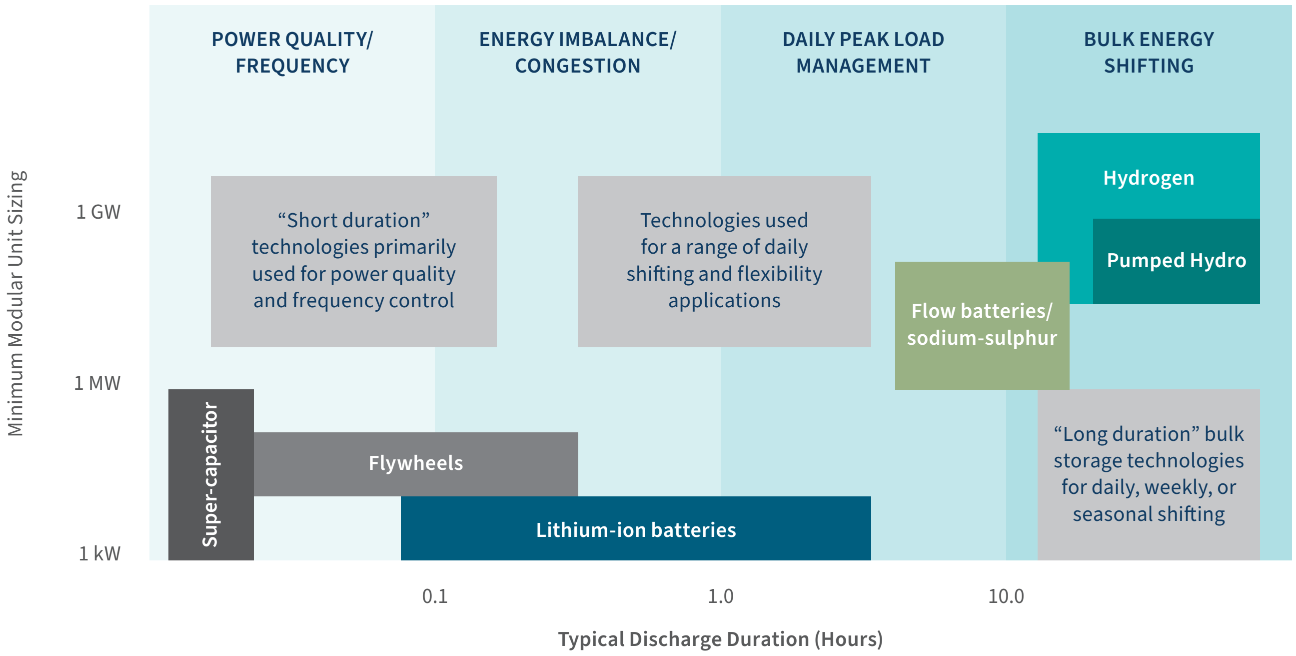
- **Pathways for Incentivising Storage Deployment** provides recommendations for accelerating energy storage deployment in India.

Landscape of Energy Storage Technologies

Rapid global growth of electricity demand, coupled with increasing VRE generation, has driven a renewed interest in grid-scale energy storage. Within India, CEA projections estimate installed capacity of at least 19 GW (128 GWh) of PSP, and approximately 42 GW (208 GWh) of BESS will be required to integrate 392 GW of VRE (100 GW of wind, and 292 GW of solar) by 2030 to meet future demand cost-effectively.[27]

Different energy storage technologies' technical and financial performances may be preferable for various use cases. Innovations in energy storage technology can potentially disrupt current assumptions about energy storage cost, safety, energy and power density, and performance (see **Exhibit 2**, next page).[28] To efficiently meet system needs, planners and DISCOMs will require a comparative framework for the performance and financial characteristics of energy storage technologies.

Exhibit 2 Energy storage technologies and their applications



Note: Approximations for illustrative purposes, reflect typical minimum modular unit size. Projects utilitising these technologies, such as lithium-ion BESS, can scale from kW to MW to GW depending on project need and design.

RMI Graphic. **Source**: Adapted from "Energy Storage 101," StorageWiki, Electric Power Research Institute, last edited December 13, 2024, **https://storagewiki.epri.com/index.php/Energy_Storage_101**.

Performance parameters and characteristics

The energy storage technology landscape is evolving rapidly, with multiple emerging technologies heading towards commercialisation this decade. The suitability of technologies to provide services will be determined by their specific performance parameters and characteristics. These metrics will also influence the scalability of the technology, how and where the technology can be sited, and appropriate grid applications. For example, energy density is not a critical consideration for most utility-scale storage projects, especially when connected at generation or transmission.

Yet energy density may be a more important factor for projects in dense urban settings, such as distribution-linked storage or BTM applications, where space is a constraint. Other performance metrics, such as discharge duration and RTE, are key for determining a project's levelised cost and which services a technology can economically provide. Storage performance parameters are defined in **Exhibit 3** on page 29.[29]

Exhibit 3 Storage performance parameters

Parameter	Unit	Description
Design Parameters		
Nominal Power Capacity	kW	The rated amount of power that can be charged and discharged.
Power Density - Gravimetric	kW/kg	Nominal power capacity divided by system mass.
Power Density - Volumetric	kW/m^3	Nominal power capacity divided by system volume.
Nominal Energy Capacity	kWh	The rated amount of energy that can be discharged.
Energy Density - Gravimetric	kWh/kg	Nominal energy capacity divided by system mass.
Energy Density - Volumetric	kWh/m^3	Nominal energy capacity divided by system volume.
Depth of Discharge	$\%_{cap}$	Energy capacity that can be charged/discharged without severely degrading nominal energy capacity, measured relative to full capacity.
Usable Energy Capacity	kWh	Energy capacity that can be discharged, accounting for the depth of discharge (DoD).
Energy-to-Power Ratio	Hours	Usable energy capacity divided by nominal power capacity.
Discharge Duration	Hours	Time to discharge usable energy capacity at nominal power. Same as energy-to-power ratio.
Max C-rate	1/Hours	The maximum rate at which the storage system can discharge relative to its usable energy capacity. Inverse of energy-to-power ratio or discharge duration.
Response Time	Seconds	Time between the idle state and the maximum power.
Operational Parameters		
State of Charge	$\%_{cap}$	The fraction of energy stored at any moment in time, measured relative to full capacity.
Round-Trip Efficiency	%	Proportion of energy discharged over energy required to charge for a full charge-discharge cycle.
Self-Discharge	$\%_{cap}$	Unavoidable loss of state of charge that occurs when a storage system is idle. This loss is highly dependent on the usage profile and can be measured per cycle or averaged across all cycles in a year.
Degradation	$\%_{cap}$ per year; $\%_{cap}$ per cycle	Rate of loss of usable energy capacity incurred by cycles and/or time lapse due to changes in state of charge or operational temperature.
Cycle Life	#	Number of complete charge-discharge cycles before the end of usable life.
Technical Lifetime	Years	Number of years before the end of usable life with no operation.
State-of-Health	%	Actual energy capacity relative to nominal energy capacity.
End-of-Life Threshold	%	Actual energy capacity relative to nominal energy capacity at which the storage system is taken out of service.

RMI Graphic. **Source:** *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value,* Oliver Schmidt and Iain Staffel, Oxford University Press, 2023.

Financial metrics and characteristics

For system planners and project developers, determining the suitability of a specific energy storage project or technology to deliver a targeted end service requires balancing technical performance with economic considerations. Assessment of a storage project's economic viability must encompass the full range of cost categories, including installed cost, operations, and decommissioning. Planners and developers can also take multiple approaches for analysing a storage project's cost. Total project cost, specific power, and specific energy costs are metrics for determining either the entire system or component costs; the levelised cost of storage and the annuitised capital cost are common approaches for developers and offtakers to determine per-unit costs. For planners and grid operators, total system cost is a way to assess the system costs and benefits of storage deployment. This section will review cost categories, financial metrics, and how and when to apply them.

Cost categories

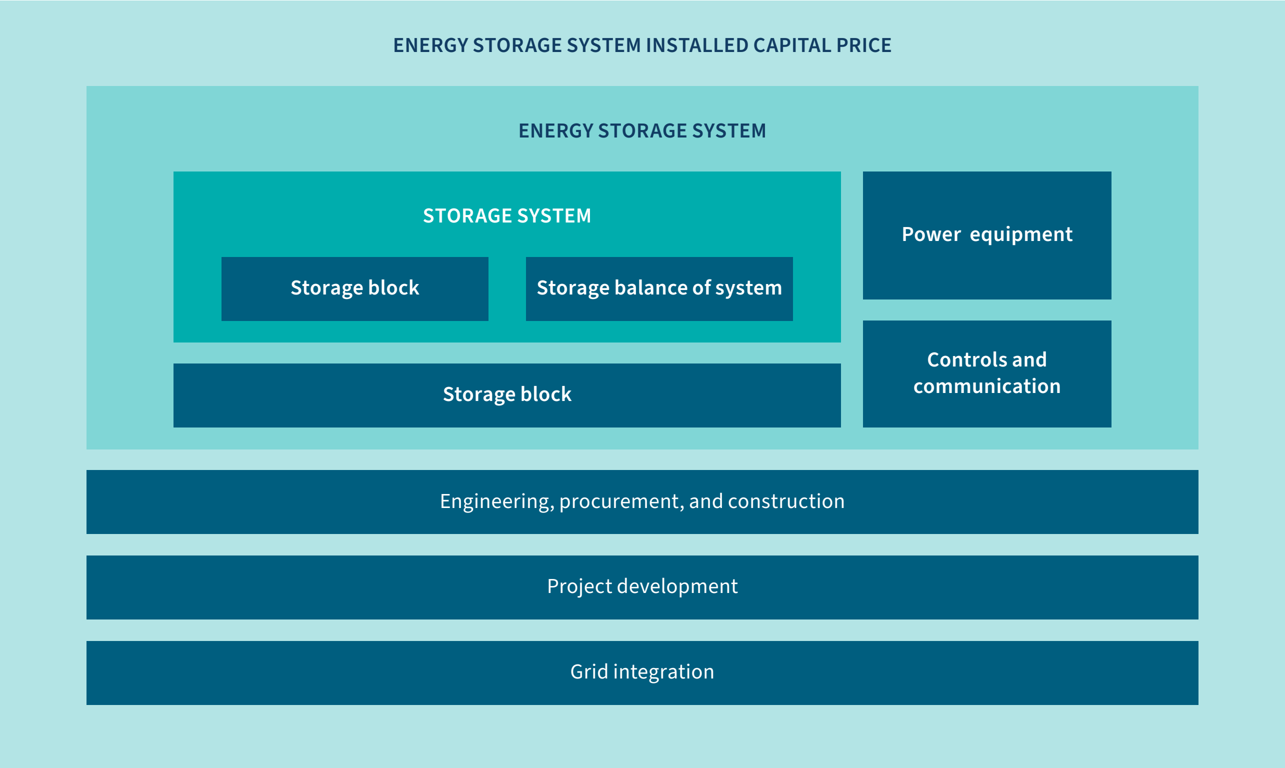
The cost of an energy storage project is influenced by several factors across three principal categories: installed capital cost, operating cost, and decommissioning cost. One key consideration is that the total scope of energy storage project costs extends beyond material costs.

Installed capital price

Installed capital price encompasses the up-front costs required for building a storage project, including the necessary hardware, software, communications systems, labour, site development, and system integration (see **Exhibit 4** page 31).[30] The exact composition of these costs will vary by technology.

For battery storage, the storage block comprises the battery modules and racks, while the balance of system includes containers; heating/cooling system; safety disconnects; and fire extinguishers. However, for PSP, reservoirs comprise the entire storage system. For a detailed breakdown of installed components by technology type, see **Energy storage system equipment and installed cost comparison** (on page 61).

Exhibit 4 Cost components of an energy storage system



Storage Block	₹/kWh	The unit energy cost for the energy component of the ESS, for example, battery module, rack, and battery management system (BMS) for BESS.
Balance of System (BOS)	₹/kWh	Supporting cost components for the storage block, such as container, cabling, switchgear, and HVAC for BESS.
Storage System	₹/kWh	The sum of the storage block and BOS costs, and the appropriate level of granularity for some storage technologies such as PSP and compressed air energy storage (CAES).
Power Equipment	₹/kW	Power conversion system and DC-DC converter for batteries or electromechanical powertrain and powerhouse for PSP.
Controls and Communications	₹/kW	Includes the energy management system (EMS) for the ESS and is responsible for ESS operation; typically represented as a fixed-cost scalable with respect to power.
System Integration	₹/kWh	Cost charged by the system integrator to integrate components of the energy storage system into a single functional system. Tasks include procurement and shipment of equipment to the site and integration with the power equipment to provide a turnkey system.
EPC	₹/kWh	Includes nonrecurring engineering costs and construction equipment, as well as siting, installation, and commissioning of the ESS.
Project Development	₹/kWh	Costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.
Grid Integration	₹/kW	Costs associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers.

RMI Graphic. **Source**: Adapted from Vilayanur Viswanathan, et al., *2022 Grid Energy Storage Technology Cost and Performance Assessment,* United States Department of Energy, Pacific Northwest National Laboratory, **https://www.energy.gov/sites/default/files/2022-09/2022%20Grid%20Energy%20Storage%20Technology%20Cost%20and%20Performance%20Assessment.pdf**.

Operating and decommissioning costs

While the installed cost represents the up-front initial investment required to design, install, and operationalise an energy storage project, the full scope of the ESS project costs includes ongoing operational and decommissioning costs, which are defined in **Exhibit 5.**[31]

Exhibit 5 Operating and decommissioning costs

Operating Costs	
Fixed Operations and Maintenance (O&M) (₹/kW-year)	Includes all costs necessary to keep the storage system operational throughout its life that do not fluctuate based on energy throughput. This includes planned maintenance, parts, labour, and benefits for staff. Fixed O&M also includes major overhaul-related maintenance, which may depend on energy throughput or occur at fixed time intervals.
Round-Trip Efficiency Losses (₹/kWh)	The value of the cost of additional electricity and fuel required per kWh of energy discharged due to RTE losses.
Warranty (₹/kW-year)	Annual fees to the equipment provider for contractual performance of quality of materials and equipment, and performance assurance of the designated lifespan.
Insurance (₹/kWh)	Insurance fees to hold a policy to cover unknown or unexpected risks. The terms of this cost may depend on the developer's reputation, project complexity, location, and financial strength.
Decommissioning Costs	
Disconnection, Disassembly, Removal, and Site Remediation (₹/kWh)	Costs associated with the disconnection, disassembly, and removal of an energy storage project, as well as site remediation. These costs may vary widely based on whether the ESS is in or outside the built environment, how far materials must be transported, and whether site remediation is necessary.
Recycling and Disposal (₹/kWh)	Net costs associated with recycling and disposing of components, less any costs recouped from the sale of materials.

RMI Graphic. **Source**: Adapted from Vilayanur Viswanathan, et al., *2022 Grid Energy Storage Technology Cost and Performance Assessment,* United States Department of Energy, Pacific Northwest National Laboratory, **https://www.energy.gov/sites/default/files/2022-09/2022%20Grid%20Energy%20Storage%20Technology%20Cost%20and%20Performance%20Assessment.pdf**.

Total and specific cost

Assessments of energy storage projects must clearly consider the cost scope, including distinguishing between total cost and specific cost. Total cost refers to the investment cost of the entire storage system, including all components. Total investment cost can be specified for an energy storage project's power capacity (by dividing cost by power capacity, represented in ₹/MW) or energy capacity (by dividing cost by energy capacity, represented in ₹/MWh).

Specific cost refers to the cost of an additional component, which will impact either the project's specific power cost or specific energy cost, defined in **Exhibit 6**.[32]

Exhibit 6 Cost definitions

Specific Power Cost	The cost of components that enable the charging and discharging of energy.	Inverters, turbines
Specific Energy Cost	The cost of components that enable the storage of energy.	Battery cells, water reservoirs

RMI Graphic. **Source**: Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value,* Oxford University Press, 2023.

Total investment cost describes the all-in cost of an energy storage system, while specific investment cost can be used to assess the cost-effectiveness of adding additional power capacity or energy capacity. The ratio between specific power and specific energy investment cost indicates whether storage technologies are more cost-effective in short-duration or long-duration applications.[33, v]

Levelised cost of storage

Capital costs for energy storage technologies will vary based on input component prices, making it critical to understand how to compare costs for specific projects. Levelised cost of storage (LCOS) is a lifetime cost assessment for an energy storage project. LCOS measures the price at which a unit of energy output from a storage asset would need to be sold to cover all project costs, including taxes, financing costs, operations, and maintenance. LCOS provides excellent flexibility in comparing technologies and use cases for a specific project, focussing on

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v. The duration of storage applications is typically derived from demand-supply and tariff-based case studies, and specific energy investment costs are generally higher than specific power costs.

energy applications such as arbitrage.[34] The metric intends to provide a way to comprehensively compare the actual cost of owning and operating various storage assets.[35]

LCOS is akin to the levelised cost of electricity (LCOE) metric utilised to evaluate the break-even per MWh electricity price required for a generation resource; however, LCOS is distinct as it represents an energy storage technology that contributes to electricity generation when discharging and consumes electricity from the grid when charging. LCOS is calculated differently depending on whether it supplies electricity to the grid or provides generation capacity reliability.[36] For a high-level LCOS formula and inputs, see **Exhibit 7**.

Exhibit 7 Levelised cost of storage formula and inputs

$$\text{LCOS}\left[\frac{\text{₹}}{\text{MWh}}\right] = \frac{\text{investment + O\&M + charging + end of life}}{\text{energy capacity * cycles per year * lifetime}}$$

Investment	Accounts for all cost components required to serve a specific application (e.g., power conversion to enable fast response).
	Includes replacement cost to account for degradation.
O&M	Cost to operate, insure, and periodically service technology components.
Charging	Reflects RTE, because more energy is purchased than discharged (respective power price depends on application).
	Also accounts for auxiliary energy (e.g., air conditioning).
End of Life	It can be a cost or a value, depending on the reusability or recyclability of the technology, its components, and raw materials.
Energy Capacity	Electricity that is discharged each cycle; should include annual degradation.
	If it refers to electricity charged (against common practice), RTE and DoD must be accounted for here.
Cycles per Year	Determined by the application served by the storage system.
	It can significantly impact degradation and overall lifetime, as cycle life is a limiting factor for most technologies.
Lifetime	Option 1 **Technical:** Number of years after which energy capacities degraded (e.g., to 80%)
	Option 2 **Economic:** Pre-defined number of years (e.g., secured revenue)

RMI Graphic. **Source**: Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value,* Oxford University Press, 2023.

LCOS represents the total cost of ownership over the project lifetime, rather than the up-front investment cost.[37] LCOS is sensitive to key input parameters that will impact the project's energy output as a function of cost. The most impactful are investment cost, DoD, annual cycles, and discount rate. The most significant factor is investment cost, where a 20% reduction can lead to an approximate 14% decrease in LCOS. For performance criteria, discharge duration acts as a limitation for the installed energy capacity, resulting in a significant impact on energy discharged over the project's lifetime.[38]

Annuitised capacity cost

Annuitised capacity cost (ACC)[vi] is an approach to assessing the lifetime cost of an energy storage asset by dividing all costs incurred during the lifetime of the system by its power capacity and lifetime (in contrast to energy delivered, assessed through LCOS). The ACC represents lifetime power, defined as the product of power capacity and system lifetime (in years), expressed in ₹ per MW-year. The ACC metric of lifetime cost assessment is useful for storage applications that value the provision of power instead of energy, such as frequency regulation.[39] For a high-level ACC formula, see **Exhibit 8**.[40]

Exhibit 8 Annuitised capacity cost of storage formula

$$\text{ACC} \left[\frac{\text{₹}}{\text{MW-year}} \right] = \frac{\text{investment + O\&M + charging + end of life}}{\text{power capacity * project lifetime}}$$

RMI Graphic. **Source**: Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value,* Oxford University Press, 2023.

Like LCOS, the ACC calculation demonstrates sensitivity to input parameters. The strongest sensitivity is to discharge duration, which increases investment cost with no impact on the power capacity provided. A 20% increase in duration may result in an approximately 15% increase in ACC. Typically, ESSs meeting power applications (such as frequency response or frequency regulation) will see discharge duration limited to under 1 hour. ACC also demonstrates high sensitivity to other inputs, including investment cost, discount rate, and annual operation cycles.[41]

[vi] ESS project capacity reflects both power and energy capacity. For the definition of ACC, "capacity" refers to a project's power capacity.

Total system cost

For system planners and operators, energy storage will also affect overall electricity system costs as part of a suite of potential investment strategies. While LCOS and ACC are appropriate methods for assessing the lifetime costs of technological applications for a specific project, they do not reflect output variability or the impact of a technology's operation on the electricity system in terms of impact on reliability.[42] Therefore, the project lifetime cost metrics are insufficient for determining how a project will impact total system cost (TSC). TSC is a holistic approach to compare changes in the whole system that can derive the economic value of adding alternative power generation or other system technologies, akin to a cost-benefit analysis, with the intent to determine the overall net cost or benefit to the grid. This is especially critical for system planners, as long-term investments are difficult to address once integrated into the grid.[43]

Overview of energy storage technologies

Energy storage technologies represent the spectrum from well-understood, incumbent products such as PSP and commercial LiBs, to new and emerging technologies such as sodium-ion batteries and metal-air batteries. Despite signs of great promise, some of these emerging technologies face significant barriers before they achieve the technological readiness levels or manufacturing scale necessary to emerge as viable alternatives to existing lithium-ion technology. New energy storage technologies will require many cycles of improvement at lab-scale and in manufacturing processes before being ready for large-scale commercialisation. Categories of energy storage by technology type are summarised in **Exhibit 9** on page 37.[44]

Exhibit 9 Storage technologies

Storage Tech	Characteristics	Examples
Electrochemical	Generally, have a higher density than mechanical and thermal energy storage, with RTE ranging from as high as 95% (lithium-ion) to 40% (metal-air).	Batteries, including lithium-ion, sodium-ion, solid state, flow, and metal-air
Mechanical	Electrical energy can be converted into various forms of mechanical energy, such as gravitational potential energy and kinetic energy. Some forms are suitable for large-scale and long-duration storage. A common feature is that mechanical storage technologies have lower energy density than chemical or electrochemical, and as a result, tend to have larger footprints, require geologically favourable locations, and are not well suited for use in small-scale facilities.	Flywheels, CAES, and gravitation, including pumped hydro, stacking blocks, and rail
Thermal	Attributes suitable for long-duration storage, including the ability to store heat effectively in low-cost, non-toxic materials. Can be integrated with existing power generation units. However, face low RTE and system engineering challenges to enable low-cost installations.	Molten salt, molten sulphur, and heat storage (sand, gravel, concrete)
Chemical	Energy stored in the form of chemical fuels that can be readily converted to mechanical, thermal, or electrical energy for industrial and grid applications. Large storage capacities and long discharge durations are achievable, with many pathways for production, storage, and end use. However, face safety hazards associated with chemical and physical propertiesand have low volumetric energy densities, which require larger storage volumes, and low RTE for electricity storage and recovery.	Hydrogen, ammonia, hydrocarbons, and alcohols
Electrical	High power output, high cycle life, low-cost input materials, and well-suited for fast-response grid support applications. However, some technologies require high temperatures for operation, which raises safety concerns. Currently faces high system costs.	Capacitance and superconducting magnetic storage

RMI Graphic. **Source**: Robert Armstrong, et al., *The Future of Energy Storage: An Interdisciplinary MIT Study,* Massachusetts Institute of Technology (MIT), 2022, **https://energy.mit.edu/wp-content/uploads/2022/05/The-Future-of-Energy-Storage.pdf**; "Energy Storage Technologies," EPRI Energy Storage Wiki, accessed Jan 28, 2025, **https://storagewiki.epri.com/index.php/Energy_Storage_101#Energy_Storage_Technologies**; *Chemical Energy Storage,* United States Department of Energy (DOE), National Energy Technology Laboratory (NETL), 2021, **https://netl.doe.gov/sites/default/files/2021-02/Chemical_Storage.pdf**; Randheer Singh, et al., *Need for Advanced Chemistry Cell Energy Storage in India: Part II of III*, NITI Aayog and RMI India, 2022, **https://rmi.org/insight/need-for-advanced-chemistry-cell-energy-storage-in-india/**.

Lithium-ion batteries

LiBs refer to a suite of electrochemical storage technologies with a lithium anode. In LiB technologies, lithium ions move from anode to cathode internally, while electrons move externally to create an electrical current that powers a device. While LiBs found initial widespread utilisation in appliances and electronics, a rapid decline in global costs, performance improvements, and growth of supply chains have led to a rapid adoption of lithium-ion technology for EVs and stationary storage on the electric grid. Fast response time, high RTE, and power output have made LiBs especially economic for providing electricity grid services such as balancing, voltage support, and energy arbitrage for shorter durations.

Lithium-ion battery components

A battery is comprised of an anode, cathode, separator, electrolyte, and two current collectors (positive and negative). For LiBs, the anode and cathode store the lithium. The electrolyte carries positively charged lithium ions from the anode to the cathode and vice versa, through the separator. The movement of the lithium ions creates free electrons in the anode, which creates a charge at the positive current collector. The electrical current then flows from the current collector through a powered device to the negative current collector. The separator blocks the flow of electrons inside the battery; these comments are displayed in **Exhibit 10** on page 39.[45]

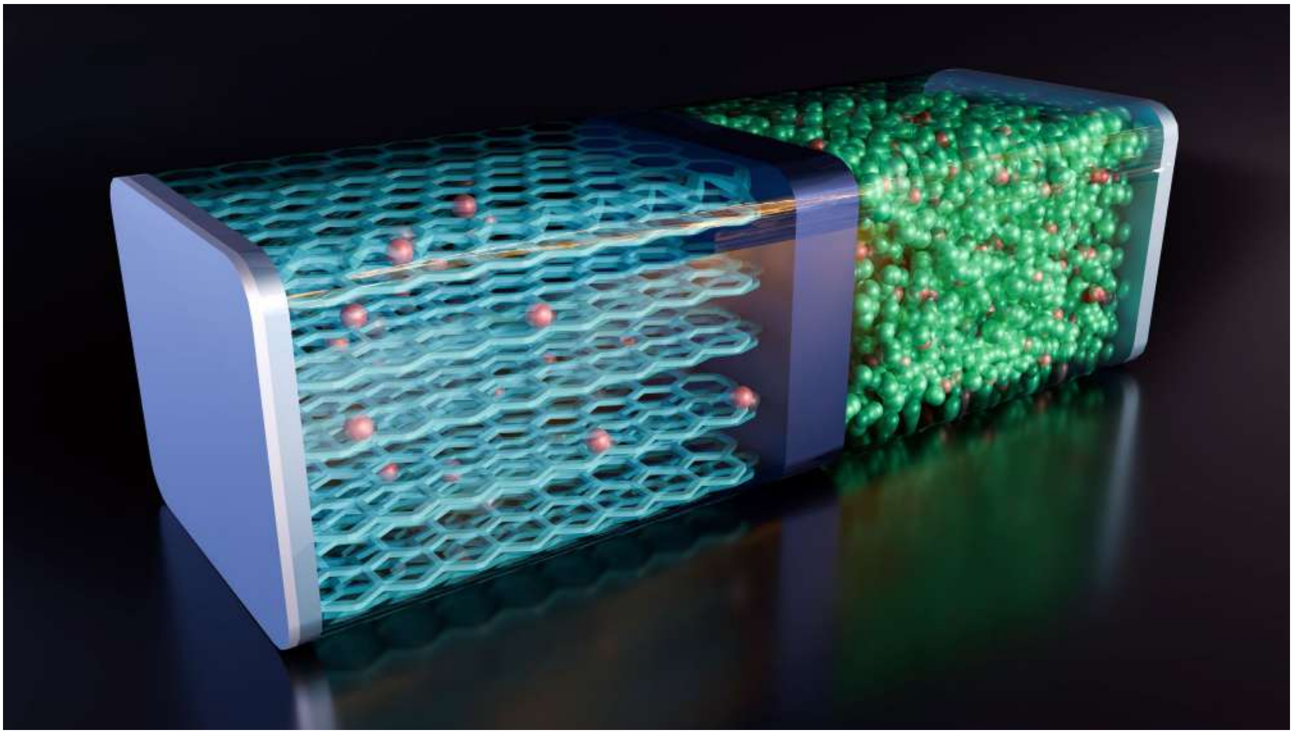
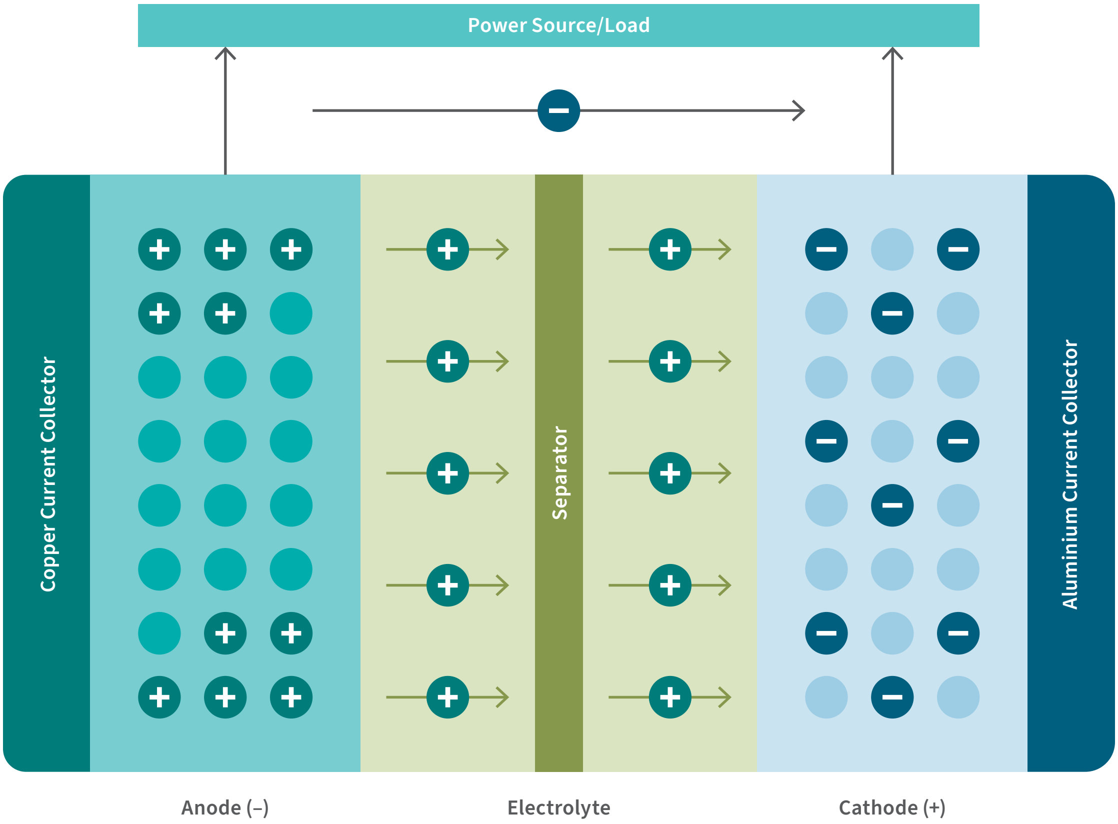


Exhibit 10 Components of a lithium-ion battery, during discharge



Electrodes	The positively and negatively charged ends of a cell, attached to the current collectors.
Anode	The negative electrode.
Cathode	The positive electrode.
Electrolyte	A liquid or gel that conducts electricity.
Current Collectors	Conductive foils at each electrode of the battery that are connected to the terminals of the cell. The cell terminals transmit the electric current between the battery, the device, and the energy source that powers the battery.
Separator	A porous polymeric film that separates the electrodes while enabling the exchange of lithium ions from one side to the other.

Note: During discharge, the positively charged lithium ions move through the electrolyte from anode to cathode, while electrons move through the connected device. When charging, the lithium ions and electrons move from the cathode to the anode.

RMI Graphic. **Source**: *How Lithium-ion Batteries Work,* DOE, 2023, **https://www.energy.gov/energysaver/articles/how-lithium-ion-batteries-work**; "What Are Lithium-Ion Batteries?," UL Research Institutes, last modified September 14, 2021, **https://ul.org/research/electrochemical-safety/getting-started-electrochemical-safety/what-are-lithium-ion**.

Lithium-ion battery chemistries

The anode, cathode, and separator determine the chemistry of the LiB. Every battery chemistry involves trade-offs among attributes such as energy density, safety, durability, material availability, and cost. In stationary applications, system cost and lifetime are prioritised — sometimes over the expense of energy density or RTE, depending on use case. LiBs tend to be constrained to specific architectures that yield lower power costs but higher energy costs. Historically, these architectures have tended to make lithium-ion batteries more competitive for short-duration applications (less than four hours of storage). Projected declines and international case studies may indicate that lithium-ion is becoming more competitive for long-duration storage uses, up to eight hours.[46, vii]

Advantages and limitations

Over the past decade, LiBs have seen significant declines in weighted global prices, with pack and cell prices falling by more than 75%.[47] Price declines have enabled LiBs to provide a broader range of grid and power services economically, leading to accelerating installed capacity and indicating that LiBs have become a mature energy storage technology. As global supply chains continue to build, diversify, and mature, LiBs can be expected to see additional cost declines.

LiBs also provide technical and performance advantages. The cells and packs are modular, enabling them to be scaled to project or system need, and allowing LiBs to be sited at any point along the grid (at generation, within the transmission and distribution network, or behind the meter; siting and values are covered in *Battery Storage Applications and Value*, **page 89**. This enables system planners and utilities to design a project tailored to specific system or user needs. LiBs also provide good cycle life and RTE, making them very effective for short-duration energy arbitrage (typically under six hours). Near-instantaneous response times also enable LiBs to effectively provide a range of ancillary services to maintain grid balance, including frequency support, voltage support, ramping support, and inertia support.

Compared to other new and emerging storage technologies, LiBs may have a relatively long lifespan. However, LiBs still face capacity fade, degradation over time that diminishes the battery's capacity. The rate of capacity fade can be impacted by factors such as temperature, charging rates, and cycling frequency.[48] And while LiBs are well-suited to providing energy arbitrage over short durations (less than six hours), they are less economic when arbitrage over longer time frames is required.

[vii] For additional information on lithium-ion battery chemistries and materials, see **Appendix B**.

LiBs also face perceived safety risks, as some chemistries are prone to thermal runaway, the process where a battery overheats and catches fire. While not all chemistries face the same risk of thermal runaway, addressing safety concerns requires comprehensive battery management systems (BMS) and safety protocols to ensure the battery system is operating within safe parameters.

Mineral and material availability are also concerns. Despite the growing global supply chains, lithium is still a relatively rare mineral with limited existing global extraction, refining, and processing capacity. In India, for example, the currently extractable lithium reserves are limited, and known reserves are still in early stages of development. This requires reliance on imports, which could pose energy security risks.

Sodium batteries

Sodium batteries refer to a range of electrochemical energy storage technologies where sodium is a principal component of the battery's chemical materials. Sodium-based batteries are seeing renewed attention as a potential viable alternative to lithium-based chemistries due to the accessibility of sodium, the sixth most abundant element in the Earth's crust.[49] A range of sodium-based battery technologies are being researched. Key chemistries include: sodium-ion batteries (SiB) and sodium-sulphur batteries.

Sodium-ion batteries

SiBs may be an alternative to lithium-ion for both stationary storage and mobility applications. SiBs are structured and operated much like LiBs. Due to similar working principles, LiB manufacturing plants can be transitioned to SiB with limited capital outlay, and the R&D advancements that have contributed to LiB advancement can be applied to SiB manufacturing.[50]

Significant efforts have been put into the development of SiB cathode materials, with potential structures including: layered transition metal oxides (noted for high capacity and voltage, ideal for high-energy density applications), polyanionic compounds (noted for thermal stability and safety), and Prussian blue analogue (characterised by a unique open framework structure, which enables fast sodium-ion diffusion and rate capability).[51] In addition, the graphite anode material most commonly used for LiBs does not intercalate readily with sodium ions, meaning SiBs require alternative anode materials such as hard carbon and soft carbon.[52]

Yet SiBs continue to face challenges for commercial deployment and scalability. Sodium also has a mass three times that of lithium, resulting in a lower energy density.[53] The larger sodium ions can alter the structural dynamics of electrode materials, leading to reduced cycle life and possible inefficiencies.[54] This is due to the redox potential, which characterises the tendency for an atom or molecule to gain or lose electrons in a chemical reaction. The redox potential of sodium is about 10% lower than that of lithium, meaning SiBs supply less energy for each ion that arrives in the cathode than lithium-ion batteries.[55] Some SiB chemistries currently face a fast reduction in the charge the battery can hold, impacting reliability, especially for applications requiring consistent energy outputs.[56]

Despite existing technical challenges, the opportunity for performance improvements and price reductions keeps SiBs a potential economic challenger for LiBs. The fastest and most certain way for SiBs to be price-advantageous is to reduce material intensity by increasing material and cell-level energy densities, where the biggest drivers of forecasted SiB cell prices in 2030 and 2040 are upper-voltage cut-offs, cathode- and anode-specific capacities, and electrode thickness.[57]

Sodium-sulphur batteries

Sodium-sulphur (Na-S) batteries were initially developed in the 1960s for potential EV applications but are now typically seen as an option for grid applications. Na-S batteries are high-temperature batteries that use molten sodium as the negative electrode, molten sulphur as the positive electrode, and a solid sodium-ion conductor as the solid electrolyte. Na-S batteries tend to have high energy density, inexpensive, non-toxic raw materials, and relatively long cycle lives (4,500 cycles or 15 years).[58] However, Na-S batteries present a few drawbacks: high self-discharge rate due to the need to maintain high operating temperatures (between 300°C and 350°C), relatively low discharge rates limiting applications for 6-hour discharge duration, safety risks associated with the high reactivity of sodium with water, and uncertain cost reduction potential.[59]

Advantages and limitations

SiBs offer the opportunity to provide many of the same power system services that LiBs do, while relying on materials that are more common and accessible. This reduces reliance on imported materials for cell manufacturing and the associated risk to energy security. There is still a great opportunity to shift SiBs from the R&D and start-up phases to commercialisation, with potential cost advantages to be realised through scaling. However, realising these cost advantages will also require overcoming physical and chemical constraints and building confidence in performance reliability through demonstration projects providing grid services.

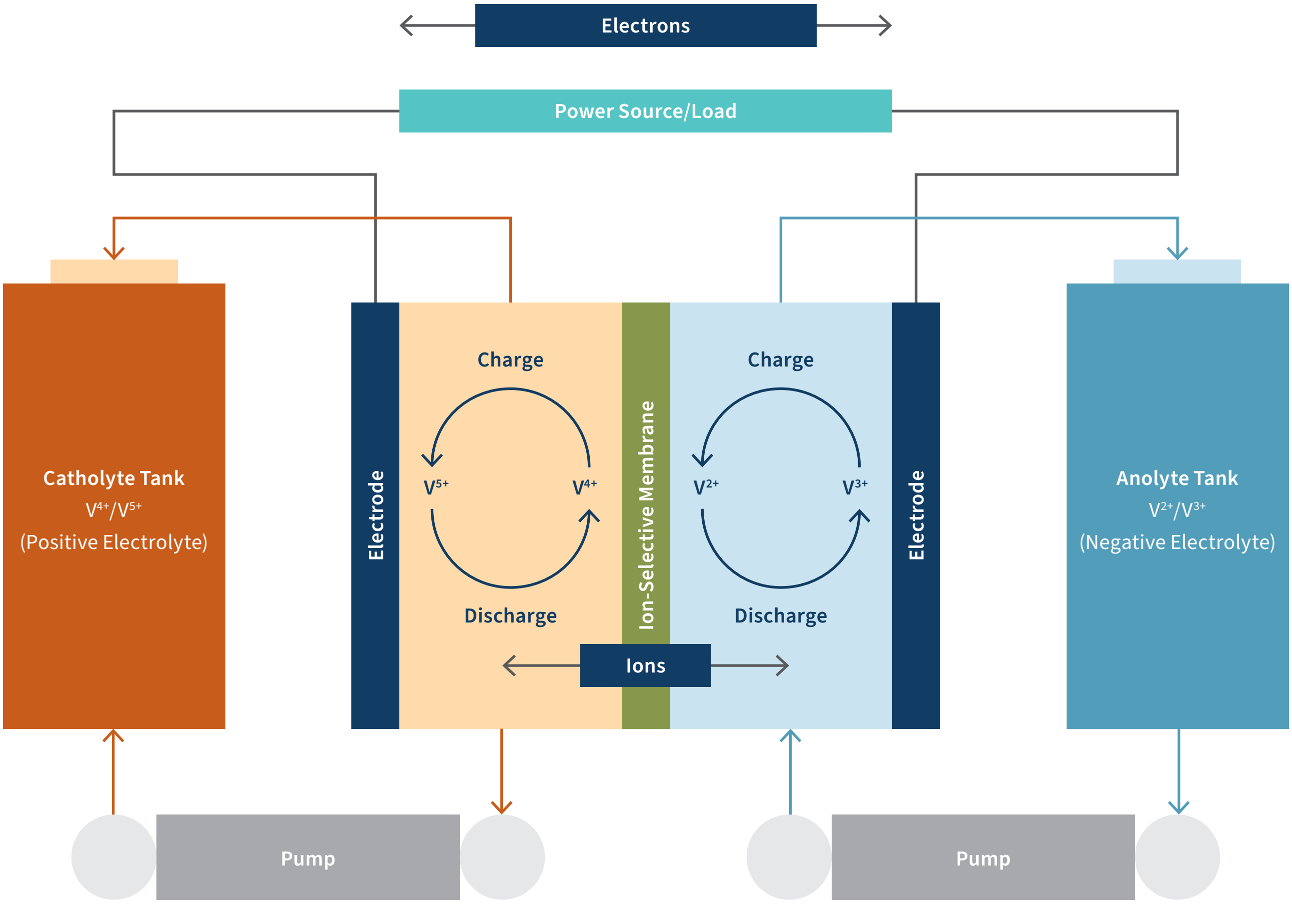
Flow batteries

Flow batteries are an electrochemical energy storage technology where the energy is stored in liquid electrolytes held in external tanks, rather than in solid electrodes like in conventional batteries. The amount of energy that can be stored is determined by the size of the external electrolyte tanks, and thus, the battery holds promise for holding hundreds of megawatt-hours of energy.

At the core of flow batteries are two large tanks that hold liquid electrolytes, one positive (catholyte) and one negative (anolyte), and a cell stack where the electrochemical reaction occurs between the electrolytes. Each electrolyte contains dissolved "active species" that react to release or store electrons. During charging, one species is oxidised (releases electrons), and the other is reduced (gains electrons). While discharging, the roles are reversed. Pumps are used to circulate the two electrolytes through separate electrodes; each made of a porous material that provides abundant surface area for the electrochemical reaction to take place. A thin membrane between the adjacent electrodes keeps the two electrolytes from coming into direct contact and reacting, which would result in energy waste. The components of a flow battery are illustrated in **Exhibit 11** on page 44.[60]

Image source: *Commercial flow batteries* from Redflow Limited, **https://www.science.org/content/article/new-generation-flow-batteries-could-eventually-sustain-grid-powered-sun-and-wind**.

Exhibit 11 Components of a traditional redox flow battery with vanadium



RMI Graphic. **Source**: Adapted from BE&R Consulting, "Vanadium Flow Batteries Revolutionise Energy Storage in Australia," November 7, 2023, **https://berconsulting.com.au/2023/11/07/vanadium-flow-batteries-revolutionise-energy-storage-in-australia/**.

When the battery is being discharged, active species on the negative side (anode) oxidise, releasing electrons that flow through an external circuit to the positive side (cathode). The active species there then get reduced, absorbing electrons. Simultaneously, ions in the electrolytes pass through the membrane between the electrodes to help complete the reaction and keep the system electrically neutral. Once all the species have reacted and the battery is fully depleted, the system is recharged by using electricity from the grid to reverse the electrochemical reactions.

Flow batteries have two main categories: traditional redox flow batteries and hybrid flow batteries. Redox flow utilises redox reactions (a chemical reaction in which the atoms change their oxidation numbers) of the electrolyte solutions for energy storage. Hybrid flow batteries incorporate one solid electrode along with a flowing electrolyte. Vanadium redox flow batteries are the commercial leaders, while zinc-bromine flow batteries, a type of hybrid flow battery, are a popular alternative chemistry.

Among different flow battery chemistries, vanadium redox flow batteries are the most viable chemistry today due to key advantages. Vanadium does not degrade, resulting in a longer lifespan and lower maintenance cost. Since both electrolytes comprise vanadium, if some of the vanadium in one tank flows through the membrane to the other side, there is no permanent cross-contamination of the electrolytes, only a shift in oxidation states that can be easily remediated. However, resource availability is a significant drawback. Vanadium is found worldwide, but in dilute concentrations, making extraction difficult. There are limited places where vanadium is produced and supply chains are unreliable. As a result, vanadium prices are both high and extremely volatile. Research is on to develop new chemistries, such as chemically synthesised organic electrolytes; however, these chemistries are still far off from competing with vanadium redox flow batteries on economic viability. Other flow battery chemistries are reviewed in **Exhibit 12**.[61]

Exhibit 12 Review of flow battery chemistries

Chemistry	Type	Notes
Iron-Chromium	Traditional Redox	• The hydrogen evolution problem of the anode reduces the energy efficiency of the battery. • The cross-contamination of the cathode and anode will reduce battery capacity and efficiency, requiring high selectivity of the ion-conducting membrane used. • The redox property of chromium is poor, and the optimal working temperature of the battery is high.
Zinc-Bromine	Hybrid Redox	• Cathode adopts Br-/Br2 electric pair, anode adopts Zn2+/Zn electric pair. • Single deposition flow batteries, mostly used for user-side arbitrage and improving power stability. • Commercially viable, second most deployed flow battery chemistry after all-vanadium.
All-Iron	Hybrid Redox	• Has higher utility and lower cost than vanadium. • Divided into acidic and alkaline systems, acidic all-iron flow batteries are relatively mature in commercial development. • Anode hydrogen evolution reaction presents a technical problem and the need to suppress the formation of iron hydroxide precipitates, reducing the operating efficiency and capacity.

RMI Graphic. **Source**: Adapted from Vince Sprenkle, et al., *Technology Strategy Assessment: Findings from Storage Innovations 2030,* Flow Batteries, DOE, Energy Earthshots, 2023, **https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Flow%20Batteries.pdf**; Tycorun, "Analysis of different types of flow batteries in energy storage field," March 13, 2023, **https://www.tycorun.com/blogs/news/types-of-flow-batteries**.

Advantages and limitations

A major advantage of flow batteries is that the location where energy is stored (the tanks) is separated from where the electrochemical reactions occur (the cell stack, also called the reactor). As a result, the capacity of the battery (how much energy it can store) and its power (the rate at which it can be charged and discharged) can be adjusted independently by either increasing the size of the tanks or increasing the size of the reactor, respectively. This flexibility makes it possible to design a flow battery to suit a particular application and to modify it if required in the future. However, flow batteries generally have lower energy density than current LiBs, meaning they require more space to deliver the same amount of energy. Further, flow batteries tend to have lower round-trip efficiencies than conventional battery chemistries, meaning more energy is lost during charge-discharge cycles. Lower round-trip efficiency hinders the ability of flow batteries to compete for many short-duration services economically.

Box 1 Global flow battery projects

The first phase of the world's largest vanadium redox flow battery was commissioned in Dalian, Liaoning Province, China, in May 2022. The system, developed by Rongke Power, has a capacity of 100 MW/400 MWh, with plans to expand to 200 MW/800 MWh. The battery is designed to lower the peak load in Dalian City, but can play a role at the provincial level as well by improving the grid's capability to integrate new renewable sources.[62]

Apart from Rongke Power, Sumitomo Electric, a Japanese company, is another leading developer. It has been deploying vanadium redox flow batteries since 2001, and now has over 100 MWh in Japan, Taiwan, Belgium, Morocco, and the United States.[63]

Metal-air batteries

Metal-air batteries (MABs) refer to a range of electrochemical storage technologies that utilise oxygen in ambient air as the cathode. MABs are gaining traction as potential candidates for the next generation of batteries beyond Li-ion technology due to their simplicity in design, safety, and much higher theoretical specific energy than conventional battery systems. The effective utilisation of oxygen in ambient air makes MABs lightweight and economical to construct.

When discharging, the metal electrode in an MAB releases electrons (metal oxidation reaction), which are transferred across the external circuit to the air side. The oxygen in the air flows through a porous host and is reduced to oxide ions (oxygen reduction reaction) by accepting surplus electrons from the cathode, provided by an external circuit. The reaction mechanism and the transport of metal ions depend on the choice of the electrolyte.

In MABs, an alloyed metal rod acts as an anode during the discharge. The cathode is usually a porous catalyst structure that allows air passage and provides a site for the oxygen reduction/evolution reaction. MABs consist of four types of electrolytes: aqueous (water as solvent), non-aqueous (organic solvent), hybrid (two distinct electrolytes separated by a solid electrolyte barrier), and solid. **Exhibit 13** provides an overview of a variety of MAB chemistries.[64]

Exhibit 13 Overview of MAB chemistries

Battery	Metal-Electrode	Electrolyte	Air-Electrode
Li-air	Lithium rod	Liquid electrolytes (usually non-aqueous solution): Li-salts mixed in an organic solvent. For example, LiNO3 and LiTFSI in dimethyl sulfoxide (DMSO) Solid electrolytes are preferred due to stability issues; some examples include oxide-based ceramic electrolytes, such as sodium superionic conductors (NASICON), and perovskite-type oxides, such as lithium lanthanum titanate	Porous structure carbon nanotubes/graphene Pt-group metal oxides
Zn-air	Zinc rod	Alkaline aqueous media (LiOH, KOH, and NaOH)	Mixture of carbon support with porous structure made up of Polytetrafluoroethylene (PTFE)
Mg-air	Mg-Al alloys with some portion of Zn, Ca, Sn	Usually an aqueous NaCl or NaOH solution	Carbon nanotube composites
Al-air			

RMI Graphic. **Source**: Tao Li, Meng Huang, Xue Bai, and Yan-Xiang Wang, "Metal–Air Batteries: A Review on Current Status and Future Applications," *Progress in Natural Science: Materials International* 33, no. 2 (2023): 151–171, **https://doi.org/10.1016/j.pnsc.2023.05.007**; Abdul Ghani Olabi, et al., "Metal–Air Batteries: A Review," *Energies,* 14, no. 21 (2021): 7373, https://doi.org/10.3390/en14217373; Md. Arafat Rahman, Xiaojian Wang, and Cuie Wen, "A Review of High-Energy-Density Lithium–Air Battery Technology," *Journal of Applied Electrochemistry* 44 (2014): 5–22, **https://doi.org/10.1007/s10800-013-0620-8**.

The theoretical specific energy of MABs is much higher than that of existing battery technologies such as lead-acid, nickel-cadmium, and lithium-ion, highlighting the advantages of their lighter construction (see **Exhibit 14**, page 48).[65] However, actual specific energies are still lower because of unsolved techno-economic challenges due to the low technology readiness level.

Exhibit 14 Theoretical specific energy for MAB chemistry

Technology	Theoretical Specific Energy [Wh/kg]
Sodium-air (Na-O$_2$)	1,600
Zinc-air (Zn-O$_2$)	1,100
Magnesium-air (Mg-O$_2$)	2,900
Aluminium-air (Al-O$_2$)	2,800
Lithium-air (Li-O$_2$)	3,500
Iron-air (Fe-O$_2$)	1,200

RMI Graphic. **Source**: Abdul Ghani Olabi, et al., “Metal–Air Batteries: A Review,” *Energies* 14, no. 21 (2021): 7373, **https://doi.org/10.3390/en14217373**.

While MABs demonstrate potential, each MAB technology has merits and demerits and sits at a different technology-readiness level (see **Exhibit 15**).[66]

Exhibit 15 Review of advantages and challenges of MAB chemistries

Chemistry	Challenges
Li-air	1. Safety concerns if proper manufacturing standards are not maintained 2. A chemically and electrochemically stable solid-state electrolyte not found 3. Low lifetime over repeated cycles
Zn-air	1. Dendritic growth in Zn anode and its corresponding morphology change 2. Air electrode failure is common 3. Low coulombic efficiency
Mg-air	1. Producing a high-purity (4N-grade or 99.99% pure) metal anode is extremely costly 2. Low coulombic efficiency
Al-air	
Na-air	Restricted working conditions due to extreme sensitivity to moisture
Fe-air	Dendritic growth in the Fe rod causes degradation in cell performance

RMI Graphic. **Source**: Tao Li, Meng Huang, Xue Bai, and Yan-Xiang Wang, “Metal–Air Batteries: A Review on Current Status and Future Applications,” *Progress in Natural Science: Materials International* 33, no. 2 (2023): 151–171, **https://doi.org/10.1016/j.pnsc.2023.05.007**; Abdul Ghani Olabi, et al., “Metal–Air Batteries: A Review,” *Energies* 14, no. 21 (2021): 7373, **https://doi.org/10.3390/en14217373**.

Advantages and limitations

MABs have the potential to provide a variety of advantageous technical characteristics. As they rely on oxygen rather than heavy materials and complex chemistries, MABs have high theoretical energy density and require fewer materials, which are typically more common and have existing, robust supply chains. However, despite their material advantages and energy density, MABs currently face limitations that may hinder performance in power-sector applications. Factors such as weight and density, where MABs demonstrate an advantage over incumbent technologies such as LiBs, are less critical for most front-of-meter, grid-scale energy storage applications. In addition, current designs begin to see performance degradation after as few as 100–300 cycles.[67] The limited cycle life of existing MAB chemistries hinders application to critical high-value services, such as energy arbitrage that may require more frequent cycling.

Pumped storage projects

Pumped storage projects (PSPs) use gravitational energy from the difference in height between two water reservoirs to store energy.[68] Energy is stored by pumping water from the lower reservoir to the upper one, typically during off-peak hours when demand for electricity is low. Power is then generated by releasing water from the higher reservoir through a hydraulic turbine and into the lower reservoir.[69] PSPs are large-scale facilities that include an upper reservoir, a lower reservoir, a penstock or tunnel, a pump/turbine, and a motor/generator. The pump/turbine and motor/generator are located in a powerhouse that is connected to a local electrical substation.[70] There are two types of PSPs: “open loop,” which have an associated natural water source like a river for both the reservoirs; and “closed loop” (or off-river PSP), where the same water is cycled between the two reservoirs for pumping and generation.[71]

PSP is a highly mature technology and remains the most developed and widely commercialised form of energy storage for power sector applications worldwide. With robust deployment through the 20th century, there was over 179 GW of operational PSP capacity worldwide in 2023.[72] This represents approximately 94%–95% of global electricity storage capacity (GW) and 99% of global electricity storage energy (GWh).[73] Global PSP storage capacity is anticipated to grow from 2021 to 2030, with greenfield capacity exceeding a cumulative 9,000 GWh. Meanwhile, technical advances enabling pumping turbines to be installed in more diverse geographical conditions can contribute to global growth on the existing infrastructure of 3,300 GWh.[74] Projects in India are anticipated to account for 80% of storage energy capacity growth.[75]

Advantages and limitations

PSPs provide several critical advantages for providing storage services. PSPs can generate power continuously for a long duration (depending on the storage capacity of the reservoir), and tend to operate with an RTE of 70%–80%.[76] PSPs also demonstrate low specific energy capacity costs and enable independent sizing of energy and power capacities.[77] While most projects are analysed over a 30-year period, properly maintained reservoirs for PSP stations could remain operational for 100 years or more. The electromechanical components of PSP facilities are typically designed for 40–60 years (though useful life may be longer), and rotors of other electromechanical equipment with shorter design lifetimes can be refurbished or replaced at a cost that represents a small percentage of the total value of a PSP station. Considering such practices, the actual operational lifespan of a PSP facility depends on the durability of the civil works.[78]

PSPs are capable of quick start-stop, with faster ramping capabilities than conventional thermal generators. These performance metrics enable PSPs to provide a range of services to the grid, including smoothing load fluctuations, frequency and voltage support, and energy arbitrage. PSPs are especially well-suited to addressing long-duration storage needs, such as the seasonal mismatch between VRE generation and load.[79]

PSPs are well-suited to provide a wide range of grid services; however, project development and deployment face challenges. PSPs involve large civil engineering projects and utilise large volumes of water. While PSP facilities generally offer the lowest energy storage capacity costs due to the ability to discharge for long durations, their large scale and high capital expenses result in high power capacity costs and long development timelines. Construction expenses typically range from hundreds to thousands of crore (equivalent to millions to billions of US dollars). Civil works (e.g., dams, reservoirs, penstock tunnels, powerhouse caverns) and land acquisition typically account for 60%–70% of total construction for new PSP stations.[80]

The substantial up-front capital costs require projects to have access to financing, with public entities often playing a key role in meeting funding requirements. Equity financing is rarely a practical option for a private project developer because it entails large up-front capital requirements; and commercial financing poses challenges, especially if the owner is unable to secure a long-term buyer willing to make fixed payments in exchange for services provided by the project.[81] In addition, many facets of a project's costs will be site-specific, and ultimately, the opportunity for PSPs are geographically limited. Developers have historically prioritised the development of lower-cost sites before considering less favourable locations, indicating a risk for future PSP projects to face cost increases over time.[82]

PSP facilities also have significant environmental impacts, including on land and aquatic ecosystems. The operation of open-loop PSP systems that utilise one or more river dams can change flow patterns, water levels, turbidity, and temperature and cause adverse effects on flora and fauna in the connected water body or riparian zone. While hydro generation may face drought risk, closed-loop PSP projects are more resilient to changes in weather patterns, such as drought or low-water years, because the water is not released into the natural stream flow.[83]

PSPs in India

The first PSP in India commenced in 1970 at Nagarjuna Sagar in Telangana, with an installed capacity of 705.6 MW, and was commissioned during the 1980–1985 Five-Year Plan.[viii] Currently, six PSP sites are operational in India, totalling 3.3 GW of installed capacity.[84, ix] Eight sites, totalling 9.95 GW of capacity, are under implementation, and four sites, totalling 4.1 GW, have been concurred by CEA, but not yet taken up for construction.[85] CEA has identified 180 prospective PSP sites in India (including both on- and off-river sites), representing a cumulative installed capacity potential of 202.2 GW.[86]

The GoI has taken steps to streamline and accelerate PSP commissioning and deployment. In April 2023, the MoP released "Guidelines on Pumped Storage Projects" (PSP Guidelines) to promote PSP development. The PSP Guidelines seek to meet the 19 GW of PSP projected by CEA to be required by 2030. The guidelines aim to create a framework needed to promote the development of new PSP facilities, such as a clear competitive bidding process for PSP procurement, clear rules for developers to follow once awarded a project, and tax benefits that will be considered.[87] In addition, the PSP Guidelines indicate that PSP will be eligible for concessional climate financing, such as through government green bonds.[88]

The renewed government initiatives to accelerate PSP development are seeing some success. For example, in April 2025, the Avaada Group signed an agreement with the state of Maharashtra to build two PSP facilities with a combined storage capacity of 3.65 GW. The project represents a cumulative investment of ₹15,100 crore (US$1.27 billion),[x] is expected to create 3,800 direct employment opportunities, and will enable RTC renewable power and grid balancing services.[89]

[viii] The Five-Year Plans of India were a series of national development programmes implemented by the Government of India from 1951 to 2017. These were conceptualised and monitored by the Planning Commission until its replacement by the NITI Aayog (National Institution for Transforming India) in 2015.

[ix] Sardar Sarovar PSP (1,200 MW) and Kadana PSP (240 MW) in Gujarat are excluded from this figure as they are operational but not working in pumping mode.

[x] US$1=₹88.27.

Additional storage technologies

While global trends in BESS price declines and historic establishment of PSP have driven the energy storage industry, several other technologies may also provide services in certain applications. Some of these technologies have yet to achieve broad commercialisation, have a limited scope of application, or may be well-suited to meet anticipated needs for long-duration or seasonal energy storage in the future.

Gravitational energy storage

Gravitational energy storage (GES) refers to a mechanical bulk energy storage system that uses the potential energy of a mass at a given height. The general concept involves lifting the storage medium (such as sand, concrete, gravel, or rock), with the kinetic energy of the heavy weight held at a high elevation being extractable using an electric induction generator as the weight is lowered.[90] Varieties include cranes lifting the mass, moving it along a rail line on an incline (such as at a mountain), or raising it within an underground space, such as an abandoned mine shaft. Similar to PSP, GES is suitable for long-duration energy stage; given fast response times and "black start" capability, such systems could also provide energy services and load shifting.[91] GES is an immature technology, with no projects demonstrating commercial viability at scale; however, a number of start-up pilots have been initiated (see **Exhibit 16**, page 53).

Exhibit 16 Overview of GES pilots

Organisation	Type	Energy Storage Density	Output	Capacity	Efficiency	Response Time	Applicable Locations
Energy Vault	Crane Lifted	>1	4 MW	35 MWh	90	2.9 seconds	Flexibility in site location
ARES	Inclined (rail)	>1	50 MW	12.5 MWh	75–86	Seconds	Mountainous terrain
MGES	Inclined (rail)	>1	500 kW	0.5 MWh	75–80	Seconds	Mountainous terrain
Gravitricity	Underground	>1	<40 MW	1–20 MWh	80–85	Seconds	Abandoned mine

RMI Graphic. **Source**: Adapted from Liyang Liu, Yiming Ma, Yakai Li, Ymin Peng, Rufei He, Yao Li, "Review of Gravity Energy Storage Research and Development," *2023 8th International Conference on Power and Renewable Energy,* Institute of Electrical and Electronics Engineers (IEEE), September 2023, **https://ieeexplore.ieee.org/document/10353860**.

The energy density of GES systems is like that of PSP, with adjustments for the relative density of the matter being lifted compared to water. In addition, GES systems may be considered like PSP facilities in size and footprint (inclined GES systems have considerably larger land footprints because the grades involved are typically 6%–7%, compared to the vertical drop of other projects). Unlike PSP systems, GES systems typically require complex machinery and engineered materials, resulting in higher energy capacity costs. Most GES systems are also modular, which can potentially avoid large up-front capital costs and construction times typically faced by PSP systems.[92]

Current research on GES is still in the exploratory stage, with a need to focus on selection methods for technology routes under specific conditions. This includes a need for further understanding of technical economic metrics, as well as an understanding of materials, costs, and other optimal parameter design methods.[93]

Compressed air energy storage (CAES)

Compressed air energy storage (CAES) is a form of mechanical energy storage that uses electricity to compress and store ambient air for later use. The compressed air is withdrawn from the storage medium (historically, underground salt caverns or other porous rock formations), expanded, and passed through a turbine (similar to a gas turbine) to generate electricity. Compared to other storage technologies, CAES typically has lower energy capacity costs, as it uses off-the-shelf components from more established technologies like compressors. However, it is constrained by the availability of suitable storage media. As CAES must switch between compression and expansion phases when charging and discharging, it may have a slower response time than other storage technologies (such as LiB). Additionally, some studies indicate that CAES has relatively lower RTE, but direct comparisons are difficult as CAES designs rely on two different energy inputs: electricity for the compressor and fossil fuel for heating the air for expanding/discharging. Combined, these technical characteristics make CAES suitable for applications like providing peak capacity, secondary and tertiary operating reserves, and long-duration energy storage. As CAES relies on spinning turbines to generate and store electricity, it can also provide system inertia, which is critical for integrating high levels of VRE.[94]

CAES systems typically come in three configurations, which vary in how the heat produced in the compression is used and stored:

- **Diabatic CAES (D-CAES):** The heat generated during compression is expelled irreversibly to the environment and restored by gas combustion upon expansion

- **Adiabatic CAES (A-CAES):** The heat generated during compression is captured, stored separately from the compressed air, then returned during expansion — sometimes with additional heat — to increase power output.

- **Isothermal CAES:** aims to minimise or prevent the formation of compression heat

D-CAES systems are at the commercial stage, but project development is restricted by the unique geological formations required for gas storage, which must be impermeable and have storage capacity ranging from several hours to over 24 hours. In addition, the need for additional heat during the expansion phase results in a decreased RTE of approximately 50%. A-CAES plants store the heat generated by compression and deliver it later to the turbine during the expansion stage, improving RTE to 55%–70%.[95] While D-CAES is a commercial technology, no plant has been constructed since 1991, and no active grid-scale A-CAES plants are operating; however, a series of small-scale A-CAES facilities have been commissioned in Europe, Canada, the United States, and China.[96]

Isothermal CAES projects would, in principle, be more efficient than D-CAES or A-CAES. This process would continuously remove heat from the air as it is compressed (rather than after each compression stage), so that the air temperature remains constant. The process is then reversed for expansion. Isothermal CAES has been the subject of R&D and commercial pilot efforts, but no large-scale system has been built.[97]

Flywheel energy storage

Flywheel technology is a mechanical device that converts electrical energy to and from rotational kinetic energy. To charge, electricity is used in an electric motor to spin the flywheel; the process is reversed when electricity is needed, with the motor that accelerated the flywheel acting as a generator extracting energy from the rotating flywheel to discharge.[98] Flywheels are established, widely commercialised, and primarily used in smaller-scale applications relative to other mechanical energy storage technologies.

Flywheel ESSs consist of three main elements: a motor-generator, low-friction bearings, and a rotor (also known as a flywheel).[99] To reduce friction losses, it is common to place flywheels inside a vacuum with magnetic levitation.[100]

Flywheels can provide a range of grid stability support services, such as frequency regulation, as the technology can provide high power for short durations and quick responses during charge-discharge cycles. Flywheels can be used for maintaining power quality by quickly absorbing or injecting power to maintain nominal voltage and frequency level. At smaller scales, flywheel ESSs have been used in uninterruptible power supply applications, rapidly responding to loss of power from the grid until slower, longer-lasting resources like diesel generators can come online.[101]

While costs are comparable to other technologies on a power basis, on an energy basis, flywheels are significantly more expensive than similar alternatives like batteries. Relatively high costs have hindered deployment compared to other technologies, outside of specific short-duration applications.[102]

Hydrogen energy storage

Hydrogen energy storage is a chemical energy storage system for electricity (electrons-to-electrons, or power-to-power) that relies on the production, storage, and eventual reconversion of hydrogen into electricity. The conversion can occur through the combustion of hydrogen gas or the direct conversion of hydrogen and oxygen in a fuel cell. While many methods can convert water into hydrogen gas, the most mature is electrolysis, which uses electricity to split the water molecule into hydrogen and oxygen.

Electrolysis is an efficient process (72%–82%) across a wide range of power levels, making hydrogen production from electricity a flexible option that could help balance fluctuations in supply and demand and absorb surpluses of renewable electricity.[103]

Once hydrogen has been produced, it can be stored aboveground in tanks or underground, for example, in salt caverns or depleted natural gas reservoirs.[104] Conversion back to electricity can be done through thermal power generation units, such as gas turbines, steam turbines, or combined-cycle power plants. Combustion of hydrogen in this manner may produce nitrogen oxide (NOx) emissions, which must be controlled by premixing air and fuel or by diluting the fuel with steam, water, or nitrogen.[105] Hydrogen can also be used through a fuel cell, which takes the hydrogen and oxygen as fuel inputs and transforms the hydrogen into electric power and water; hydrogen fuel cells are still a nascent technology, and the development of megawatt-scale stationary fuel cells that could be used for power generation is not at a commercial level.[106] Reconversion to electricity generally results in RTE below 40%.[107]

In January 2023, India launched the National Green Hydrogen Mission, which aims to make India the global hub for the production, use, and export of green hydrogen (hydrogen produced solely from renewable energy sources) and its derivatives, and to enable India to assume technology and market leadership in green hydrogen.[108] Among many investments in pilots and demand-side creation, the mission includes an outlay of ₹17,490 crore through 2030 to incentivise local manufacturing of electrolysers and the production of green hydrogen.[109] These initiatives aim to boost domestic green hydrogen production, targeting industrial applications.

Despite projected price declines for hydrogen, economically competitive applications in the power sector are limited. The need for compression to achieve sufficient energy density, among other technical considerations, affects performance. This results in a low RTE for re-electrification (below 40%), ultimately increasing costs. RMI analysis indicates levelised costs can range (depending on configuration and technology) from approximately ₹30/kWh to ₹60/kWh.[xi]

These costs are three to five times higher than those of contemporary technologies, such as PSP and BESS, and limit hydrogen's competitiveness in most electric applications.[110] However, in power markets with very high VRE penetration (exceeding 80% of energy share), energy storage on the scale of weeks to months (also known as seasonal storage) may be required. In these instances, hydrogen may play a role in meeting bulk power system needs. Hydrogen's main value will probably come not from seasonal energy storage, but from helping electrify hard-to-abate sectors like transport and industry.[111]

[xi] This analysis is based on RMI work under review for a peer-reviewed journal, publication pending.

Storage technology considerations

For system planners and storage procurers, determining the most applicable energy storage technology will be based on several factors stemming first from the targeted end use or end uses. Performance and economic metrics will be key determinants of appropriate technologies, with other factors such as project timelines, completion risk, and supply chain risk, as well as critical selection criteria. This section provides high-level comparative frameworks and supply chain risk assessments.

Techno-economic comparison

For potential grid-scale storage technologies, key performance and cost parameters enable a straightforward techno-economic comparison (see **Exhibit 17**, page 58).[112] Costs for electrochemical technologies, such as batteries, reflect stand-alone system costs for accurate comparison. However, batteries are often co-located with generation, such as solar, which can reduce shared system cost components (*see PV + BESS configurations*, **page 97**). Unit costs reflect global benchmarks for storage unit costs (a pack for batteries and a system for mechanical technologies). Balance-of-system and development costs reflect the Indian context, as they can vary by country and tend to be lower in India than in Europe or the United States.[113]

Exhibit 17 Grid-scale storage technologies and their techno-economic parameters

Lithium-Ion Phosphate		
Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 142 (pack)	**2030 Global Unit Cost ($/kWh)** 67 (pack)
BoS & Development Cost ($/kWh) 4-hour: 66 (India) 10-hour: 26 (India)	**2022 LCOS (₹/kWh)** 4-hour: 7.0 (India) 10-hour: 5.9 (India)	**2030 LCOS (₹/kWh)** 4-hour: 4.5 (India) 10-hour: 3.5 (India)
Storage Duration 0–12 hours	**Typical Specific Energy (Wh/kg) Capacity** 90–160	**Typical Cycle Life** 3,000
Technical Calendar Life (Years) <16	**Round-Trip Efficiency** 86%	

Nickel Manganese Cobalt		
Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 170 (pack)	**2030 Global Unit Cost ($/kWh)** 67 (pack)
BoS & Development Cost ($/kWh) 66 (India)	**2022 LCOS (₹/kWh)** 9.7 (India)	**2030 LCOS (₹/kWh)** 6.2 (India)
Storage Duration 0–8 hours	**Typical Specific Energy (Wh/kg) Capacity** 190–270	**Typical Cycle Life** 2,000
Technical Calendar Life (Years) <13	**Round-Trip Efficiency** 83%	

Vanadium Redox Flow		
Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 284 (pack)	**2030 Global Unit Cost ($/kWh)** 237 (system)
BoS & Development Cost ($/kWh) 95 (India)	**2022 LCOS (₹/kWh)** 14.7 (India)	**2030 LCOS (₹/kWh)** 12.9 (India)
Storage Duration 6–12 hours	**Typical Specific Energy (Wh/kg) Capacity** ~35	**Typical Cycle Life** 5,000
Technical Calendar Life (Years) <12	**Round-Trip Efficiency** 65%	

Zinc Bromine Flow		
Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 258 (pack)	**2030 Global Unit Cost ($/kWh)** 206 (system)
BoS & Development Cost ($/kWh) 116 (India)	**2022 LCOS (₹/kWh)** 17.2 (India)	**2030 LCOS (₹/kWh)** 14.8 (India)
Storage Duration 2–12 hours	**Typical Specific Energy (Wh/kg) Capacity** ~70	**Typical Cycle Life** 5,000
Technical Calendar Life (Years) <10	**Round-Trip Efficiency** 70%	

Exhibit 17 Grid-scale storage technologies and their techno-economic parameters (continued)

Sodium Sulphur

Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 280 (Pack)	**2030 Global Unit Cost ($/kWh)** 120 (pack)
BoS & Development Cost ($/kWh) 200 (India)	**2022 LCOS (₹/kWh)** 15.2 (India)	**2030 LCOS (₹/kWh)** 9.3 (India)
Storage Duration 0–12 hours	**Typical Specific Energy (Wh/kg) Capacity** ~110	**Typical Cycle Life** <3,500
Technical Calendar Life (Years) <13.5	**Round-Trip Efficiency** 75%	

Sodium-Ion

Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 77 (cell)	**2030 Global Unit Cost ($/kWh)** 40 (cell)
BoS & Development Cost ($/kWh) 70 (India)	**2022 LCOS (₹/kWh)** N/A	**2030 LCOS (₹/kWh)** N/A
Storage Duration 0–12 hours	**Typical Specific Energy (Wh/kg) Capacity** ~160	**Typical Cycle Life** <6,000
Technical Calendar Life (Years) <10	**Round-Trip Efficiency** ~80%	

Aluminium Air

Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 500 (system)	**2030 Global Unit Cost ($/kWh)** 400 (system)
BoS & Development Cost ($/kWh) N/A	**2022 LCOS (₹/kWh)** 14.0 (India)	**2030 LCOS (₹/kWh)** 10.6 (India)
Storage Duration 0–20 hours	**Typical Specific Energy (Wh/kg) Capacity** 1,300	**Typical Cycle Life** <10,000
Technical Calendar Life (Years) N/A	**Round-Trip Efficiency** 83%	

Iron Air

Storage Type Electro-Chemical	**2022 Global Unit Cost ($/kWh)** 20 (pack)	**2030 Global Unit Cost ($/kWh)** 10 (pack)
BoS & Development Cost ($/kWh) 200 (India)	**2022 LCOS (₹/kWh)** 3.5 (India)	**2030 LCOS (₹/kWh)** 2.4 (India)
Storage Duration 0–100 hours	**Typical Specific Energy (Wh/kg) Capacity** 600	**Typical Cycle Life** N/A
Technical Calendar Life (Years) N/A	**Round-Trip Efficiency** 50%	

Exhibit 17 Grid-scale storage technologies and their techno-economic parameters (continued)

Pumped Storage Projects

Storage Type Mechanical	**2022 Global Unit Cost ($/kWh)** 4-hour: ~$780/kW (system, India) 10-hour: ~1,000/kW (system, India)	**2030 Global Unit Cost ($/kWh)** 4-hour: ~$780/kW (system, India) 10-hour: ~1,000/kW (system, India)
BoS & Development Cost ($/kWh) N/A	**2022 LCOS (₹/kWh)** 4-hour: 7.3 (India) 10-hour: 3.8 (India)	**2030 LCOS (₹/kWh)** 4-hour: 7.3 (India) 10-hour: 3.8 (India)
Storage Duration 4–12 hours	**Typical Specific Energy (Wh/kg) Capacity** N/A	**Typical Cycle Life** N/A
Technical Calendar Life (Years) ~60	**Round-Trip Efficiency** 80%	

Gravitational Storage

Storage Type Mechanical	**2022 Global Unit Cost ($/kWh)** 380 (system)	**2030 Global Unit Cost ($/kWh)** 350 (system)
BoS & Development Cost ($/kWh) N/A	**2022 LCOS (₹/kWh)** 12.7 (India)	**2030 LCOS (₹/kWh)** 11.5 (India)
Storage Duration 6–14 hours	**Typical Specific Energy (Wh/kg) Capacity** N/A	**Typical Cycle Life** N/A
Technical Calendar Life (Years) ~60	**Round-Trip Efficiency** 80%	

Compressed Air

Storage Type Mechanical	**2022 Global Unit Cost ($/kWh)** 150 (system)	**2030 Global Unit Cost ($/kWh)** 150 (system)
BoS & Development Cost ($/kWh) N/A	**2022 LCOS (₹/kWh)** 17.7 (India)	**2030 LCOS (₹/kWh)** 17.7 (India)
Storage Duration 0–24 hours	**Typical Specific Energy (Wh/kg) Capacity** N/A	**Typical Cycle Life** N/A
Technical Calendar Life (Years) 60	**Round-Trip Efficiency** 52%	

RMI Graphic. **Source**: Adapted from Priyanka Mohanty, et al., *Review of Grid-Scale Energy Storage Technologies Globally and in India,* Lawrence Berkeley National Laboratory, Electricity markets & Policy, Energy Analysis & Environmental Impacts Division, August 2023, **https://eta-publications.lbl.gov/sites/default/files/review_of_energy_storage_technologies_in_india_091523.pdf**; Erik D. Spoerke, et al., *Technology Strategy Assessment: Findings from Storage Innovations 2030,* Sodium Batteries, DOE, Energy Earthshots, 2023, **https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Flow%20Batteries.pdf**.

Energy storage system equipment and installed cost comparison

Up-front project costs are a critical consideration for assessing project risk, financing requirements, and, ultimately, project bankability. The complexity of a project's design can have important cost implications. For example, creating balance-of-systems, power equipment, controls, and communication for battery storage projects requires sourcing a wide variety of components and establishing supply chains to procure them at scale. However, the advantage is that once supply lines are established and components have been standardised (where possible), scaling may accelerate. In addition, cells account for only approximately 35% of the project's cost, meaning the raw material cost for critical components has a diluted impact on overall project cost.[114] For example, a 100% increase in lithium hydroxide cost will only increase battery pack cost by approximately 3%; it is unlikely that raw material will be a limiting factor for battery storage deployment at scale, and will have a limited impact on price projections based on experience curves in the long run.[115, xii] **Exhibit 18**, on page 62 provides an overview of the cost components for various energy storage technologies.[116]

[xii] Price projects based on an LFP pack assuming US$130/kWh and a lithium hydroxide price of US$7/kg.

Exhibit 18 Total installed cost comparison for storage technologies

				Lithium-Ion	Sodium-Ion	Redox Flow	Hydrogen	PSP	Gravitational	CAES
ESS INSTALLED COST	ENERGY STORAGE SYSTEM (ESS)	STORAGE SYSTEM	**Storage block**	Lithium-ion modules in racks	Sodium-ion modules in racks	Stacks and electrolyte tanks	Electrolyser, fuel cell stacks, and cavern	Reservoir(s)	Bricks, pistons, and mineshaft	Cavern
			Balance of system	Container, cabling, switchgear, and HVAC			Blowers, humidifiers, mass flow controllers, and compressors		Cranes, valves, and seals	
						Pumps and piping				
			Power equipment	Power conversion system and DC-DC converter			Rectifier and inverter	**Electromechanical power train:** Pumps/turbines, motors/generators, and powerhouse construction	**Electromechanical power train:** Pumps/turbines, motors/generators, and powerhouse construction (as required)	**Power island with electromechanical power train:** Compressors, turbines, and generators
			Controls and communications	Controls/energy management system						
			System integration	System integration			Included in the above costs			Included in storage system and power equipment costs
			Engineering, procurement, and construction	EPC				Included in the above ESS costs	EPC fee, project development, and grid integration	Included in the above ESS costs
			Project development	Project development				Contingency fees		
			Grid integration	Grid integration						

RMI Graphic. **Source**: Adapted from Vilayanur Viswanathan, et al., *2022 Grid Energy Storage Technology Cost and Performance Assessment,* United States Department of Energy, Pacific Northwest National Laboratory, 2022, **https://www.energy.gov/sites/default/files/2022-09/2022%20Grid%20Energy%20Storage%20Technology%20Cost%20and%20Performance%20Assessment.pdf**.

Supply chain risk and assessment

Securing the supply chain for energy storage technologies will be a critical consideration for policymakers. As the scope of energy storage technologies expands, so does the complexity of the energy storage supply chain. The supply chain now includes sourcing raw materials, refining and processing raw materials, cell manufacturing, pack assembly, component and subcomponent manufacturing, and system integration.[117] With insufficient supply chains, projects risk failure to adequately source necessary materials, putting project completion and financing at risk. In addition, poorly diversified supply chains that rely heavily on imports from a single source can pose energy security risks.

Avoiding one-country sourcing and having multiple supply options, to the extent possible, will provide redundancy so that a developer can quickly pivot if any one supplier encounters delivery constraints. Sourcing materials from multiple regions and suppliers, exploring substitute raw materials, and investing in recycling are all parts of risk mitigation.[118, xiii]

The Government of India has taken steps to indigenise parts of the energy storage supply chain. Approved in May 2021, the PLI Scheme for advanced chemistry cell (ACC) batteries under the National Programme on ACC Battery Storage provided ₹18,100 crore (approximately US$2.05 billion) to establish a domestic battery manufacturing sector. The PLI Scheme secured bids from 10 companies, totalling 128 GWh of capacity, which was 2.6 times the targeted tender volume; the winning bids were announced in March 2022.[119] However, the PLI scheme focussed only on the indigenisation of one aspect of the energy storage supply chain (cell manufacturing) and prioritised technical characteristics better suited to mobility applications than to grid storage. Policymakers should consider developing frameworks for assessing energy storage technologies by supply chain risk and take additional steps to mitigate these risks to avoid delays in project development and deployment. **Exhibit 19** provides an example framework for assessing technology supply chain risks.[120]

[xiii] For additional insight into strategies to address rising battery mineral demand through reuse and recycling, refer to: *The Battery Mineral Loop: The Path from Extraction to Circularity*.

Exhibit 19 Energy storage supply chain risk assessment framework

Significant Domestic Supply	Domestic supply is evaluated as significant if the domestic market supply can meet at least 50% of the estimated domestic demand.
Projected Significant Domestic Demand	The projected domestic demand is significant if the CAGR is projected to be greater than 2% for at least five years. If the specific projected demand for a sector or subsector cannot be determined, then the demand for the end product can be used as a proxy.
Significant Global Market	If the market for the sector or subsector exceeds a certain threshold, such as US$5 billion (~₹44,142.5 crore), it is considered significant.
Projected Significant Global Market	If the CAGR for the reviewed sector is projected to be greater than 2% for at least five years, it is considered significant. If the specific projected demand for a sector or subsector cannot be determined, then the demand for the end product can be used as a proxy.
Competitiveness of the Domestic Market	The number of companies in the specific sector or subsector indicates domestic competitiveness. The presence of more than three domestic companies in the industry suggests a competitive market.
Competitiveness of Domestic Suppliers in the Global Market	Domestic suppliers are competitive if they capture at least 30% of the market.
Security of Supply Chain	This criterion can be measured in two ways: identification as a critical mineral or the amount imported. If the material is identified as a critical mineral or contains a significant amount (>10%) of a critical mineral, the supply is insecure. For other materials, if the amount imported exceeds 50%, it is significant and may be at high risk of insecurity.
Environmental, Climate, and Human Rights Concerns	This criterion addresses important external factors that can affect the development of the supply chain. If the current supply chain relies on slave labour or typically disadvantages specific sectors of society, it becomes less resilient and more important to develop an alternative source. If an industry has been identified as having significant energy demands, hazardous waste issues, or human rights issues, it may be considered high risk for insecurity.

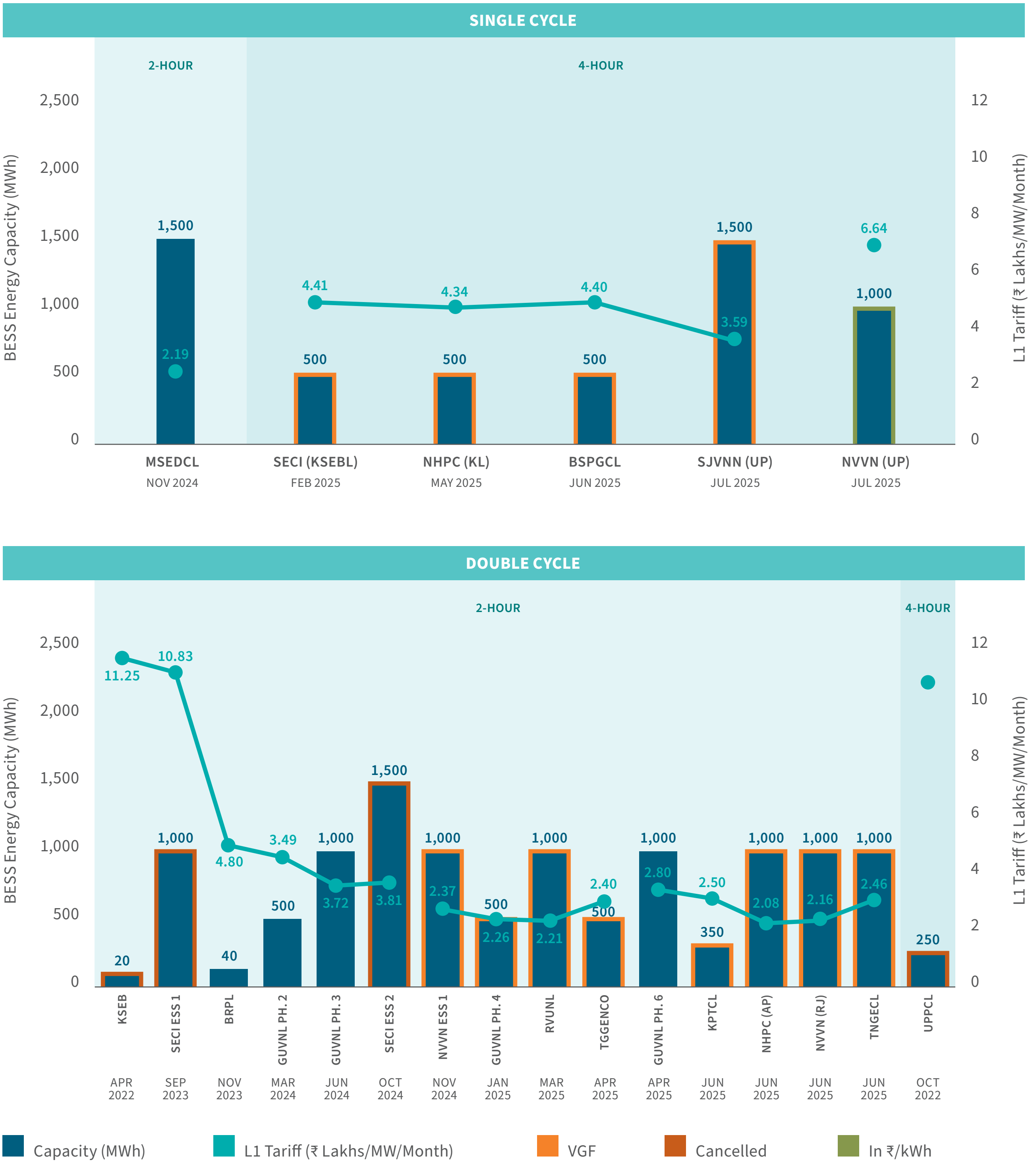
RMI Graphic. **Source**: Adapted from *Grid Energy Storage: Supply Chain Deep Dive Investment,* US Department of Energy, 2022, **https://www.energy.gov/sites/default/files/2022-02/Energy%20Storage%20Supply%20Chain%20Report%20-%20final.pdf**.

Battery Storage Cost Trends and Procurement Options

Declining costs globally and flexible project planning, sizing, and application have made BESS technologies an increasingly significant contributor to power systems seeking to integrate high volumes of VRE generation, as well as other DERs. Projections within India estimate installed capacity of 19 GW (128 GWh) of PSP, and approximately 42 GW (208 GWh) of BESS will be required to integrate 392 GW of VRE (100 GW of wind and 292 GW of solar) by 2030.[121] Critically, Indian states and DISCOMs are experiencing changing energy supply portfolio needs, with increasing demand, the addition of renewable energy, and reduced annual capacity factors and utilisation of the thermal fleet. Yet the value of BESS capacity to the grid is not just limited to enabling the integration of VRE. India's power sector is also facing rapidly growing demand, with record peak loads exceeding previous CEA projections. As a versatile and flexible resource, BESS can also provide critical grid support to address looming grid challenges cost-effectively.

Globally, BESS prices have seen a consistent declining trend, with the lithium-ion pack weighted average price dropping 20% to a global average of US$115 per kWh (approximately ₹10,148.75 per kWh) in 2024; the largest annual drop since 2017.[122] BESS tender prices in India are similarly demonstrating rapid declines. Stand-alone BESS prices in India dropped from approximately ₹10.83 lakh/MW/month in spring 2022 to ₹2.02 lakh/MW/month for two hours of storage and ₹3.59 lakh/MW/month for four hours in summer 2025. Further reductions have been realised through viability gap funding and capital expense subsidy support, representing a cumulative 75% cost decline (see **Exhibit 20**, page 66).[123]

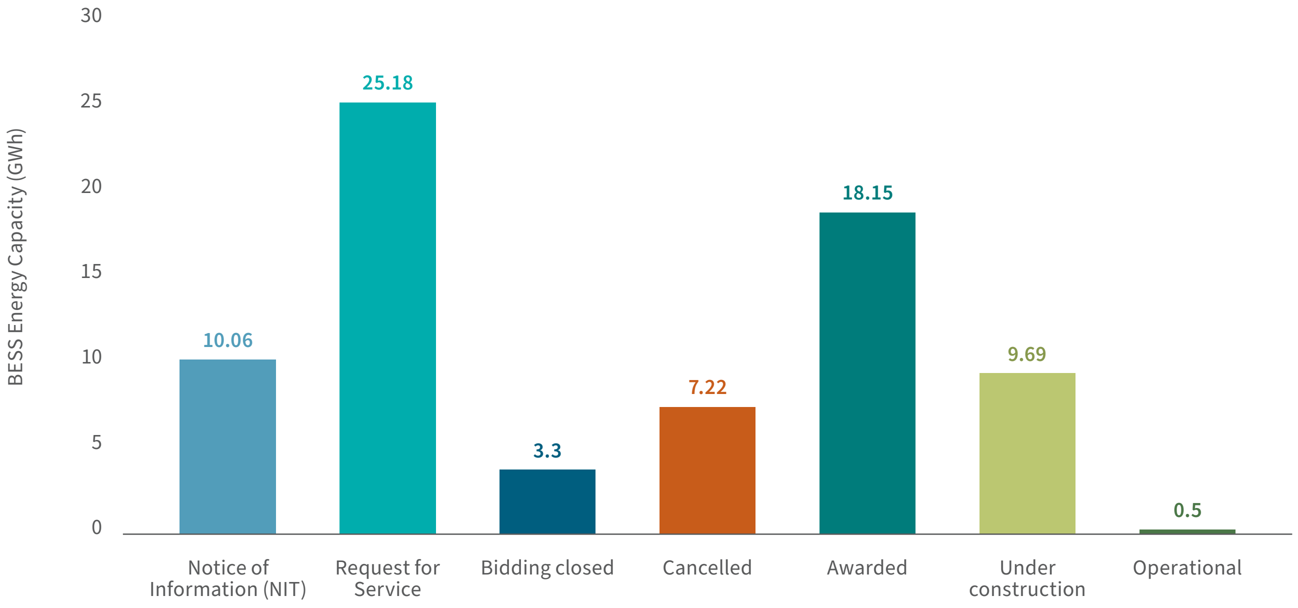
Exhibit 20 Stand-alone BESS tariff trends, 2022-2025



RMI Graphic. **Source**: Adapted from "1H 2025 Energy Storage Update – India," Debmalya Sen, last modified July 2025, **https://www.linkedin.com/posts/debmalya-sen_1-h-2025-energy-storage-update-india-activity-7348873268998586368-i7ix**.

Economies of scale, low metal and component prices, adoption of lower-cost LFP batteries, and a slowdown of EV sales growth have driven global price declines.[124] Combined, these factors have led to a growing pipeline of battery storage projects. As of July 2025, over 58 GWh of BESS projects were in the tendering pipeline, and 0.5 GWh of BESS capacity procured through competitive bidding is operational, with approximately an additional 1 GWh anticipated to come online by H2 2025 (**see Exhibit 21**).[125] Despite this growing success, projects continue to face risks, with 7.22 GWh cancelled. Resolving challenges and risks to project development is a key element for ensuring the success of this emerging technology.

Exhibit 21 BESS capacity by tendering stage, July 2025



RMI Graphic. **Source**: "1H 2025 Energy Storage Update – India," Debmalya Sen, last modified July 2025, **https://www.linkedin.com/posts/debmalya-sen_1-h-2025-energy-storage-update-india-activity-7348873268998586368-i7ix**.

A DISCOM or other offtaker's need for RE and storage will vary widely by portfolio, load profile, demand growth, system peakiness, and geography (among other factors). The ability of DISCOMs and other offtakers to procure storage will also be influenced by factors such as system readiness and access to finance. Combined, the diverse need for storage and procurement capabilities prevents a one-size-fits-all approach to BESS procurement and contracting. The inherent flexibility of BESS projects enables a wide range of ownership, business, and contracting models. DISCOM's or other stakeholders can tailor an offtaker or ownership agreement to meet their system needs.

BESS projects are flexible across several factors: a project can be sited or sized to a specific location (including co-located with generation); BESS can be utilised as both a generator (discharging during periods of high demand) as well as a load source (charging during periods of high generation); they can aid in providing firm capacity for VRE resources, or provide additional flexibility; offtakers can also contract for battery capacity (typically in terms of power calculated by ₹ per MW per month), energy (typically in terms of energy calculated by ₹ per kWh), or a blended contract of both. This section explores a range of BESS procurement strategies pursued within India.

Tender planning framework

Globally, utilities and other procurement entities have utilised a variety of contracting structures and models, including various public–private partnership arrangements. The procurement models vary across designations of responsibilities for planning, financing, procurement, construction, operation, and revenue, and ultimately ownership and risk allocation across stakeholders. For a DISCOM seeking to procure BESS resources, multiphase planning processes must be undertaken to determine the most suitable contract to tender (see **Exhibit 22**).[126] Key questions for project planning and tender design will revolve around ownership and business models, contract structure, time-differentiated rates, and firmness/dispatchability of power supply.

Exhibit 22 Four phases of project tender planning

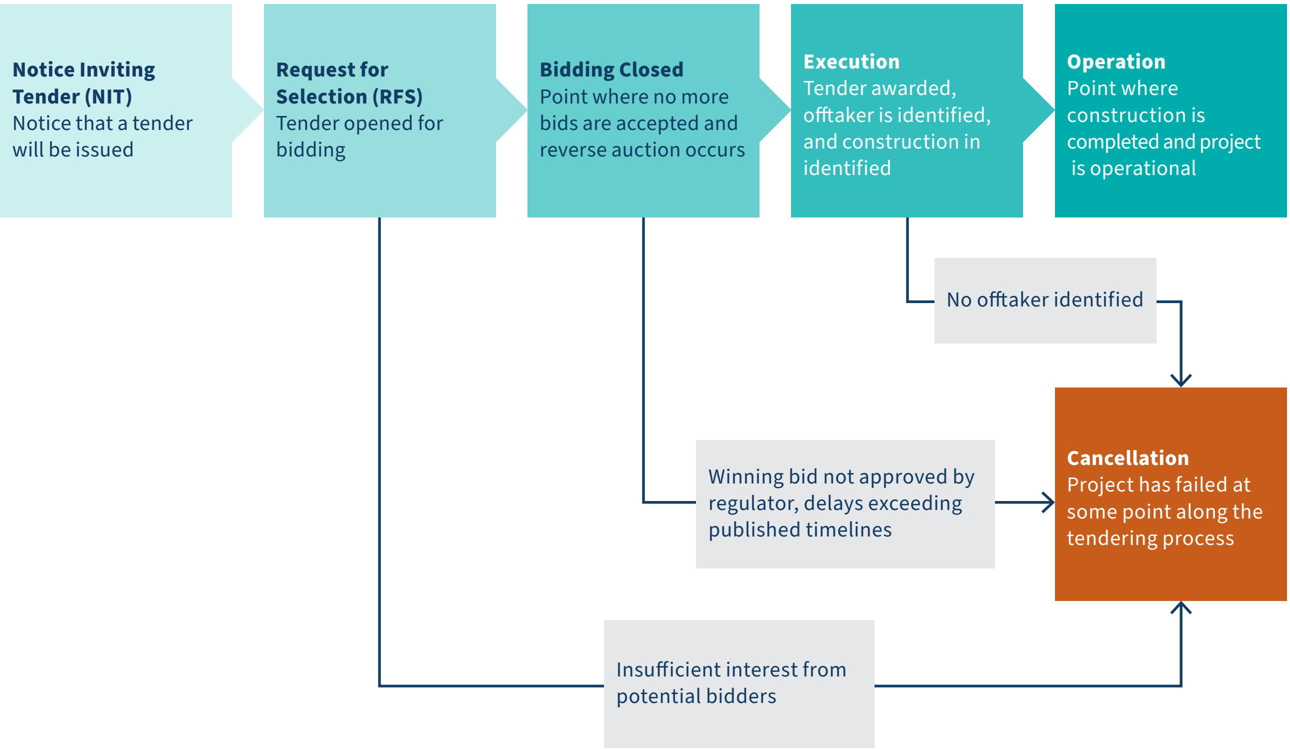
PLANNING	
Phase 1 **Overall System Planning**	**Conduct planning analysis and studies** • Demand and needs assessment • Least-cost planning and VRE integration studies **Interpreting outputs of planning analysis and studies** • Potential of storage procurement needs as part of an overall generation capacity mix and injection points
STRATEGY	
Phase 2 **Project Definition and Initial Assessment**	**Define the project** • Type, location, size, use cases, and requirements **Assess project requirements** • Dispatchability or firmness requirements • Control requirements and need for time-variant use of energy
Phase 3 **Assessment of Business Model Options**	**Consider business and ownership model options** • Direct ownership or third party • Single capacity contract, blended energy contract **Consider variations of energy contracts** • Time-differentiated rates, 24/7 firm power supply
Phase 4 **Selection and Implementation of Business Model**	• **Determine the most suitable business model** • **Prepare a term sheet** • **Prepare and implement a procurement strategy**
IMPLEMENTATION	
Develop and issue project tender	

RMI Graphic. **Source**: Adapted from *Unlocking the Energy Transition: Guidelines for Planning Solar-Plus-Storage Projects,* ESMAP and World Bank Group, 2023, **https://documents1.worldbank.org/curated/en/099112223104540303/pdf/P1790740c740f800c0a7960bac2a93b3f8c.pdf**.

Procurement and tender process

Public procurement of goods and services in India is a multi-step competitive process designed to ensure transparency and economic efficiency (see **Exhibit 23**).[127]

Exhibit 23 Tendering process in India



RMI Graphic. **Source**: RMI Analysis

In March 2022, the MoP issued the "Guidelines for Procurement and Utilisation of Battery Energy Storage Systems as part of Generation, Transmission and Distribution assets, along with Ancillary Services."[128] The guidelines and subsequent amendments aim to facilitate the procurement of BESS while ensuring transparency and fairness in the procurement process and establishing a standardised risk-sharing framework between stakeholders to encourage competition and enhanced bankability. Recent adoption of discovered tariffs through tariff based competitive bidding routes in states such as Rajastan, Gujarat, and Maharashtra demonstrate the evolving nature of ESS procurement mechanisms.

Key criteria include:

- A minimum of two qualified bidders must participate.
- Bids shall be submitted in a single stage, with two parts: technical bid and financial bid. Technical bids shall be opened first, and only financial bids of those who qualify in the technical bid evaluation stage shall be opened.
- Minimum term of a battery energy storage purchase agreement (BESPA) shall be 12–15 years.

Failure to appropriately adhere to the public procurement tendering process may put a project at risk. SECI's 500 MW/1,000 MWh stand-alone BESS pilot project underscores the importance of navigating the tendering process. SECI initially issued a letter of award (LoA) in January 2023, with a discovered tariff of ₹10.83 lakh/MW/month. However, due to delays in issuing the LoA and the signing of the BESS agreement and BESPA, the project timelines exceeded those outlined in the tender procurement documents. In January 2025, CERC rejected SECI's petition to adopt tariffs for the stand-alone BESS pilot project.[129] CERC cited misalignment with prevailing market conditions due to delays, allowing developers to benefit from falling battery costs and resulting in undue advantages at the expense of public resources and consumer welfare.[130]

As more energy storage-linked projects progress through the tendering process and enter execution and operational phases, key learnings and best practices will emerge to reduce cancellation risk. Stakeholders in India have already seen greater success in the tendering process. In 2022 and 2023, 10 and 12 energy storage-linked tenders were cancelled, respectively. In 2024, tender cancellations fell significantly, with only two of 35 tenders being cancelled.[131] There are two key trends: the number of energy storage-linked tenders issued annually is growing, while the number of cancellations is rapidly declining. These trends indicate growing stakeholder familiarity and success with the tendering process.

Ownership models

The ownership model is a key initial determinant for the BESS project. For a project's ownership, DISCOMs generally can either outright purchase the BESS or contract with a third party, such as a large central entity like SECI or an energy service company (ESCO). Under the third-party ownership model, the BESS asset is owned and operated by a third party that provides specific storage services under a contractual agreement, such as a PPA.[132] The ownership model selected should reflect the needs, preferences, and technical and operational capabilities of the DISCOMs. Contract structures are critical for allocating risk for project development, construction, and performance between the parties. In addition, these contract constructs are not mutually exclusive, as a utility may offer a PPA with an option to purchase the project at the end of its term.[133] Both ownership models present trade-offs regarding flexibility and risk (see **Exhibit 24**, page 71).[134]

Exhibit 24 Ownership models

DISCOM Owned	Third-Party Ownership[xiv]
Use case defines technical specifications	Use case defines desired results
Located within the distribution network	Flexibility with location
Greater financing burden	Lower entry cost
Greater responsibility for EPC	Monitors development
Responsible for commissioning	Pay for performance agreement (₹/kWh)
Responsible for operations or contracting out operations	Responsibilities defined per agreement and warranties
Operational changes allowed within the limits of warranties	Limited changes allowed, as defined or negotiated
Greater Flexibility	**Lower Risk**

RMI Graphic. **Source**: Adapted from *Emerging Best Practices for Procurement of Battery Storage and Solar-Plus Systems,* Solar-Plus for Electric Co-ops, Cliburn and Associates, September 2021, **https://nccleantech.ncsu.edu/wp-content/uploads/2021/09/procurement_guidance_brief_09_2021.pdf**.

Since 2019, energy storage and RE projects tendered within India have explored a breadth of ownership and contracting models to ensure a reliable energy system. Recent DISCOM-owned projects include BSES Rajdhani Power Limited's 20 MW (40 MWh) pilot in Delhi tendered in October 2022, Gujarat Urja Vikas Nigam Limited's multi-phase BESS tenders issued through 2024, and the Calcutta Electric Supply Corporation's 40 MW (80 MWh) tender issued in August 2025. These projects represent one aspect of the variety of approaches DISCOMs are taking to procure storage through stand-alone storage contracts and PPA models. The nature and structure of these contracts have significant implications for developers and planners, which will then influence the discovered tariff for a tendered project.

[xiv] From the DISCOM perspective, a third party could include an independent power producer or a large central entity such as SECI or NTPC.

Stand-alone battery storage capacity contracting

Stand-alone BESS projects refer to independent battery systems that are not co-located with other generation sources. These projects are charged from the grid and respond to overall grid conditions to provide critical transmission- or distribution-level services. Stand-alone BESS capacity contracting offers the buyer key critical advantages:[135]

- Buyer has a high level of flexibility
- Enables the buyer to optimise assets to produce energy and other ancillary services jointly, and is most likely to capture the maximum benefits of value stacking
- Auction design and award can be relatively simple, as remuneration is based on ₹/MW/month and the lowest bid is awarded the contract

However, DISCOM-owned stand-alone battery storage is relatively new, and the risk allocation profile puts greater risk to the buyer (i.e., the DISCOM). Some production and resource variability risk, which is typically borne by the seller in a typical PV PPA, is shifted to the buyer, for example, by firming energy through its own portfolio of resources. In addition, the model requires secure, uninterrupted communication between the dispatcher and the assets to fully utilise the assets' dispatchability remotely.[136]

Numerous project development frameworks have been pursued that allocate responsibility and risk across DISCOMs and the contracted developer. This includes site permitting, project financing, design, procurement, construction, operation, and end-of-life management.

The most popular contracting models explored to date within India include engineering, procurement, and construction (EPC), build-own-operate (BOO), and build-own-operate-transfer (BOOT). Cumulatively, these models represent 96% of storage tender capacity procured through competitive bidding within India.[137, xv] Unlike PPAs, in which most of the burden lies with the contracting entity, these approaches distribute responsibilities and risk between the DISCOM and the developer (see **Exhibit 25**). This section will explore these contracting structures and their respective advantages and disadvantages in greater detail.

Exhibit 25 Stand-alone BESS contracting responsibilities

Service	Responsible Party		
	EPC	**BOO**	**BOOT**
Site Permitting/Preparation	DISCOM	DISCOM or Developer	DISCOM or Developer
Financing	DISCOM	Developer	Developer
Project Design/Engineering	Developer	Developer	Developer
Procurement	Developer	Developer	Developer
Construction	Developer	Developer	Developer
Operation/Monitoring and Evaluation	DISCOM or Developer	Developer	Developer
End-of-Term Ownership	DISCOM	Developer	DISCOM

RMI Graphic. **Source**: Adapted from Liyang Liu, Yiming Ma, Yakai Li, Ymin Peng, Rufei He, Yao Li, "Review of Gravity Energy Storage Research and Development," *2023 8th International Conference on Power and Renewable Energy,* Institute of Electrical and Electronics Engineers (IEEE), September 2023, **https://ieeexplore.ieee.org/document/10353860**.

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xv. As of January 2025

Engineering, procurement, and construction agreements

An EPC agreement refers to a project delivery approach in which the DISCOM contracts with an entity to oversee all project design and construction activities, as detailed in **Exhibit 26.**[138]

Exhibit 26 EPC activities

Engineering	The phase involves the design and planning of the BESS project, including site assessment, system design, specifying the required equipment and components, and creating engineering plans and drawings.
Procurement	The phase during which necessary equipment, materials, and components are sourced and purchased. This would include batteries, inverters, control systems, cables, transformers, and other infrastructure required for the BESS project.
Construction	In this phase, the actual construction of the BESS project takes place, including site preparation, equipment installation, electrical and mechanical work, and all necessary infrastructure to make the BESS operational.

RMI Graphic. **Source**: "What is EPC in energy storage system industry?," GTCAP, November 6, 2023, **https://www.greenteche.com/what-is-epc-in-energy-storage-system-industry.html**.

EPC projects tend to be on a full-wrap, turnkey, and fixed-price basis, defined in **Exhibit 27.**[139]

Exhibit 27 EPC project aspect definitions

Full-Wrap	The developer is responsible for warranting and the performance of all subcontracts and vendors (including, in the case of a BESS project, the batteries and inverters) and for completing the project in its entirety on time.
Turnkey	The developer is responsible for coordinating the activities of all the other contractors and delivering a completed project to the DISCOM.
Fixed-Price	The price paid by the DISCOM will be set in advance and, absent certain previously agreed-to exceptions, the developer will not be entitled to pass through any cost increase to the utility.

RMI Graphic. **Source**: "A 2024 Update on Utility-Scale Energy Storage Procurements," Morgan Lewis, March 4, 2024, **https://www.morganlewis.com/pubs/2024/03/an-update-on-utility-scale-energy-storage-procurements**.

The EPC project approach designates the contractor as a single point of responsibility for all design, engineering, procurement, construction, commissioning, and testing activities. If a problem arises, only one party is accountable for resolving the issue and providing compensation. The risk of cost overruns, as well as the benefit of cost savings, rests with the contractor. Under the EPC agreement, the DISCOM would own the BESS project and typically would be responsible for site permitting (including ensuring suitable environmental conditions or handling change orders associated with site suitability or readiness), financing, interconnection, and operation. DISCOMs can use EPC contracts to leverage pre-existing sites, which may ease permitting and maximise opportunities to defer capital expenditure. Advantages and disadvantages of this model are detailed in **Exhibit 28**.[140] Approximately 43% of battery storage tenders procured in India between 2018 and 2024 have utilised the EPC model.[141]

Exhibit 28 Advantages and disadvantages of EPC agreement for DISCOMs

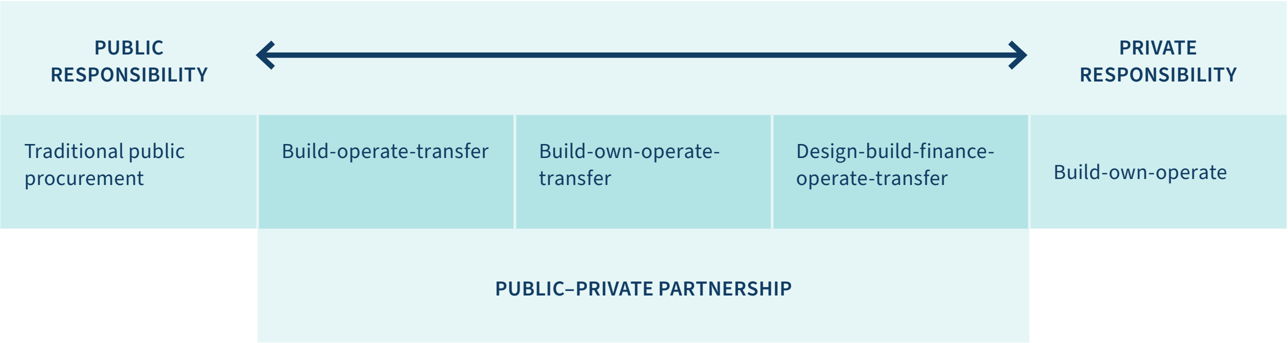
Advantages	Disadvantages
Single point of responsibility	Typically, a higher contract price
Fixed contract price: cost overruns borne by the contractor	The DISCOM has limited authority to intervene in project design and construction on a day-to-day basis
Fixed contract completion date: contractor liable for delays in project completion	DISCOM is responsible for site permitting and readiness
Performance guarantee: the contractor is liable for any performance issues with the operations	DISCOM is responsible for project financing
Defects liability: contractor is liable for any defects caused due to poor construction of infrastructure (typically within 12–24 months of completion)	DISCOM is responsible for overseeing or contracting for project operation, monitoring, and evaluation
Minimisation of risks for DISCOM	
Operational changes allowed within the limits of warranties	Limited changes allowed, as defined or negotiated

RMI Graphic. **Source**: "A 2024 Update on Utility-Scale Energy Storage Procurements," Morgan Lewis; "Advantages and Disadvantages of an EPC Contractor in an SPC Green energy project (minority investor)," *Structures Insider,* June 29, 2024, **https://www.structuresinsider.com/post/advantages-and-disadvantages-of-an-epc-contractor-in-an-spc-green-energy-project-minority-investor**; "What is EPC in energy storage system industry?," GTCAP.

Concession agreeements

Concession partnerships are public–private partnerships in which the financing, construction, and operation of an infrastructure asset are shared between a government entity and a private-sector partner. Globally, a wide array of concession agreements has been utilised, with varying degrees of risk and responsibilities allocated across public and private stakeholders, depending on project needs and stakeholder strength and ability. These partnerships enable greater spending efficiency, with greater accountability and the promotion of innovation. **Exhibit 29** highlights the scale of some frequently utilised concession agreement examples.[142]

Exhibit 29 Schematic scale of the public procurement classification



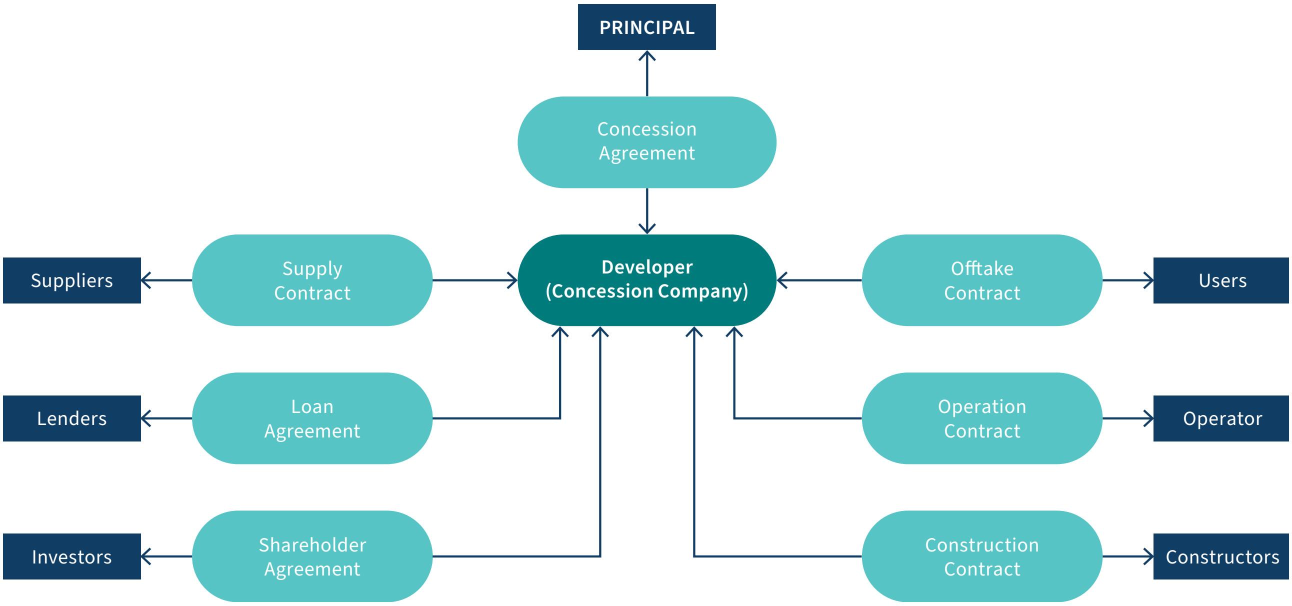
RMI Graphic. **Source**: Adapted from Rifat Akbiyikli and David Eaton, "A Comparison of PFI, BOT, BOO and BOOT Procurement Routes for Infrastructure Construction Projects," *Fifth International Postgraduate Research Conference in the Built and Human Environment* (April 2005): 13–15, **https://www.irbnet.de/daten/iconda/CIB16757.pdf**.

Concession agreements have so far played a critical role in BESS procurement in India. In March 2022, the MoP issued "Guidelines for Procurement and Utilisation of Battery Energy Storage Systems as part of Generation, Transmission and Distribution assets, along with Ancillary Services." These guidelines referred to earlier in this section outline minimum project size and bid capacity requirements for intra-state and inter-state projects, and recognise projects built through the build-own-operate-transfer (BOOT) and build-own-operate (BOO) public–private partnership models.[143] Subsequently, these partnership models have been utilised for approximately 65% of battery storage projects procured in India since 2018.[144]

Build-own-operate-transfer

The BOOT framework is a private sector participation model in which the developer establishes a project company to finance, design, construct, own, and operate an asset for a designated period of time (the concession period) before ownership is transferred to the principal (the government or DISCOM entity). The developer (or concession company) undertakes financing, design, construction, and operation to minimise direct cost risk to the principal.[145] The BOOT framework enables infrastructure projects to avoid delay or implementation risks associated with a principal organisation's budget or bureaucratic constraints. During the operational phase, which falls within the concession period, the developer manages day-to-day activities, maintenance, and service provision. The developer typically collects user fees or tariffs to enable private equity to earn a return on investment during the agreed-upon term. This arrangement alleviates financial, construction, and operational risk from the principal entity; a typical structure is detailed in **Exhibit 30**.[146]

Exhibit 30 Typical structure of a BOOT project



RMI Graphic. **Source**: "Build, Own, Operate, and Transfer," WallStreetMojo, ed. Ashish Kumar Srivastav, August 16, 2023, **https://www.wallstreetmojo.com/build-own-operate-and-transfer/**; Rifat Akbiyikli and David Eaton, "A Comparison of PFI, BOT, BOO and BOOT Procurement Routes for Infrastructure Construction Projects," *Fifth International Postgraduate Research Conference in the Built and Human Environment* (April 2005): 13–15, **https://www.irbnet.de/daten/iconda/CIB16757.pdf**.

At the end of the concession period, ownership of the project is transferred from the developer to the principal.

Build-own-operate

A BOO concession arrangement is very similar to the BOOT model, with a key distinction in ownership at the end of the contracted period. Under the BOOT model, ownership of the asset is transferred to the nodal agency at the end of the PPA tenor at a particular residual life. In the BOO model, the asset remains with the developer and can be further monetised at their discretion. The choice of model will influence the augmentation strategy for the BESS project and will also allow the developer to create additional revenue lines. Ultimately, this allows the developer to optimise tariffs and returns, as the developer can anticipate utilising the project for additional offtake agreements or as a merchant asset at the end of the concession period.

Storage power purchase agreements

Energy PPAs are standard contracts between an electricity generator and a buyer that define the commercial terms for the sale of electricity between the two parties; they are frequently utilised for RE projects.[147] PPAs allow DISCOMs to access renewable energy without the need for significant up-front investments in energy infrastructure. For a DISCOM, the key advantage of a PPA is that it allows the DISCOM to avoid the risks associated with the ownership of a project or the project's failure to perform. If the project does not provide the contracted service, the project owners will not be paid; continued failure to perform may result in contract termination. Moreover, if the project is over budget or behind schedule, the developer is responsible for all incremental costs and delays.[148]

While several provisions of RE PPAs may be "plug-and-play" in battery storage contracts, certain provisions warrant special consideration (see **Exhibit 31**, page 79).[149]

Exhibit 31 Special considerations for battery storage PPAs

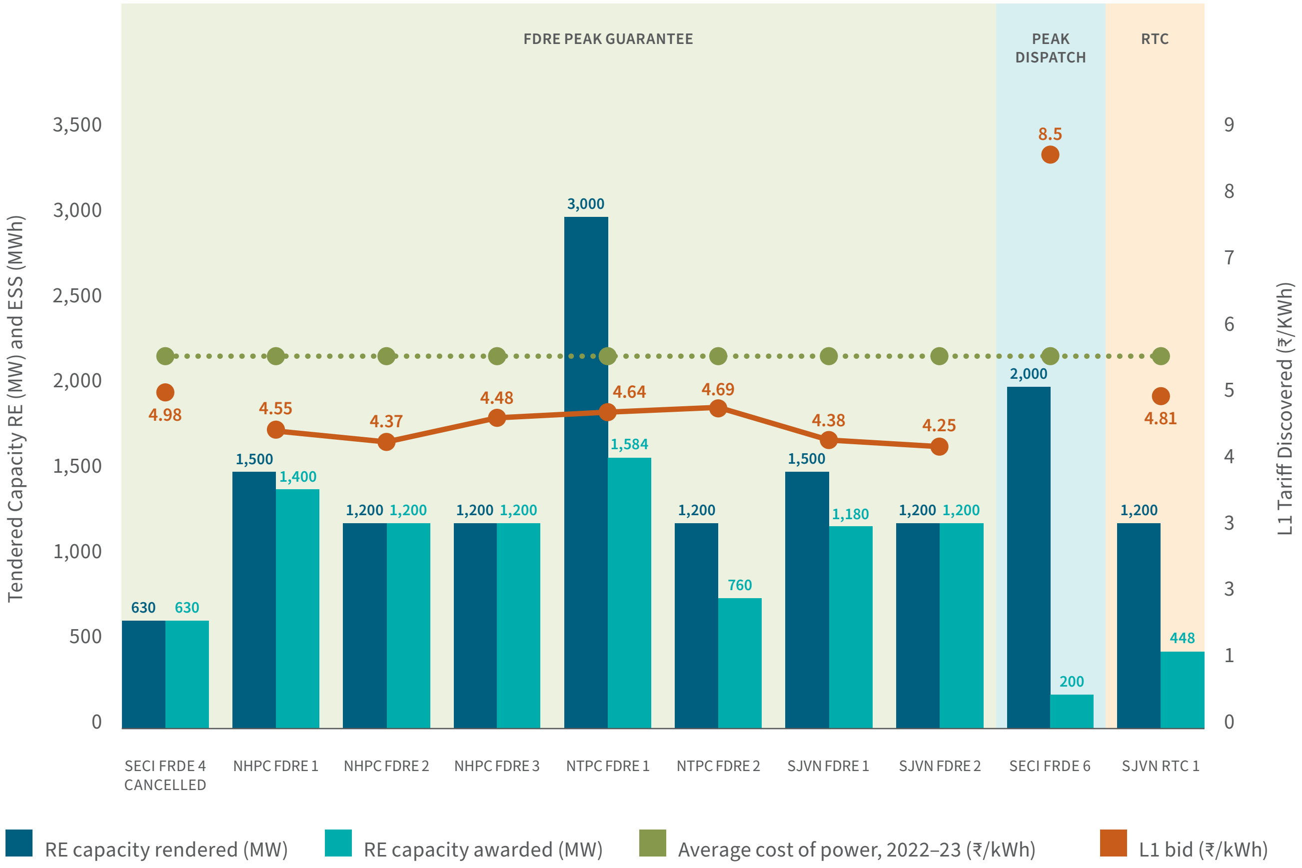
Defining the Product	Given that energy storage can operate as a generation resource and as an energy load (or "sink"), it is important for all parties to understand how the storage system will be used. The rights to various services and products from the system must be allocated, and appropriate compensation determined. Each service and product that will transfer under the PPA should be clearly defined.
Setting the Term	Battery storage PPAs can be considered on both short- and long-term horizons, as the ability to replace battery components extends a project's life. For co-located BESS and RE projects, establishing the delivery term may be combined or separated for various products and services, which will need to be determined by the parties.
Performance Guarantees	The parties should determine whether the storage system will be expected to perform at a certain rate and what the penalty for non-performance will be. In addition, the seller should understand how performance may change over time, and the PPA should account for natural degradation when negotiating performance guarantees.
Allocating Control Rights	The practicalities of which party will control the system, whether control will be on site or remote, and what authority other parties to the PPA must step in will be key, and how control of the storage system is compensated (if at all).
Manufacturer's Requirements	Some operating requirements are unique to storage, such as the amount of cycling battery storage systems are allowed each day. All parties should be aware of the requirements to manage performance expectations and avoid operating outside of the manufacturer's requirements to minimise safety and reliability risks.
Charging the System	The PPA for a battery storage system should specify charging parameters, including whether it is allowed to charge from the grid, when it may draw from the grid, and at what percentages. The way the energy is used to charge the system versus the manner in which the output is measured will need to be determined. If the PPA offtaker is the same entity that is supplying the electricity to charge the system, the pricing mechanisms may need to be negotiated.
Setting the Purchase Price	Several aspects of a PPA for battery storage include whether the PPA price will justify the cost of project construction and operation, and how delay and price volatility may impact the term of the PPA. The PPA will need to be clear regarding the rights to each product and service if a single offtaker will not be entitled to all of the multiple revenue streams.

RMI Graphic. **Source**: Adapted from Caileen Gamache, "Energy Storage: Unique PPA Considerations," *Project Finance News,* Norton Rose Fulbright, October 1, 2017, **https://www.projectfinance.law/publications/2017/october/energy-storage-unique-ppa-considerations/**.

PPA structures for grid storage procurement in india

Within India, the requirement for DISCOMs to meet renewable purchase obligations (RPOs) while reliably meeting energy demand has been a major driver of energy storage. To meet RPO targets, SECI and DISCOMs have explored multiple PPA configurations to improve VRE project capacity utilisation, necessitating storage procurement. Since 2019, these configurations have included RTC RE, load-following FDRE, peak-guarantee FDRE, and solar PV plus energy storage. The PPA configurations have been intended to meet key DISCOM needs, especially during rising evening peak demand when stand-alone solar generation declines. Projects procured under different contract models have demonstrated a range of discovered tariffs (see **Exhibit 32**).[150] While declining battery material costs will reflect in discovered tariffs, the project model and contract structure will be another key cost driver.

Exhibit 32 RTC/FDRE tariff trends, 2022–2025



RMI Graphic. **Source**: "1H 2025 Energy Storage Update – India," Debmalya Sen, last modified July 2025, **https://www.linkedin.com/posts/debmalya-sen_1-h-2025-energy-storage-update-india-activity-7348873268998586368-i7ix**; *Report on Performance of Power Utilities, 2022-23,* Power Finance Corporation of India, April 2024, **https://pfcindia.co.in/ensite/DocumentRepository/ckfinder/files/Operations/Performance_Reports_of_State_Power_Utilities/Report%20Database%202022-23%20-%20updated%20up%20to%20April%202024EntityApr.pdf**.

Round-the-clock renewable energy

RTC RE was initially explored as a means of supporting RE integration in India while providing an alternative to expensive thermal generation. This focusses on the physical aggregation of capacities from multiple generation or storage technologies, combining VRE with stable complementary power from other sources to ensure a 24/7 power supply. Generally, RTC tenders by the central nodal agencies include an annual availability requirement of 75%–85% and a time-block-wise availability of 50%.[151]

RTC tariffs allow the developer to pursue a variety of pathways to meet the project's targeted capacity utilisation factor (CUF), including blending VRE with hydropower, energy storage, thermal power (if the tender stipulations permit), or oversizing RE capacity.[xvi] Higher CUF levels call for greater oversizing of the RE component of overall project capacity; for purely RE or RE plus storage projects, the overcapacity is expected to be three or more times the contracted RTC capacity.[152]

RTC-1 tender

SECI issued the first-ever RTC tender in India (RTC-1) in October 2019. RTC-1 sought to build 400 MW of RE, with an annual CUF of at least 80%. Under this tender, solar, wind, and hybrid projects could be developed and augmented with ESS to meet the minimum requirements.[153] The contract was awarded to ReNew Power in May 2020, requiring a total portfolio capacity of 1.3 GW (400 MW from solar, 900 MW from wind, and 100 MWh from BESS), across Rajasthan, Maharashtra, and Karnataka.[154] See **Exhibit 33** on page 82 for RTC-1 tender attributes and results.[155]

[xvi] Capacity utilisation factor is the ratio of a project's actual to the maximum possible energy output over a period.

Exhibit 33 RTC-1 tender attributes and results

Tender Attribute	Condition
Capacity	400 MW
Capacity Utilisation Factor	• Annual CUF — Not less than 80% • Monthly CUF — Not less than 70%
Levelised Tariff	₹3.6/kWh
Tariff Escalation	The single first-year tariff quoted will have an escalation at 3% per annum up to the end of the 15th contract year of the term of the PPA, and shall subsequently be fixed at the tariff thereafter, not for the remaining term of the PPA
Scheduled Commissioning Date	24 months from the effective date of the PPA[xvii]
Selection of Project Technology	• RE technologies are classified as a renewable power-generating source by MNRE • For ESS, any form of storage such as BESS, mechanical storage, pumped storage, etc.
Location of Generation Sources	• May be co-located, or may be located at different locations, to be considered as a single project • ESS, if any, is mandated to be co-located with at least one of the sources of generation in the project
Penalty for Shortfall in Energy Supply	• In the case of a shortfall in generation below the energy corresponding to 80% CUF and up to (and including) 77.5% CUF: 300% of the PPA tariff for the shortfall in energy terms, in accordance with the terms of the PPA • In case of shortfall in generation below energy corresponding to 77.5% CUF: in addition to the above compensation, tariff escalation for the immediately succeeding contract year shall be removed from the applicable tariff for the corresponding contract year

RMI Graphic. **Source**: Jyoti Gulia, Vibhuti Garg, and Akhil Thayillam, *Understanding Round-the-Clock Tenders in India: The Current Context and Ways Forward,* Institute for Energy Economics and Financial Analysis, JMK Research & Analytics, 2021, **https://ieefa.org/wp-content/uploads/2021/11/Understanding-Round-the-Clock-Tenders-in-India_November-2021.pdf**.

[xvii] This project has been initiated in phases, with some commercial operations beginning in August 2023.

Firm and dispatchable renewable energy

FDRE is an approach to tender design that is an evolution of the assured peak dispatch and RTC RE contract structures. The Ministry of New and Renewable Energy notified “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” (FDRE Guidelines) in June 2023, and subsequently, the first FDRE tender was awarded in November 2023.[156] FDRE tenders are designed to align with DISCOM demand profiles. Similar to RTC, FDRE can be met by oversizing wind and solar capacity, along with energy storage. The demand profile and availability needs of the buying entities will influence the volume and composition of the portfolio. The tariffs discovered for these tenders are slightly higher than RTC due to the load curve requirement for each 15-minute to 1-hour block, which varies across the year.

The FDRE Guidelines recognise four forms of FDRE tenders: RTC RE, peak guarantee, load following, and firm delivery for fixed hours (such as peak dispatch).[157] Peak guarantee and load following may be understood as having requirements similar to those detailed in **Exhibit 34.**[158]

Exhibit 34 Characteristics of FDRE forms

Peak Guarantee	Requires a CUF of 40%, along with the availability of 90% capacity during peak periods, up to 4 hours per day.
Load Following	Requires a demand fulfilment ratio (DFR) of 75%–90% for each 15-minute to 1-hour block, reconciled monthly.[xviii]

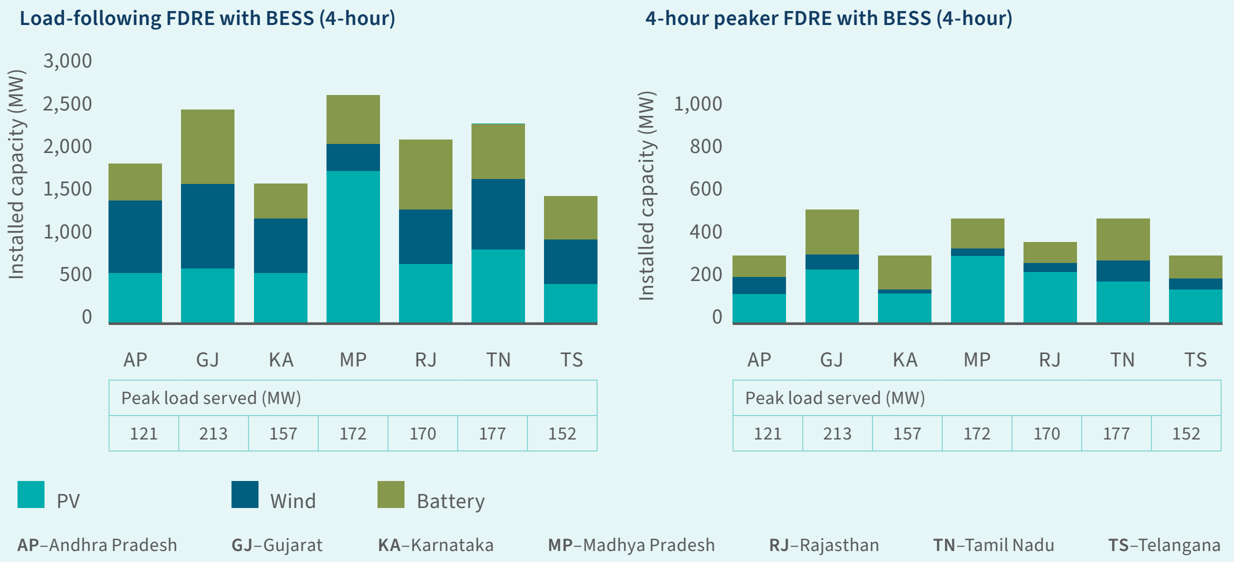
RMI Graphic. **Source**: Chitrika Grover, “ICRA Sees FDRE, RTC Projects as Key Drivers of RE Growth,” *Mercom India,* September 23, 2024, **https://www.saurenergy.com/solar-energy-news/icra-sees-fdre-rtc-projects-as-key-drivers-of-re-growth**; “ICRA Sees FDRE, RTC Projects as Key Drivers of RE Growth,” 2024; “What Is India’s New RE-Based Tender – Firm and Dispatch-Able Renewable Energy (FDRE)?,” *FSR Global,* **https://fsrglobal.org/what-is-indias-new-re-based-tender-firm-and-dispatch-able-renewable-energy-fdre/**.

For peak guarantee FDRE tenders, discovered tariffs have ranged from ₹4.38 to ₹4.69/kWh. The load-following FDRE tariff discovered for SECI is R4.98/kWh. The higher discovered tariff reflects that meeting the requirements for load-following FDRE may necessitate capacity overbuild, including greater storage and underutilisation (see **Box 2**, page 84).

[xviii] DFR is calculated as:
DFR = [Injection Scheduled by the RE provider (MW)/Demand (MW) specified by the purchasing entity for the corresponding time block]

Box 2 Comparing peak guarantee and load-following FDRE

Exhibit 35 Hypothetical comparison of peak guarantee and load-following FDRE



Load-following FDRE with BESS (4-hour)

4-hour peaker FDRE with BESS (4-hour)

	AP	GJ	KA	MP	RJ	TN	TS
Peak load served (MW)	121	213	157	172	170	177	152

RMI Graphic. **Source**: RMI Analysis

This hypothetical illustrative comparative example seeks to minimise investment costs, subject to the condition that solar, wind, and BESS generation meet hourly load for the entire year. The hourly load profile is formed by 1% of the state's annual hourly load, for a total of 8,760 hours. Peak guarantee FDRE meets the scaled load during the top 4 hours each day. The optimisation problem uses hourly RE capacity factors of RE-rich states and installed costs for BESS, solar, and wind as inputs. The maximum storage duration is four hours.[xix]

The output of this model demonstrates that, in this hypothetical example, meeting the DFR for load-following FDRE may result in significant overbuild of resources compared to the peak guarantee FDRE. This potential need for overbuild can lead to higher per-kWh costs. This price disparity seems to be reflected in real-world discovered tariffs: to date, load-following FDRE has seen discovered tariffs of ₹4.98 and ₹5.59/kWh. By contract, peak guarantee FDRE discovered tariffs have ranged between ₹4.25/kWh and ₹4.69/kWh.[159] For cost-sensitive buyers, the need for load-following services must be justified by the increased per-unit cost.

[xix] For additional modelling details, see **Appendix D**.

Solar PV + BESS

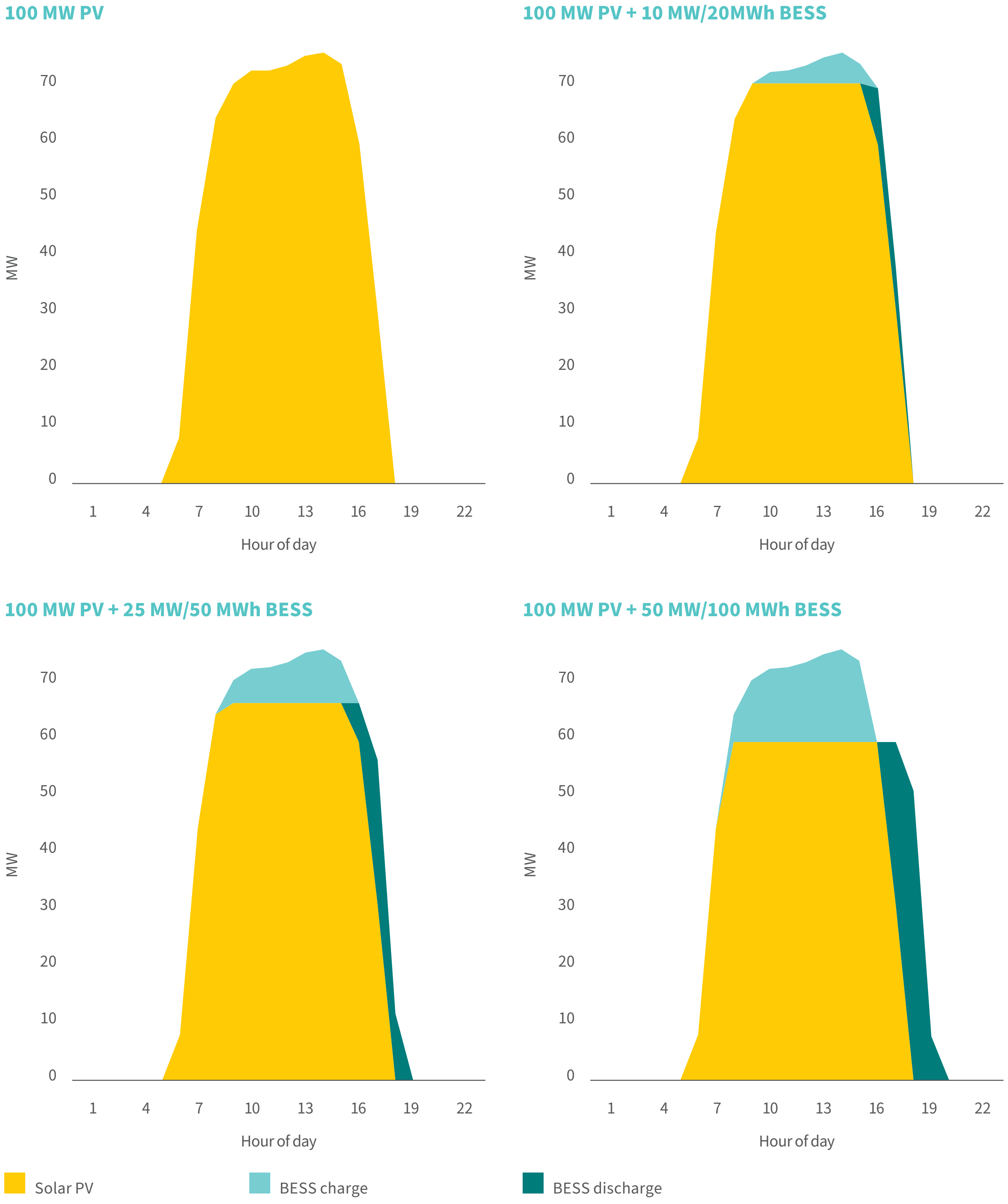
The solar PV + BESS PPA is a contract structure with growing appeal, both globally and within India. Solar PV + BESS combines the clean energy of stand-alone solar with the flexibility of battery storage, while offering cost savings from co-locating the facilities. PV + BESS contracts in India are typically structured similarly to a solar PV PPA during non-peaking hours, but with a peak guarantee. This approach to contract structure is an intuitive bridge from solar PPAs that DISCOMs and other offtakers are familiar with, while addressing key peaking support needs. In 2024 alone, PV + BESS tenders totalled 4.4 GW of PV capacity and 6.4 GWh of BESS.[160] Some key provisions of PV + BESS tenders offered include:

- Project must meet the targeted annual CUF during non-peak hours[xx]
- BESS must be co-located with at least one solar PV array
- BESS must charge from solar, with minimal allowance for charging from green open access
- Peak supply guarantee, with peak hours defined by the buyer

PV + BESS PPAs provide certain advantages compared to other contract structures, while also presenting some limitations. Unlike FDRE tenders, PV + BESS PPAs are not technology-agnostic, meaning the developer may have less flexibility to meet the required output. However, the PV + BESS PPA structure provides a relatively simple contract compared to FDRE and may frequently be procured at lower cost, given its less stringent operational requirements, co-location cost advantages, and reduced risk of overbuild. BESS size and duration will impact the project's generation profile, its ability to meet the DISCOM's needs (such as peaking), and, ultimately, the discovered PPA tariff. Determination of the appropriate ratio of PV capacity to BESS energy (accounting for both BESS capacity and discharge duration) is a critical consideration when structuring the PPA. **Exhibit 36** on page 86 shows how adding various quantities of two-hour-duration batteries to a solar PV plant enables a DISCOM to deliver more consistent generation. While this example shows how BESS could enable a flatter generation profile, BESS may also be used to reshape the generation profile (e.g., to night-time peaking).

[xx] Initially defined as 25%–27%, but amended to 19%.

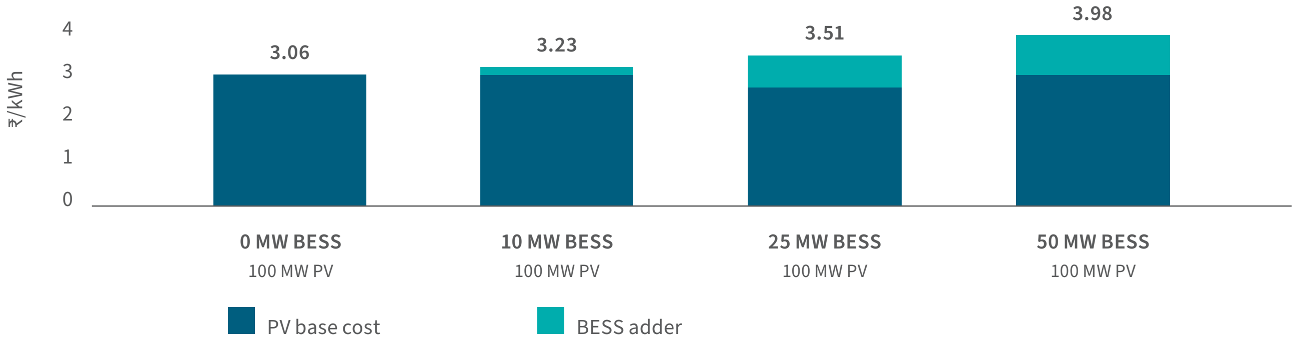
Exhibit 36 Shaping generation by adding BESS to solar PV



RMI Graphic. **Source**: RMI Analysis

This example shows how co-locating solar PV and storage enables a DISCOM to increase operational flexibility by shifting some generation from the middle of the day to the evening hours. Flexibility is valuable for a DISCOM with demand needs outside of the midday hours. But flexibility also comes at a cost. Our modelling shows that stand-alone solar costs approximately ₹3.1/kWh today. As we add battery storage, the cost of delivered energy rises. For a 100 MW solar PV + 50 MW/100 MWh BESS system, the cost of energy is ₹4/kWh.[xxi] As DISCOMs size solar PV + BESS systems, they must weigh the benefits of increased flexibility against the costs.

Exhibit 37 Estimated cost impacts of BESS added to solar PV generation projects



RMI Graphic. **Source**: RMI Analysis

Procurement Decisions

The flexible nature of energy storage and the modularity of battery storage systems enable a wide range of business and contract structures. Energy storage can be a key tool for DISCOMs and other entities seeking to meet goals economically, including daily power needs and peaking load management. The local needs assessment and economic analysis will be key drivers for identifying which contract structure will most efficiently meet the identified needs. Buyers must also consider the degree of responsibility and risk they are prepared to bear in any partnership.

One final consideration will be contract complexity. For example, many DISCOMs can procure PV + BESS through relatively straightforward and familiar contract structures to address a key service challenge: meeting load during non-solar peak hours. The various FDRE contract configurations are more complex and may address more distinctive buyer needs, but they require long-term load profile projections and contract commitments that pose a challenge for DISCOMs with dynamic, evolving demand portfolios. However, such contracts may be especially appealing for large-scale C&I consumers with more predictable electricity demand. These factors will inform the decision-making process (see **Exhibit 38**, page 88).

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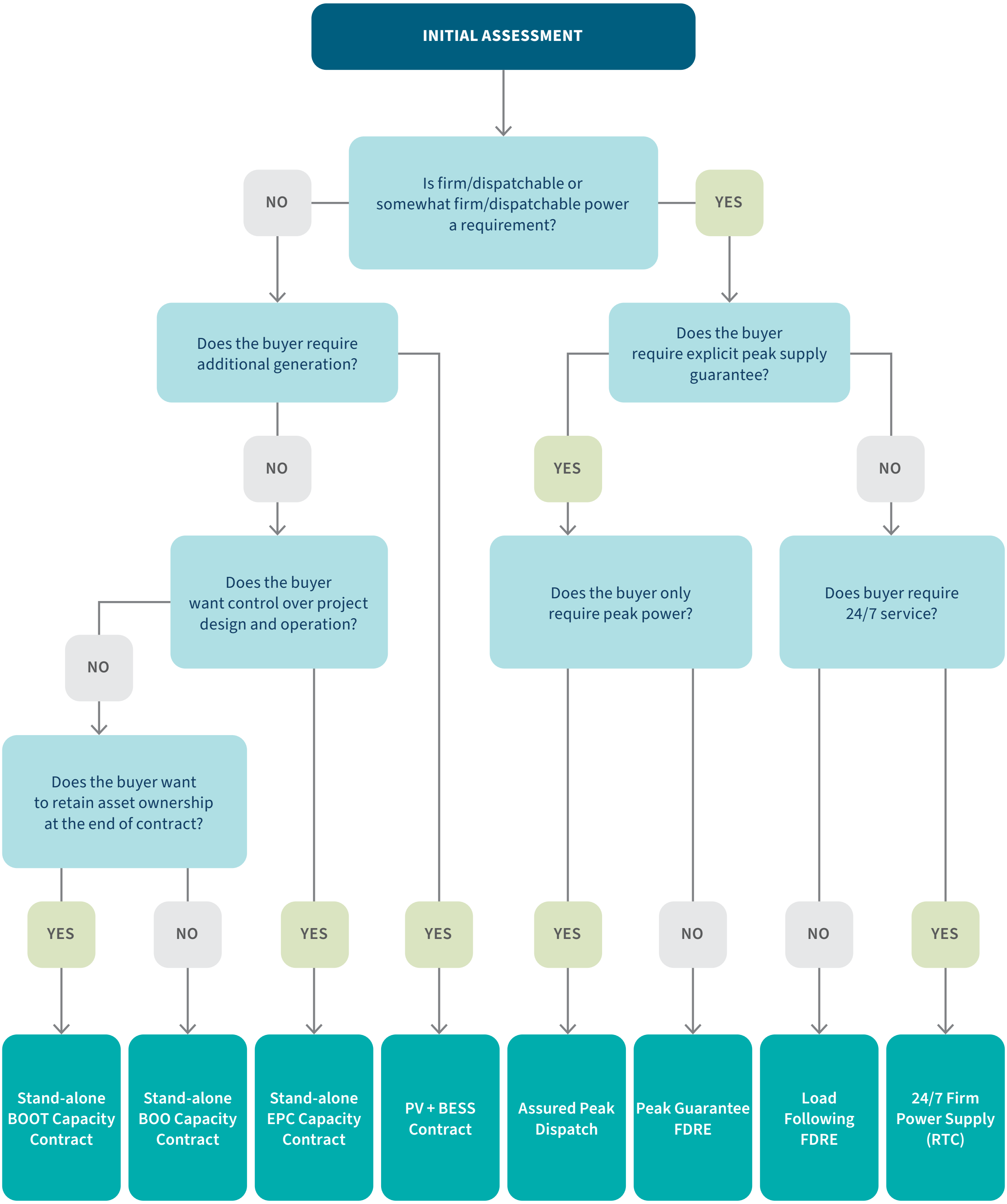
xxi. See **Appendix E**: Methodology for calculating solar PV+BESS delivered energy costs.

Exhibit 38 Energy storage procurement decision tree



RMI Graphic. **Source:** RMI Analysis

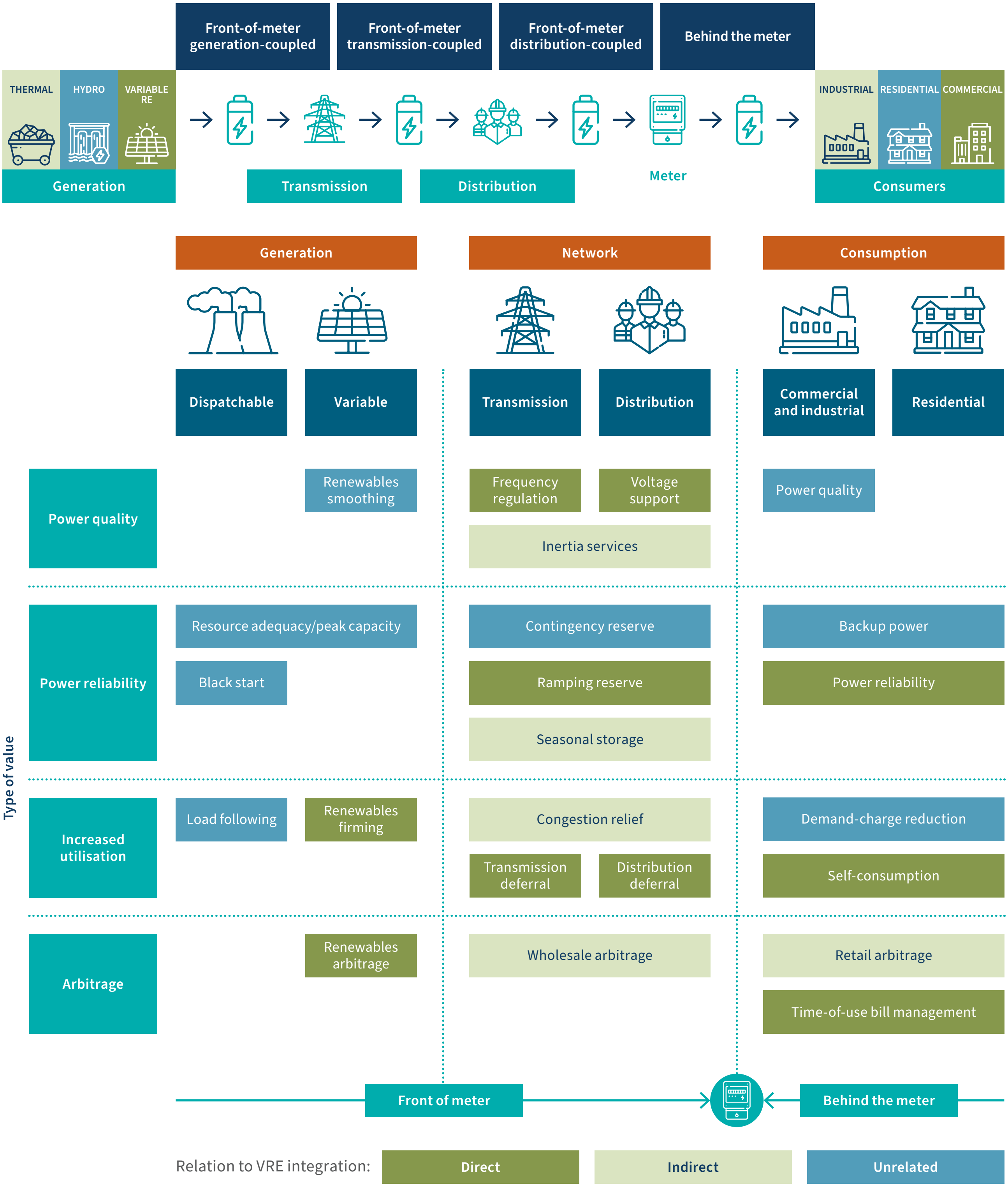
Battery Storage Applications and Value

Declining costs and system flexibility have been major drivers of increased interest in deploying BESS in India, as lower costs make more storage services economically competitive. Procurement strategies and business models for BESS offer significant flexibility, as BESS assets can be sited and sized to meet specific needs, providing services across multiple points of the grid. Despite the growing volume of tenders and the diversity of procurement models, BESS projects in India still reflect only a limited set of services the technology can provide. Most transmission or distribution site projects in India rely on energy arbitrage services for bankability, as monetisation mechanisms for some value streams, such as resource adequacy (RA) and ancillary services, are still in nascent stages. For other services, such as capital expense deferral, stakeholders lack consensus on the methodologies for determining value. This lack of clarity impacts planning for DISCOMs and project developers, as well as regulatory review and approval by SERCs.

This section will provide an overview of the services and value streams BESS can offer and discuss the status of their monetisation in India. By expanding market opportunities for BESS, India can further expand on the breadth of procurement models explored in the previous section to maximise project value and system benefits.

BESS can be coupled at each stage of the electricity system, including with generators, transmission, distribution networks, and behind the meter for consumers (see **Exhibit 39**, page 90).[161] Each of these applications can provide unique value to the coupled entity, while also benefitting the entire system and transmission and distribution utilities. The value of these applications will vary depending on the nature of the local generation mix, load, infrastructure, and load profile, among other factors. For example, distribution system upgrade needs are driven by a few predictable peak demand events that occur each year. Distribution deferral will be greater in areas with anticipated rapid growth of peak demand and an older distribution network. When combined, these applications demonstrate how BESS will be a critical component to improving India's grid security, reliability, and cost-effectiveness.

Exhibit 39 BESS applications and services across the electricity system



Type of value	Generation		Network		Consumption	
	Dispatchable	Variable	Transmission	Distribution	Commercial and industrial	Residential
Power quality		Renewables smoothing	Frequency regulation Inertia services	Voltage support	Power quality	
Power reliability	Resource adequacy/peak capacity Black start		Contingency reserve Ramping reserve Seasonal storage		Backup power Power reliability	
Increased utilisation	Load following	Renewables firming	Congestion relief Transmission deferral	Distribution deferral	Demand-charge reduction Self-consumption	
Arbitrage		Renewables arbitrage	Wholesale arbitrage		Retail arbitrage Time-of-use bill management	

Relation to VRE integration: **Direct** **Indirect** **Unrelated**

RMI Graphic. **Source**: RMI Analysis; Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value,* Oxford University Press, 2023.

The methodology and mechanics for BESS to provide these services will vary depending on market design and participation guidelines. The procurement mechanism for services may differ between administrative and market processes; not all services may be appropriately monetisable, and BESS assets may not be recognised participants in providing a service. These limitations, such as BESS projects being excluded from competing to provide primary reserve ancillary services (PRAS) or yet-to-be-determined rules on capacity credit under the RA Framework, narrow the business models and services of projects currently being tendered. The monetisable value of these services will see variance based on metrics including (but not limited to): load growth, generation and demand profiles, load factor, transmission and distribution network capacity, and VRE penetration. Optimal locations for BESS assets will be influenced by factors including RE availability patterns, network conditions (such as fixed or variable operation patterns), technical considerations (network point voltage levels), and the services being targeted.[162]

Generation-sited BESS

Combining generation and BESS is an increasingly popular model. Generation-sited BESS provides significant benefits, including enhancing grid flexibility and resilience by relieving grid stress and preventing blackouts, optimising the use of VRE through more consistent and reliable supply, and providing financial advantages to utilities and energy operators. By combining generation and storage assets, utilities and independent power producers (IPPs) can reduce infrastructure, materials, land, and soft costs, such as streamlined contracting and financing, as well as operational costs, while potentially taking advantage of existing interconnection. Given the variable nature of VRE resources, the transmission capacity used to deliver power may be underutilised for much of the year. A BESS asset co-located with VRE can reduce the transmission capacity required to integrate these resources, increase utilisation of the remaining capacity, and reduce VRE curtailment.[163]

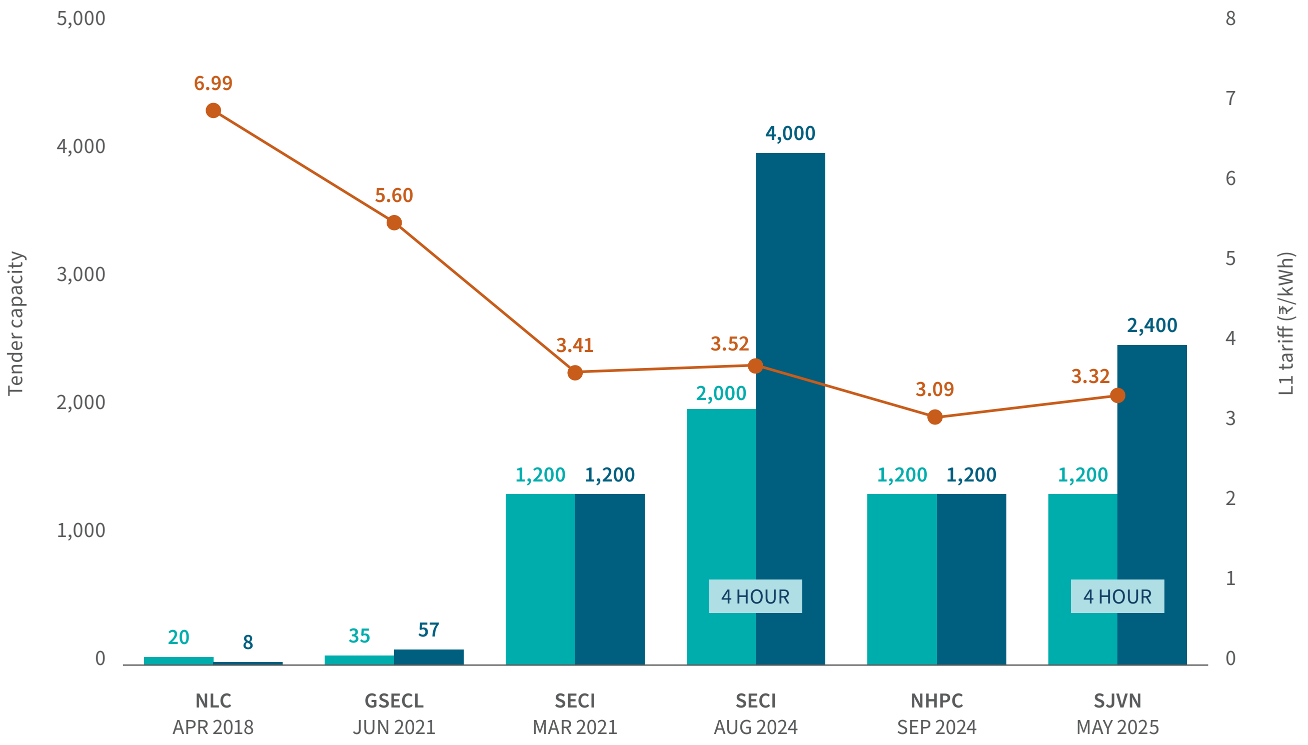
This section will explore the standard generation-sited BESS value streams and applicability within India, but will first examine the variety of PV + BESS configurations and their respective advantages and disadvantages. Understanding PV + BESS configurations is an important step toward better contextualising the scope of benefits that can be provided.

PV + BESS configurations

Widescale front-of-meter stand-alone solar deployment faces challenges as generation saturates solar-hour demand, limiting the value of solar generation for DISCOMs to meet scheduling needs. As solar PV and BESS prices continue to decline globally, the hybrid solar PV + BESS model is gaining traction as a way to shift solar generation to peak demand hours. The PV + BESS model also enables addressing intermittency issues associated with solar PV's variable production, avoiding degradation of power supply reliability, improving power quality, and providing stability to system operation. Modular and flexible design, plus system scalability, contribute to the attractiveness of the PV + BESS model. Estimates indicate that hybrid models achieve approximately 8% cumulative cost savings compared to equivalent capacity from stand-alone storage and solar systems.[164] These factors are driving the deployment of the PV + BESS model globally; as of December 2024, approximately 33 GW of PV + BESS were operating across the United States (approximately 22.8 GW of PV and 10 GW of BESS), with an additional 162 GW of PV + BESS capacity in various planning stages.[165]

Within India, the PV + BESS model has gained growing attention, with 5,600 MW of PV capacity and 8,800 MWh of BESS capacity tendered in 2024 and 2025. These projects reported tariffs ranging from ₹3.09 to ₹3.52 per kWh, even when accounting for projects with a 4-hour discharge duration. This represents a notable decline from earlier projects (see **Exhibit 40**, page 93).[166] The National Thermal Power Corporation (NTPC) also issued an invitation to bid for a 1,200 MW PV and 2,400 MWh BESS project in Rajasthan in January 2025.[167]

Exhibit 40 PV + BESS tender trends



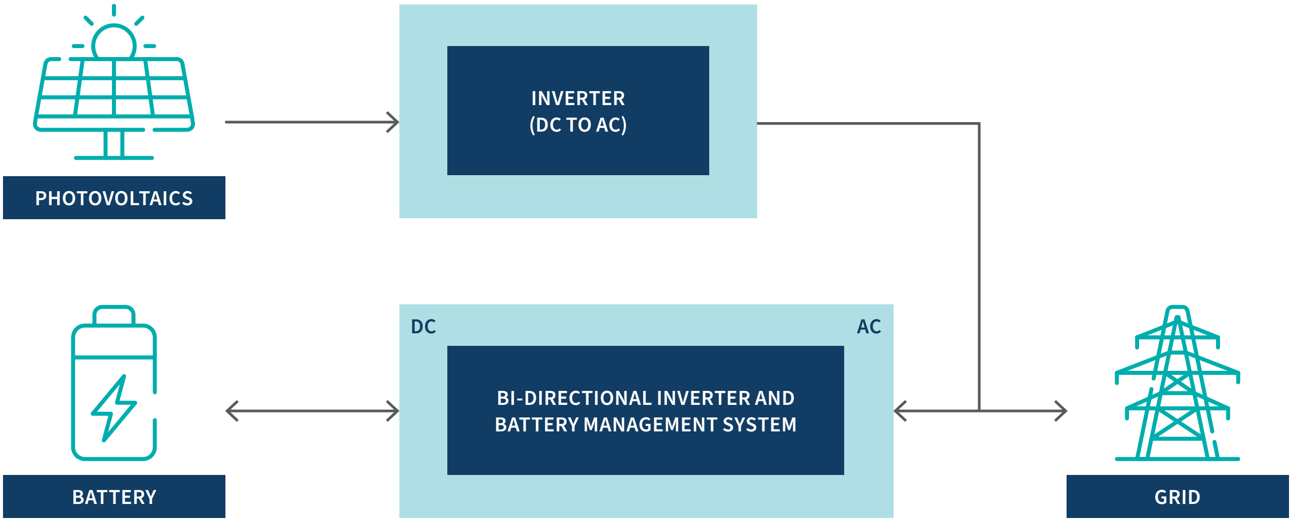
RMI Graphic. **Source**: Adapted from "1H 2025 Energy Storage Update – India," Debmalya Sen, last modified July 2025, **https://www.linkedin.com/posts/debmalya-sen_1-h-2025-energy-storage-update-india-activity-7348873268998586368-i7ix**.

Some of these cost declines are associated with PV + BESS projects' ability to share infrastructure and development costs, such as BOS, inverters, and land. BESS can also be added to existing solar arrays to improve production and minimise interconnection delays, or sited separately to maximise BESS flexibility. Developers and contractors have multiple options, allowing them to choose an approach most suited to their needs. This can include AC-coupled or DC-coupled systems, with flexible or inflexible charging. Each of these configurations has advantages and disadvantages, and planners should be aware of the suitability for the project architecture to meet end needs and impact on performance.

AC-coupled systems

In an AC-coupled system, PV generation and BESS are on separate inverters. The PV asset and battery module can be discharged at full power and dispatched together or independently, providing flexibility in how the system operates (see **Exhibit 41**, page 94).[168] In addition, the PV asset and BESS can share a grid interconnection or run on separate interconnections.[169]

Exhibit 41 AC-coupled PV + BESS



RMI Graphic. **Source**: Paul Denholm, Robert Margolis, and Joshua Eichman, *Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants: Report Summary,* National Renewable Energy Laboratory, 2017, **https://www.nrel.gov/docs/fy17osti/69061.pdf**.

AC-coupled PV + BESS systems have the following benefits:[170]

- **Retrofitting:** AC-coupled batteries are easy to install on an existing PV array, and more can be added to expand capacity as they do not need to be compatible with existing inverters.
- **Flexibility:** Installers are not restricted in where the inverters and batteries can be located. AC coupling works with any inverter.
- **Resilience:** The flexibility to install multiple inverters and batteries in different locations helps reduce the risk of an outage if an inverter fails. Having multiple inverters provides more combined power, and failures in the battery system do not affect power generation.
- **Versatility:** AC-coupled systems enable batteries to charge from either the grid or from the PV array, allowing the BESS asset to charge even when the PV asset is not generating sufficient electricity.

However, AC-coupled PV + BESS also have certain limitations:[171]

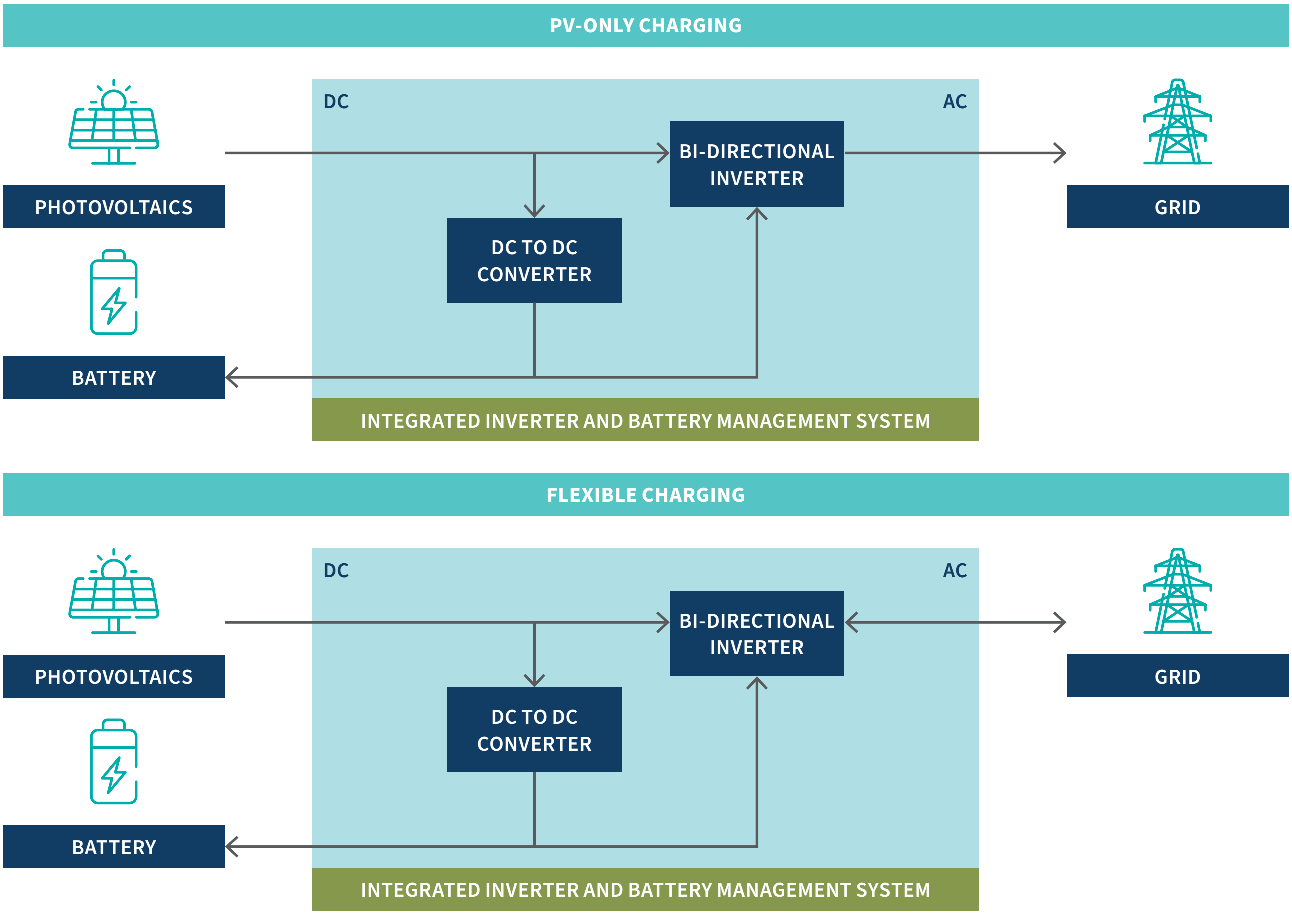
- **Cost:** AC-coupled systems require multiple inverters, increasing the cost relative to DC-coupled systems.
- **Lower Efficiency:** The stored energy in AC-coupled systems is converted three times, from DC to AC to supply the building and then back to DC to the battery and again back into AC. Each conversion results in a small amount of energy loss.

DC-coupled systems

In DC-coupled systems, the solar array and battery module use the same inverter and share the same grid interconnection, reducing equipment costs. This also reduces power losses from inverting the current and running separate interconnection lines to the grid, as the solar array and battery are dispatched as a single facility.[172] DC-coupled systems can also be configured to “flexibly charge,”in which the battery can charge from either the PV array or the grid; or DC-coupled configurations can be “tightly” coupled, in which the battery can only charge from the PV array (see **Exhibit 42**).[173]

The contract structure of the PV asset will be one factor in determining whether a flexible or tightly coupled system is more appropriate. For example, if the bulk of solar generation is already contracted through a PPA, there might not be sufficient power to charge the battery asset.[174]

Exhibit 42 DC-coupled PV + BESS



RMI Graphic. **Source**: Paul Denholm, Robert Margolis, and Joshua Eichman, *Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants: Report Summary,* National Renewable Energy Laboratory, 2017, **https://www.nrel.gov/docs/fy17osti/69061.pdf**.

DC-coupled systems offer several advantages:[175]

- **Affordability:** DC-coupled systems tend to be cheaper than AC-coupled systems, as the solar array and battery use a single inverter and less extra equipment, such as voltage transformers and switchgear.
- **Higher Efficiency:** Unlike AC systems, which convert the current multiple times, DC-coupled BESS systems only convert the current once, reducing energy losses and improving efficiency.
- **Oversizing:** DC-coupled systems allow solar panels to generate more electricity than the inverter rating. The excess energy can be used to charge the battery, whereas in the AC-coupled system, it is "clipped" or lost (see *Renewables arbitrage,* page 99).
- **Easier Interconnection:** DC-coupled solar plus storage systems use one PCS, which reduces interconnection challenges.

DC-coupled systems have certain limitations:[176]

- **Limited Flexibility:** Installers have less flexibility than with an AC system, as the inverter needs to be located close to the battery.
- **Less Resiliency:** With a single inverter in a DC-coupled system, if the inverter fails, both solar generation and battery capacity are lost.
- **Scalability Challenge:** DC-DC converter sizes typically max out at 500 kW. For a large installation, the number of DC-DC converters increases.

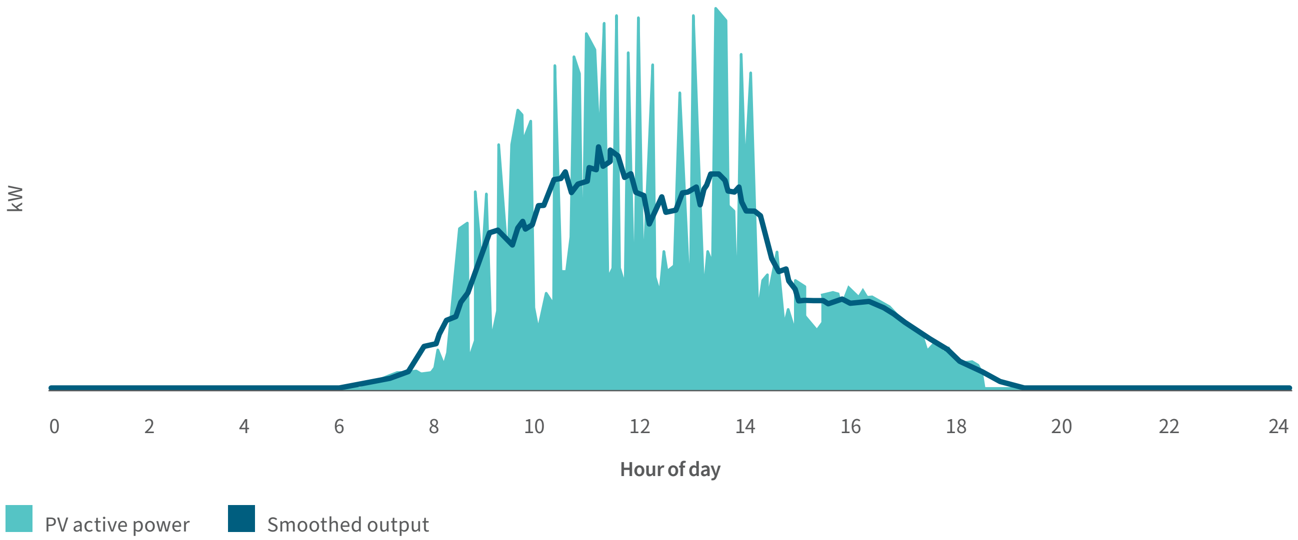
Renewables smoothing

Power fluctuations induced by variable generation (especially solar PV) create instabilities such as frequency deviations, voltage variations, and reduced power quality.[177] The implementation of BESS assets alongside VRE generation mitigates the output variation inherent in intermittent generators. BESS can be employed to address the mismatch between the renewable generation's maximum power point and the smoothed power delivered to the grid. These can typically be grouped into filtering algorithms and ramp-rate limitation (RRL) control schemes. Generally, filtering algorithms are used to mitigate rapid power fluctuations, while RRL is used for long-term power smoothing.[178]

Filtering algorithm

One example of the filtering algorithm approach is the moving average algorithm. For a simple moving average algorithm used for solar smoothing, a moving window is proposed where, at each point in time, the algorithm decides on a target power.[179] Real PV power and window size are the only inputs to the algorithm. The moving mean algorithm calculates a reference power value by averaging the recorded power data for a specific period. The difference between the real PV power data and the power after applying the smoothing algorithm will charge and discharge the battery (see **Exhibit 43**).

Exhibit 43 Simple moving average-based renewables smoothing



RMI Graphic. **Source**: RMI Analysis

The degree of smoothness can be adjusted by changing the window size; however, this will also require an increase in battery capacity. Factors such as lag/lead, battery size, and SoC management can be addressed by taking different approaches, such as:

- **Single and Half Window Based Moving Average:** the moving average is calculated for the whole window period and for the second half of the window period, addressing the lag and lead of a simple moving average approach. However, this presents additional challenges for the management of battery SoC.[180]

- **Single and Half Window Based Smoothing with Energy Compensation:** This algorithm monitors the difference in energy between target energy and actual energy, which is compensated over the following time period.[181]

Ramp-rate limitation

ESSs coordinated by ramp-rate control algorithms are often used to mitigate grid power fluctuations.[182] In RRL control schemes, the battery storage asset is used to absorb the renewable output power in cases where the ramp rate of the primary energy source exceeds a predefined limit. A variant of RRL may activate only when the injected power to the grid exceeds a predefined limit. This can avoid power system issues when renewables are quickly dispatched from the network.[183]

Renewables arbitrage

Arbitrage refers to storing electricity during periods of low prices or excess generation and dispatching it when prices are high. Energy storage projects earn revenue from the difference between the price at which power is stored and the price at which it is dispatched. Coupling BESS with VRE generation enables the storage system to arbitrage to avoid key economic or performance issues, including reducing the risk of curtailment and avoiding peak-clipping challenges.

Curtailment reduction

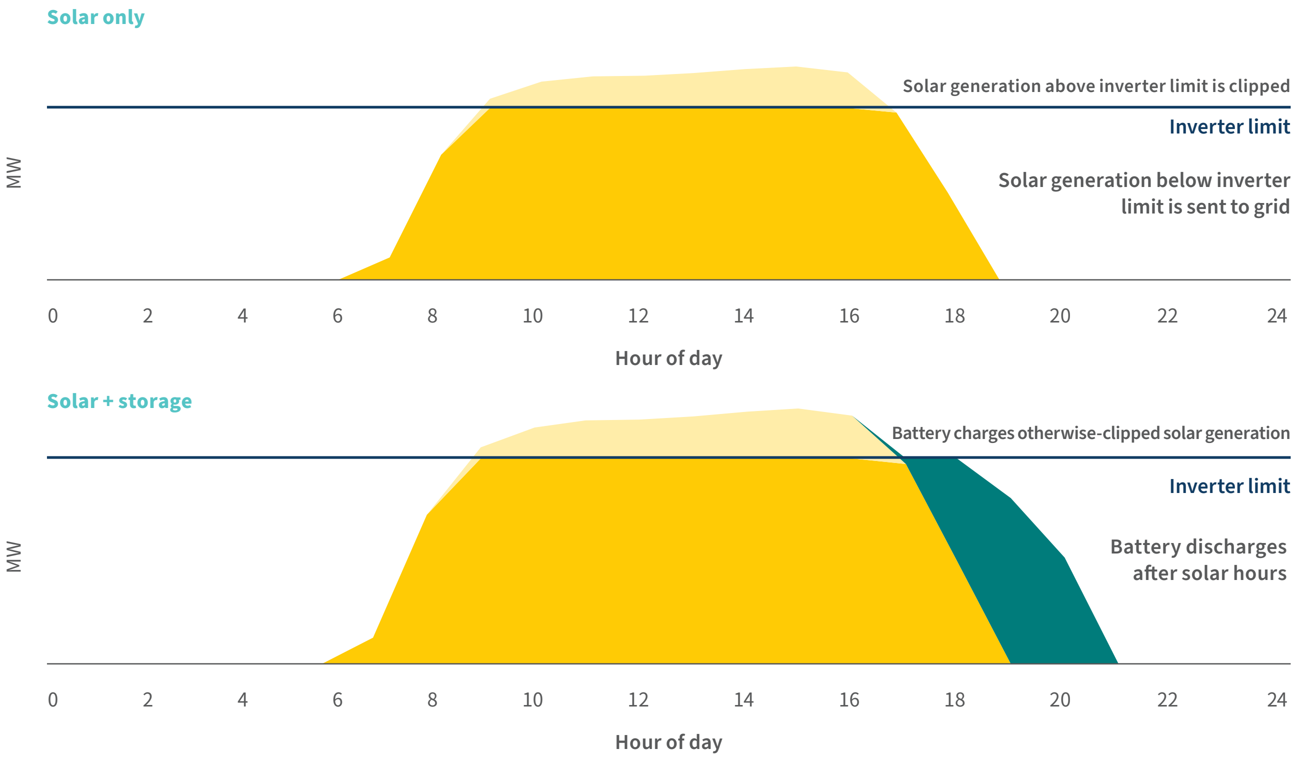
Curtailment is the deliberate restriction of electricity generated from renewable sources to prevent grid overloads and mitigate negative price scenarios during periods of oversupply or insufficient demand.[184] In India, the *Electricity Grid Code* grants must-run status to solar and wind power projects. Curtailment is permitted only to ensure grid security, for example, in situations involving transmission constraints.[185] Lacking sufficient ability to mitigate curtailment, it is likely to have a significant impact on the pace and feasibility of VRE resource deployment. Curtailment can lead to substantial losses, as developers do not fully account for it when bidding for projects, especially for VRE projects with a single-part tariff.[186] In India, must-run plants curtailed due to technical constraints must sell the non-scheduled power in the power exchange to reduce financial losses.[187]

The ability of BESS to properly address curtailment is impacted by several factors, including technical parameters of the system (system size, duration, and RTE), grid mix, and surplus ratio (between generation and consumption).[188] In a high renewable scenario for India, wind and solar curtailment may be reduced from 4% without storage to less than 0.2% with BESS (some losses will remain due to RTE).[189]

Peak clipping avoidance

Solar PV facilities are typically built with panel capacity exceeding the inverter's AC output capacity. When the panels' output exceeds the inverter's capacity, that energy is clipped and left unused. The choice of PV + BESS system architecture, as discussed in *PV + BESS configurations,* page 93, can enable a system to avoid peak clipping. Batteries that are connected to the solar PV facility behind the inverter, such as through DC coupling, can charge from the output that otherwise would be clipped. This DC-coupled configuration can increase the system's output and increase battery revenue, though the exact value is dependent on battery size, solar array, and inverter capacity.[190]

Exhibit 44 Illustrative example of avoided clipping using solar + BESS



RMI Graphic. **Source**: RMI Analysis

Renewable firming: dispatchable variable renewable generation

The changing energy portfolios experienced by Indian states and DISCOMs are driving the need for additional dispatchable assets. Dispatchable VRE with BESS can provide additional critical services for India, including peak capacity and RA, load following, and black-start services.

Several contractual approaches have been taken in India to procure firm, dispatchable renewable energy by pairing it with energy storage; see *Firm and dispatchable renewable energy,* page 84.

Peak capacity and resource adequacy

RA is a power system planning concept that minimises the risk of blackouts or brownouts while balancing the costs of maintaining a reliable power system. RA is just one of the pillars of power sector reliability, along with transmission stability, distribution reliability, operational reliability, and resilience.[191]

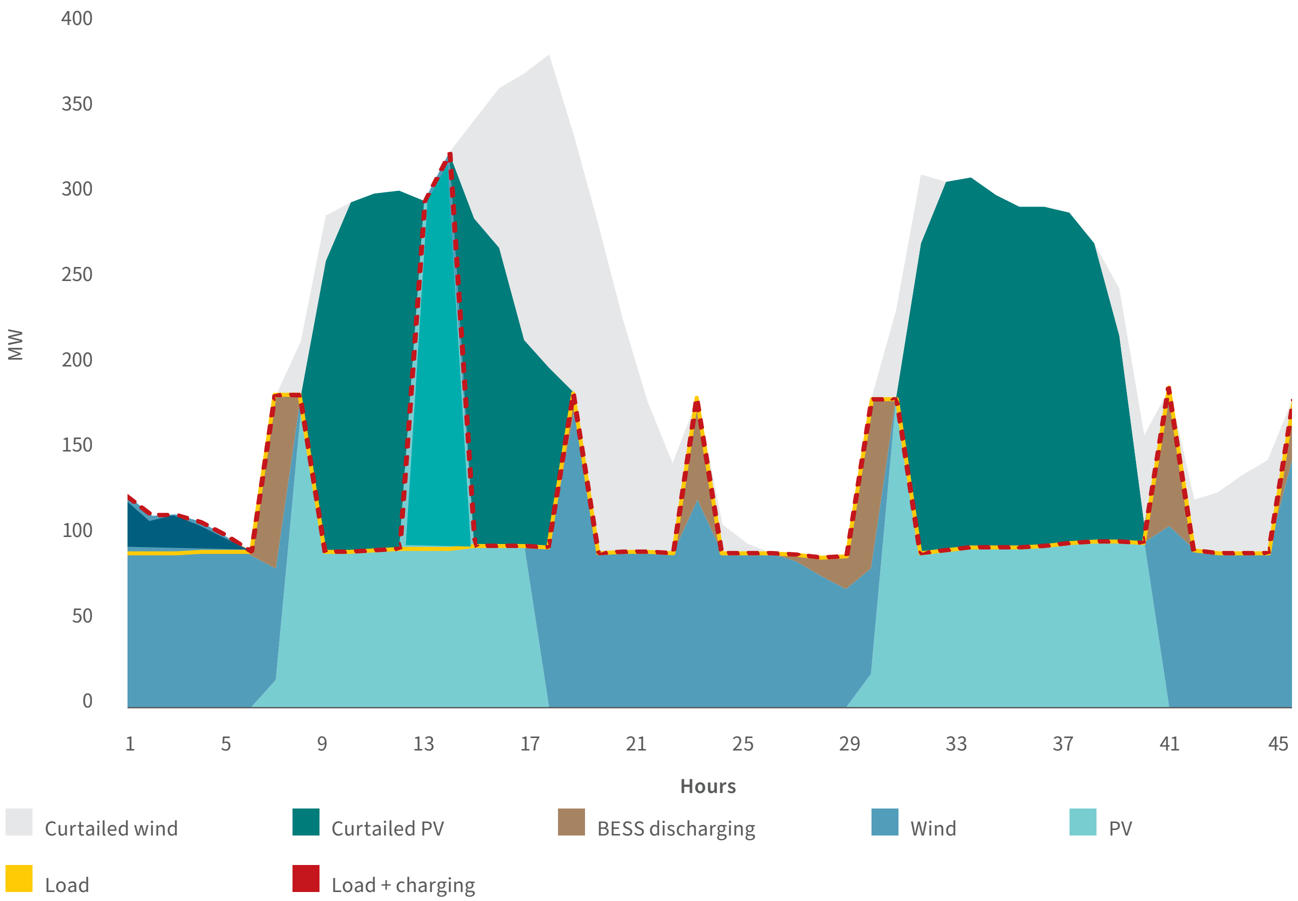
The MoP notified the "Guidelines for Resource Adequacy Planning Framework" (RA Framework) for India in June 2023.[192] The objective of the RA Framework is to ensure DISCOMs tie up sufficient capacity to serve expected demand cost-effectively and reliably. BESS assets can play an important role in providing flexible capacity to meet the DISCOM and state-level RA requirements. However, the details of the RA Framework implementation are yet to be finalised, including the national- and state-level planning reserve margin (PRM), the percentage of their peak load and capacity credits that battery resources could provide, and the corresponding reserve margins.

RA planning is a long-standing practice across the United States and other global geographies. RA value, whether monetised through bilateral contracts or capacity markets, provides strong long-term investment signals. For example, RA capacity payments in the California Independent System Operator (CAISO) have been instrumental in bringing over 13.3 GW of storage capacity online since 2019.[193] The DISCOM-level RA assessment is in the early stages of implementation for the Indian states. As this process establishes and matures over the coming years, DLS and grid storage could play a crucial role in meeting DISCOM's future portfolio capacity needs.

Load following

Load following is an operating strategy in which generators change their output to match changes in electricity demand. In the load-following strategy, VRE generation is prioritised to supply the load whenever available, and dispatchable resources such as BESS will generate output when VRE generation cannot meet demand.[194] Batteries are used for load following because they are dispatchable (with quick response times due to digital control) and can respond to load changes with less stress than mechanical systems.[195] In addition, the BESS asset charges during periods of excess VRE generation, making it suitable for systems where VRE availability exceeds load demand during those periods.[196] For example, BESS charges from surplus wind and solar energy during the night and daytime, respectively, and discharges during VRE scarcity (early morning, late night) to meet the load (see **Exhibit 44**, page 101). The time frame for the BESS load-following intervention can range from 15 minutes to 24 hours.[197]

Exhibit 45 Illustrative example of PV, wind, and BESS operating in load-following mode



Note: Illustrates two-day hourly dispatch stack, assuming 500 MW/2,000 MWh BESS.
RMI Graphic. **Source**: RMI Analysis

Black start

In the event of a grid outage, black-start generation assets are needed to restore operations to larger power stations and bring the regional grid back online without reliance on external power from the grid.[198] BESS systems designed for black-start applications typically range from 5 to 50 MW, enabling them to serve a variety of grid scales and restoration needs.[199] These systems can deliver power for between 15 minutes and one hour, providing a critical window to re-energise key grid infrastructure and initiate larger generation sources. They are typically expected to cycle 10 to 20 times per year.[200]

Network-sited BESS

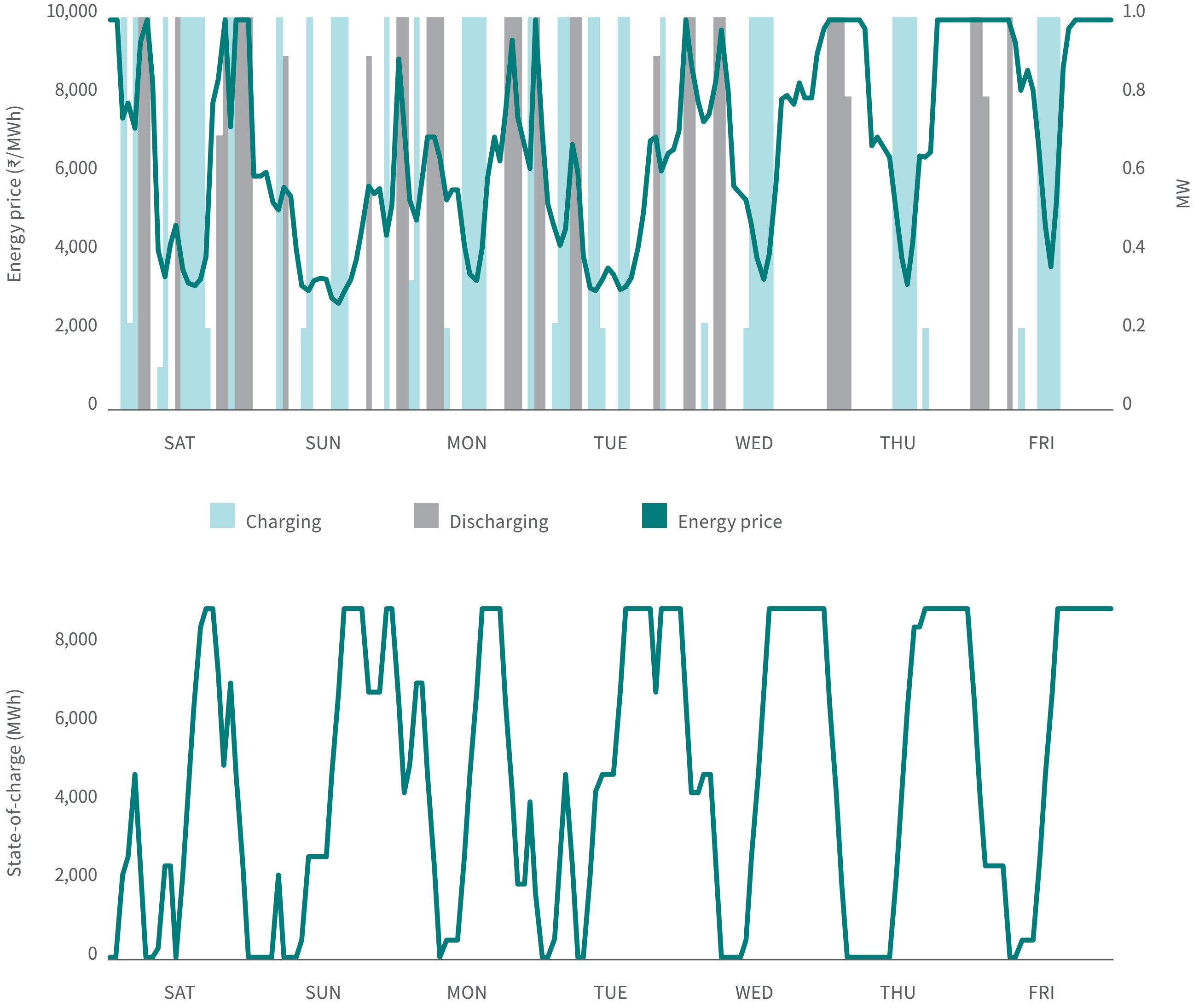
BESS systems located on the transmission or distribution network can shift the timing of power flows and provide critical services by reducing load on key transmission corridors, substations, and transformers. This can help avoid costly equipment failures and extend the life of existing assets. These assets can also provide a range of other services, including ensuring the system remains balanced and shifting load through arbitrage. While BESS assets can offer a wide range of services and value to the system, maximising their potential requires markets that enable the monetisation of these services. Mature markets with a range of products to meet system needs, both short and long term, can create valuable avenues for BESS participation. Indian markets are evolving rapidly, with the recent implementation of market-based ancillary services to create a short-term market for BESS, progress on the RA framework guidelines, and potential eligibility for BESS for capacity credits, providing long-term signals. However, these short-term and long-term market initiatives have yet to mature and achieve a streamlined implementation fully.

Wholesale arbitrage

Energy arbitrage is defined as moving electrical energy from low-value to high-value periods and plays a principal role in energy storage in electricity systems today. Daily and seasonal variations in load and supply, especially with increased VRE penetration, require a range of energy storage options that can provide intra-day shifting within four hours or across multiple days, with timespans potentially exceeding 12 hours.[201]

In India, batteries can participate in energy arbitrage on the power exchanges, such as the Indian Energy Exchange (IEX). IEX enables BESS to trade electricity on the Real Time Market (RTM) and Day Ahead Market (DAM).[202] The IEX platform accounts for most of the energy trading amongst the three power exchanges currently operating in India. At present, less than 10% of the total annual electricity requirement is procured through power exchanges, while most is procured through long-term power purchase agreements (PPAs) by DISCOMs.[203] There has been an ongoing shift toward increasing power sales through market mechanisms and reducing reliance on long-term PPAs.[204] Monitoring and maintaining a battery asset's SoC against market-clearing prices will be critical for maximising an asset's revenue potential; (see **Exhibit 46**, page 103).

Exhibit 46 Illustrative week of energy arbitrage

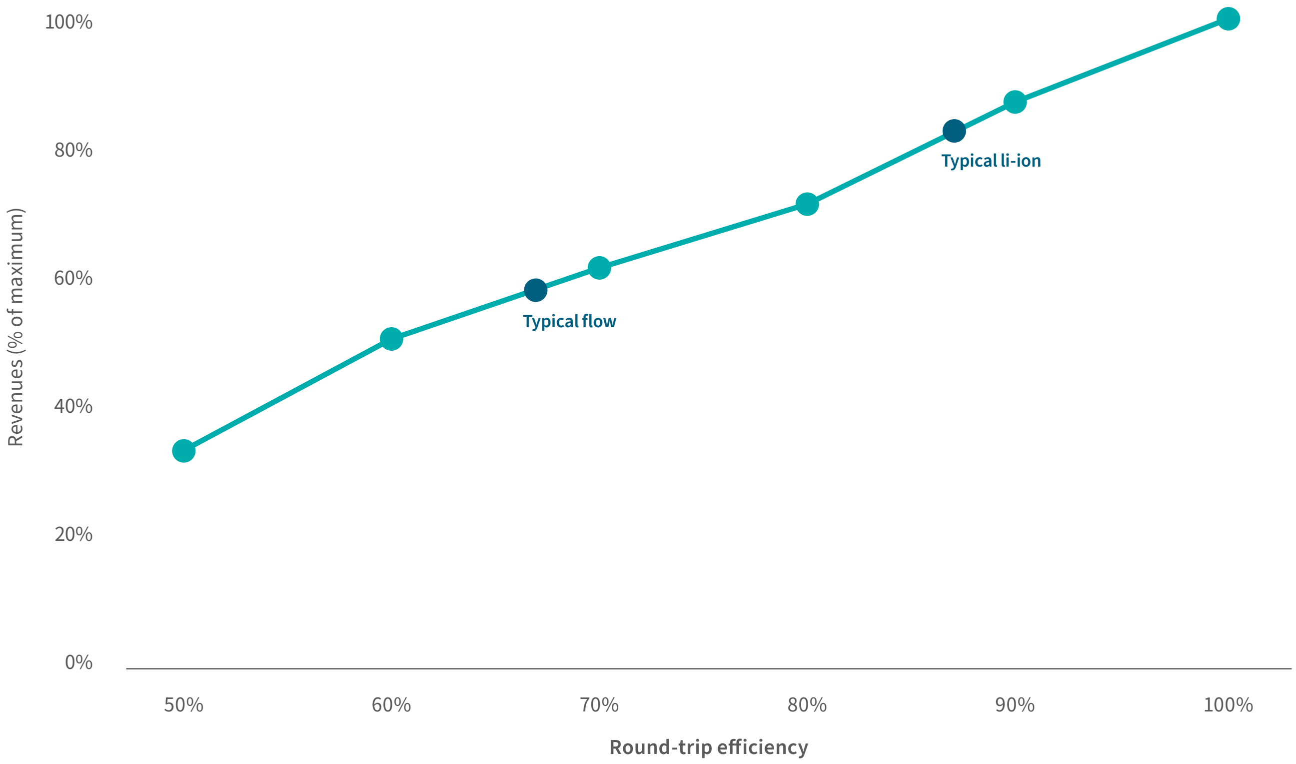


Note: Results are shown for a 1 MW/4 MWh battery, with 90% RTE.
RMI Graphic. **Source**: RMI Analysis; India Energy Exchange Day Ahead Market Data

The technical parameters of a battery storage asset — including cycle life, discharge duration, and RTE — impact how much of the theoretical value potential can be successfully captured and monetised.

RTE has a substantial impact on the value of wholesale energy arbitrage. RTE determines the arbitrage efficiency (i.e., in a market context, how many MW must be purchased to sell 1 MW). **Exhibit 47** shows battery revenues as a function of RTE for a hypothetical four-hour-duration battery participating against historical IEX prices. The efficiency losses for a typical LiB (86% RTE) cost it over 20% of the revenue it would earn with perfect efficiency. Efficiency losses in a typical flow battery (68% RTE) cost more than 40% of hypothetical revenue with perfect RTE.

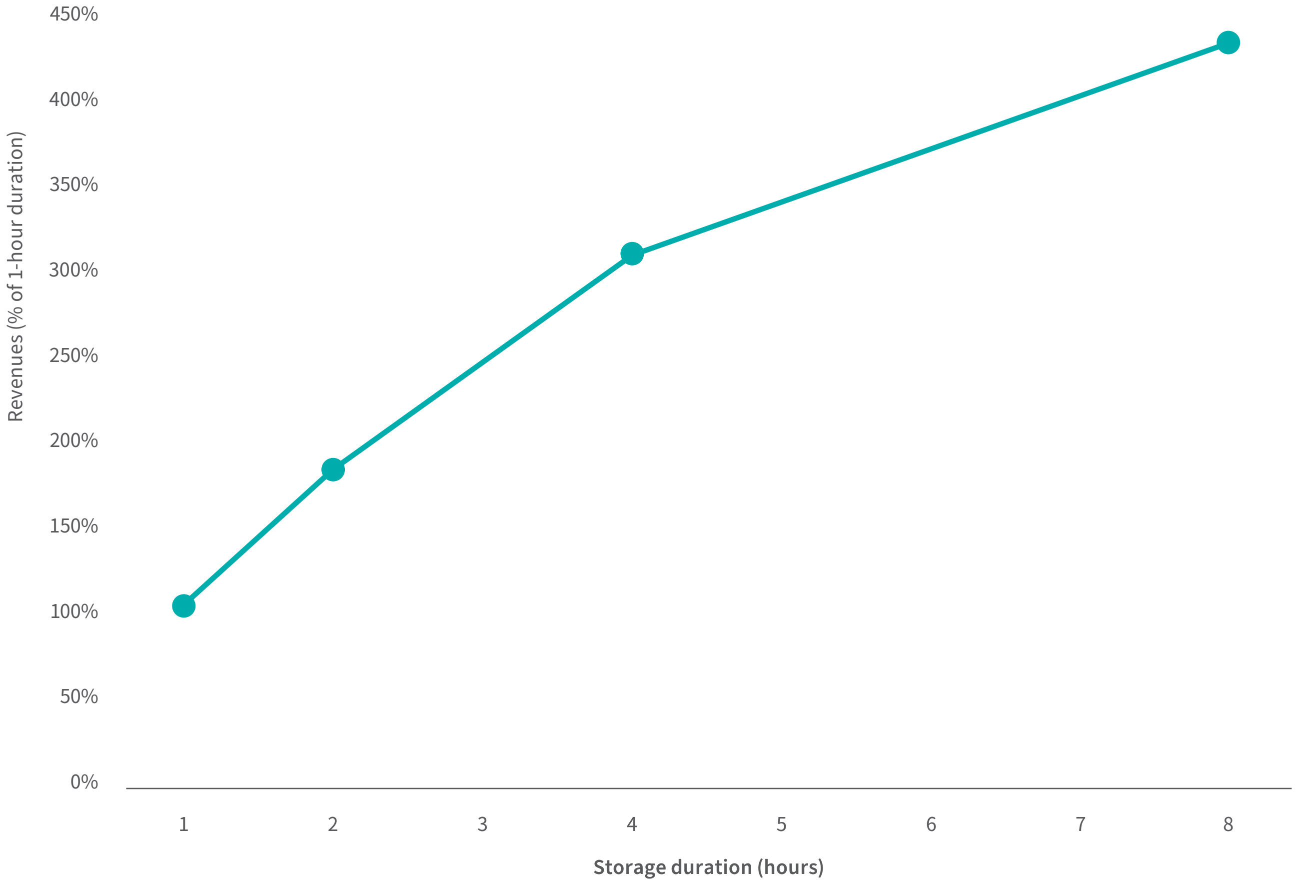
Exhibit 47 RTE% versus arbitrage value



Note: In this model, we assume equal efficiency losses during charging and discharging and perfect foresight of future prices.
RMI Graphic. **Source**: RMI Analysis

Discharge duration is another key determinant of the value of a battery system. In market contexts, battery revenues are driven by the spread between charging and discharging prices. To take advantage of sustained periods of low or high prices, therefore, longer durations of charge/discharge are needed. But on the IEX and other international energy markets, we tend to see substantial volatility on short timescales. As a result, most energy arbitrage value can be captured by relatively short-duration batteries. In today's markets, adding storage duration increases revenue potential, but at a diminishing rate (see **Exhibit 48**, page 105).

Exhibit 48 Annualised battery system revenue as a function of discharge duration



Note: The simulation optimises battery operations based on historical IEX market prices from April 2022 through November 2024.

RMI Graphic. **Source**: RMI Analysis

As power systems evolve in India and around the world, longer-duration batteries will become increasingly valuable. This is for two reasons: short-duration market saturation and growing diurnal and seasonal gaps. Short-duration batteries that come online in the near term are very effective at smoothing short-term fluctuations in supply and demand, thereby dampening short-term price volatility and reducing the need for additional short-duration batteries.

The second is due to broader system-wide changes in supply and demand. As more variable renewables come online, greater diurnal and seasonal gaps in supply and demand (and hence price) emerge. Batteries (along with other storage technologies) capable of longer discharge durations will be well-suited to balancing variable renewables and capturing the resulting energy market value. Currently, many geographies are beginning to explore and pilot long-duration energy storage (LDES) projects (see **Box 3**, page 106).

Box 3 Long duration energy storage + seasonal storage

LDES refers to technologies that can be scaled up economically to sustain electricity provision for long time horizons, spanning multiple hours, days, weeks, or months (for seasonal storage).[205] LDES complements the growing fleet of grid energy storage services, currently represented by LiBs and PSP, and is commonly defined as energy storage with the capability to discharge at full power for 8–12 hours or more.[206] Seasonal storage can capture excess generation during surplus seasons (spring to mid-summer in high-solar-PV geographies such as California) and redistribute that energy over several weeks to months during deficit seasons (mid-summer to winter).

LDES can provide energy arbitrage — namely inter-day (power shifted by 10–36 hours) and multi-day (power shifted by 36–160 hours). In addition, LDES can provide capacity, resilience, balancing, and low-carbon heat. These services can be critical for meeting essential needs; for example, LDES is well-suited to delivering the multi-day resilience required for data centres. Depending on the LDES technology, it can also provide the necessary residual heat for decarbonising industrial processes.[207]

LDES technologies can be cost-effective even with lower RTE since they fulfil different grid needs than shorter-duration technologies. However, LDES deployment currently faces several challenges, including:[208]

- **Technical:** Need for improvements in performance, supply chains, and large-scale manufacturing needs to be established, some technologies face material and geographic constraints, and limited information is available on technology feasibility and performance capabilities

- **Economic:** High cost of LDES and limited information on projected costs at full-scale deployment; skilled workforce needs to be developed

- **Market/Remuneration:** RE mechanisms typically do not capture the value of LDES, global centralised planning processes often do not look far enough out to adequately assess LDES portfolio value

- **Policy:** Utilities need to gain experience with LDES assets through pilot projects or credible third-party evaluations, distinctions should be made in storage procurement targets or mandates between short and long-duration energy storage

Box 3 Long duration energy storage + seasonal storage (continued)

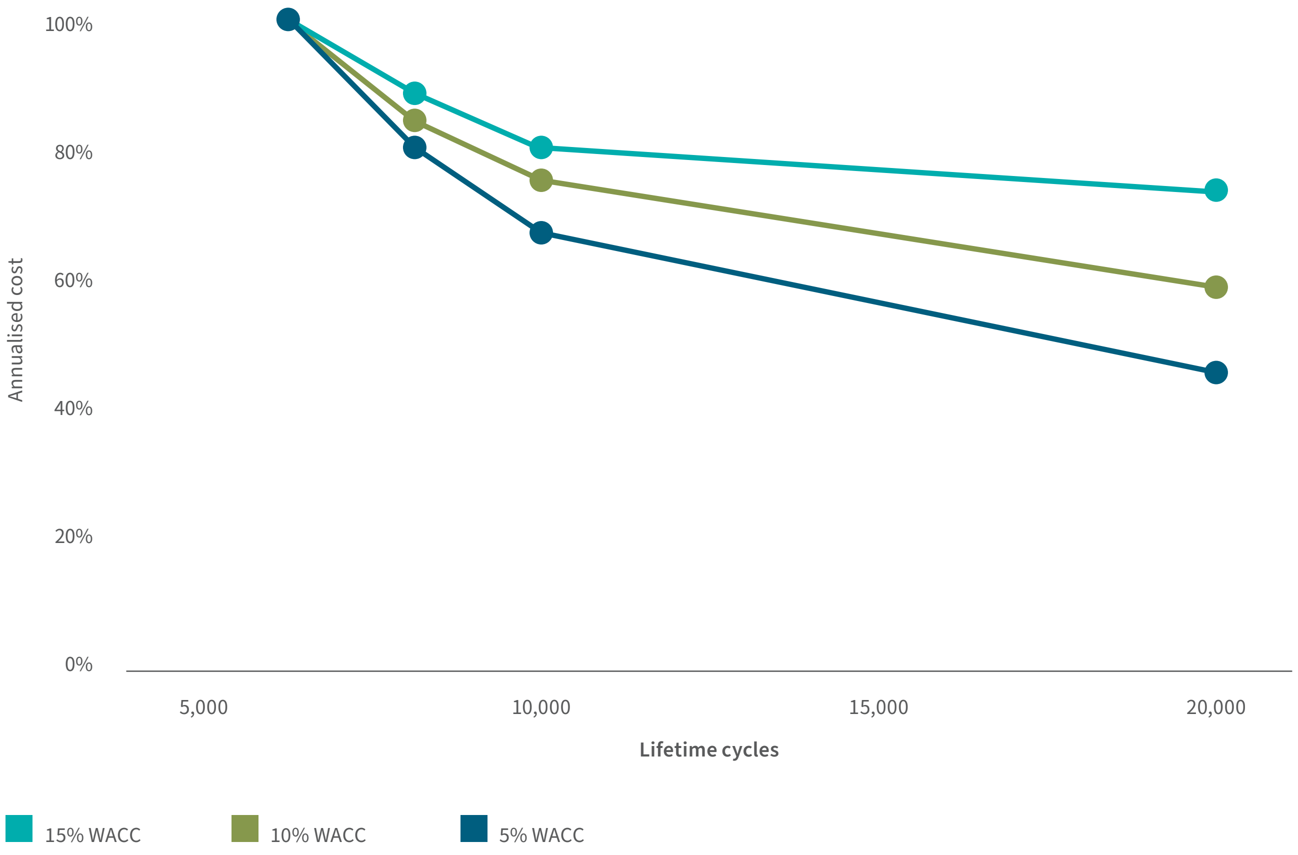
In Australia, rapid VRE deployment, an ageing thermal fleet, and high gas prices have been driving the need for LDES. New South Wales established an LDES target of 28 GWh by 2034, with a defined eight-hour duration requirement for LDES.[209] The 28 GWh target is necessary to meet projected capacity requirements as older generators retire, and future tenders may include projects with twelve-plus-hour duration. To achieve these targets, the Australia Renewable Energy Agency (ARENA) has announced multiple projects utilising novel approaches for LDES, including: AU$45 million (~₹262.35 crore) for a 200 MW LDES compressed-air project, AU$2.85 million (~₹16.6 crore) for two electrochemical LDES technologies to be installed in remote microgrids, the first ever utility-scale flow battery connected to Australia's National Electricity Market, and a solar and thermal storage pilot in Victoria.[210]

In India, most long-duration storage needs are currently met by PSP assets. However, stakeholders in India are also working to diversify the LDES portfolio with commercial and novel technologies. In October 2024, Gujarat Urja Vikas Nigam Limited (GUVNL) issued their first long-duration BESS tender. The draft tender was released to select developers and outlined a 200 MW (1,600 MWh) BESS project with an eight-hour discharge duration, capable of delivering one complete cycle per day. The tender aims to promote only commercially proven and operational technologies, reducing risks associated with novel technologies and delays.[211] The tender follows the signing of a memorandum of understanding with the LDES Council in July 2024, which seeks a comprehensive evaluation of long-term energy storage solutions for ensuring grid stability while advancing VRE integration and advanced decarbonisation.[212]

In January 2025, NTPC announced the launch of the CO_2 BESS technology project at Kudgi, Karnataka, with a capacity of 160 MWh. The CO_2 battery is based on a specialised electro-mechanical function that uses anhydrous CO_2 as the process fluid.[213] This project builds on NTPC's stated intent to establish pilots to explore novel LDES solutions.

Finally, increased cycle life offers the battery more opportunities for energy arbitrage over the asset's lifetime, thereby increasing its potential market value. The stylised example below shows the potential impact of cycle life on a battery's annualised costs — a key benchmark for potential investors. We assume a two-hour LiB, cycling twice per day. We assume the battery system lifetime is limited by its cycle life. At the CEA's 2020 benchmark of 6,000 lifetime cycles, the system lasts for about 8 years. However, as technology improves, the battery lifetime is expected to increase: 11 years in 2030 (8,000 cycles), 14 years in 2040 (10,000 cycles), and up to 27 years in 2050 (20,000 cycles). Holding the capital cost (₹/MW) constant, improvements in cycle life lead to a substantial drop in annualised costs. Increasing battery lifetimes from 6,000 to 20,000 cycles could lead to reductions in annualised costs of 30% to 55%, depending on the discount rate assumed.

Exhibit 49 Annualised battery system cost as a function of cycle lifetime, for a two-hour duration LiB



RMI Graphic. **Source**: RMI Analysis; Indian Technology Catalogue: Generation and Storage of Electricity, Government of India, Central Electricity Authority, January, 2022, **https://cea.nic.in/wp-content/uploads/irp/2022/02/First_Indian_Technology_Catalogue_Generation_and_Storage_of_Electricity-2.pdf**.

Ancillary services

Ancillary services refers to a suite of activities necessary to support the transmission of power across an interconnected grid while maintaining reliable operation and ensuring the required levels of quality and safety.[214] The range of ancillary services procured and monetised varies widely by geography and market, but can include frequency regulation, voltage support, inertia services, contingency reserves, ramping reserves, and black start. Ancillary service products are vital as they ensure the system remains in balance, and they will become increasingly critical as more VRE is integrated.

Ancillary services in India

CERC announced the creation of three ancillary service products in January 2022: primary reserve ancillary services (PRAS), secondary reserve ancillary services (SRAS), and tertiary reserve ancillary services (TRAS).[215] These products are intended to replace the singular reserve product previously procured. Ancillary services provide the grid with stability, such as addressing deviations from frequency or contingency events that misalign demand and supply. The three ancillary service products vary in response time, required duration, and participation standards (see **Exhibit 50**).[216]

Exhibit 50 Ancillary services products in India

Product	Description	Response Time
PRAS	Comes into service in the event of a sudden change in frequency and is procured through the governor action of the generator or other system stakeholder (similar to fast frequency response in other international markets). BESS is well-suited to provide PRAS given their instantaneous response. However, batteries are not currently allowed to participate in this service.	• Provided immediately when frequency deviates beyond the dead band[xxii] • Entire capacity obligation available within 45 seconds • Sustaining for at least five minutes
SRAS	Response within 30 seconds of a control signal from nodal agency, this is a change in draw or consumption (meaning SRAS-up and SRAS-down), like frequency up and down products in global markets. Participation requires a minimum capacity of 1 MW, and currently these services are procured through an administrative procedure (rather than market mechanism). The current process lacks transparency on prices and has little clarity on the processes for BESS to compete to provide these services.	• Provided within 30 seconds • Entire capacity obligation available within 15 minutes • Sustaining for at least 30 minutes
TRAS	Consisting of TRAS-up and TRAS-down, this refers to spinning/non-spinning reserve, a power supply that can be brought into or removed from the system when required. TRAS has recently started trading on power exchange platforms in India, and BESS can currently participate in this market. However, additional data on price transparency and frequency of resources committed to dispatch will be needed to strengthen the regulators' confidence in this revenue stream.	• Provided within 15 minutes • Sustaining for the next 60 minutes

RMI Graphic. **Source**: RMI Analysis

[xxii] The range of frequency deviation from the nominal value in which the system's frequency control mechanism does not respond to changes. In India, the grid operates at a nominal frequency of 50 hertz, with the inherent dead band of frequency controller not exceeding plus or minus 0.03 hertz.

BESS assets are currently regulatorily permitted to provide SRAS and TRAS, enabling some monetisation of battery storage's capabilities to offer short-term system support. However, there is still no market price clarity for SRAS and TRAS, which impacts BESS project revenue forecasts, bankability, and regulatory review. Stakeholders anticipate high demand for these services, given projected electricity demand growth rates, but there may be seasonal variation.[217] The announcement of these products is an important step for maturing and deepening India's electricity markets. Ancillary services have been among the first monetised applications for BESS resources in international markets. However, in India, they have not yet featured in most tendered project portfolios. SECI's 2022 ESS-1 tender designated capacity as a pilot for GRID-India, which functions as the National Load Despatch Centre (NLDC) responsible for the reliable operation and management of the power grid across India. The designated capacity was intended to test BESS participation in SRAS, but the project was delayed and ultimately cancelled, never becoming operational.

Box 4 Flexible ramping product in California

In markets where an increasing volume of generation is from variable resources, market operators have revisited traditional ancillary services products to develop new approaches to ensuring system stability. In November 2016, California's wholesale electricity market operator, CAISO, introduced the flexible ramping product (FRP) to real-time market operation. The FRP was introduced to help manage uncertainty from load, wind, and solar production and is aimed to help CAISO ride through extreme ramping events in the net load profile. The FRP provides flexible capacity that can be dispatched in subsequent market runs to cover realised uncertainty, and procurement is based on opportunity costs arising from trade-offs between the need for energy and the need to reserve ramping capability.[218]

While batteries represent a small portion of CAISO's balancing area's capacity, these resources provide a large amount of its ancillary services. Battery resources are frequently scheduled to provide flexible ramping capacity, and this capacity substantially increased by the fourth quarter of 2023, after CAISO implemented a FRP market enhancement (this enhancement aimed to address issues associated with congestion constraints and location marginal pricing). The fourth quarter of 2023 saw batteries consistently providing nearly 50% of scheduled FRP up and 25% of scheduled FRP down.[219]

Transmission congestion relief

During peak electricity demand, it is not uncommon for transmission lines to lack the capacity to deliver energy cost-effectively to all connected loads. This congestion on the transmission lines can lead to increased energy costs.[220]

Assets, including energy storage, can be deployed downstream of congested transmission corridors to discharge during congested periods and minimise congestion in the transmission system.[221] From a technical standpoint, these systems tend to be engineered with a specific target for the minimum number of charge and discharge cycles per year, typically falling within the range of 50 to 100 cycles. Discharge periods to alleviate transmission congestion do not follow a uniform distribution throughout the year and may only be required for a few hours annually.[222]

Box 5 Illustrative example of transmission congestion

In this stylised system, there are two generators and one load. Each generator is connected to the load via a transmission line. Generator 1 is the least expensive supplier, so the system operator will attempt to serve as much load as possible with generator 1. While generator 1 has enough generation capacity to serve all the load, its delivery is constrained by the 90 MW transmission limit. This is called transmission congestion. In this example, the least-cost option is to generate 90 MW with generator 1 and 30 MW with generator 2.

In a market context, the clearing price is the cost of the more expensive generator 2: ₹10,000/MWh. We can decompose this price into two components: the ₹7,000/MWh “energy” component, which reflects the hypothetical clearing price if the system had no transmission constraints, and the remaining ₹3,000/MWh “congestion” component. Equivalently, ₹3,000/MWh would be the marginal benefit to the system of increasing the transfer capacity of Line 1.[xxiii]

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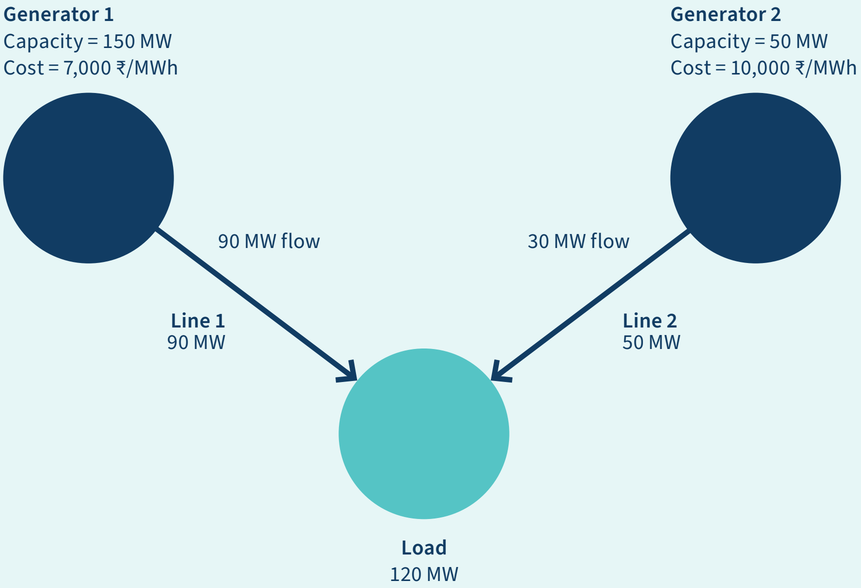
xxiii. In many global electricity markets, a third component is included to account for the costs incurred by line losses. The result is locational marginal pricing (LMP), which accounts for the differentiated costs of serving energy at many nodes across the transmission system. India’s electricity markets do not currently use nodal pricing. Moving towards nodal pricing may reveal opportunities for BESS to alleviate local transmission congestion.

Box 5 Illustrative example of transmission congestion (continued)

Exhibit 51 Illustration of transmission congestion



RMI Graphic. **Source**: RMI Analysis

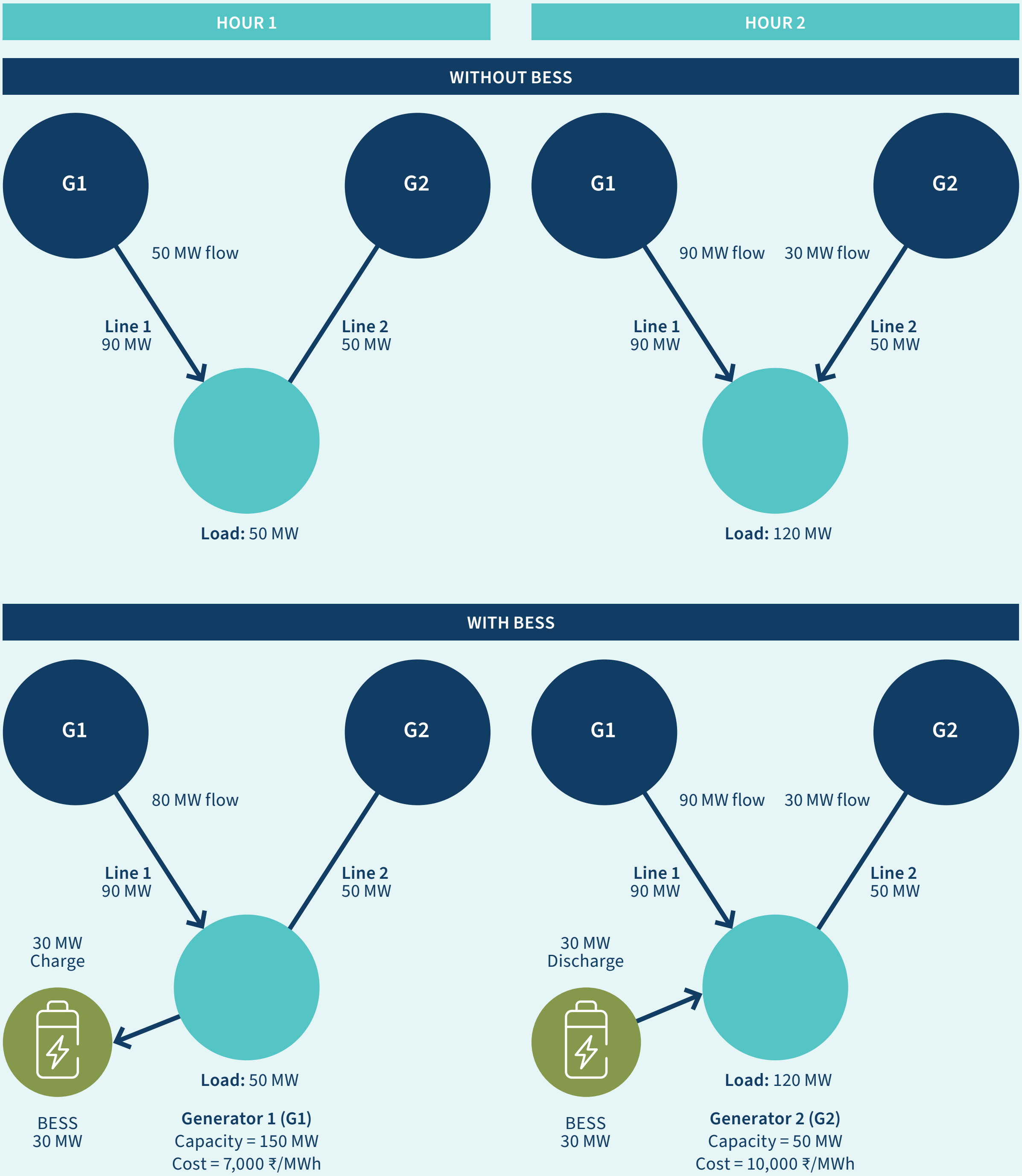
A battery can alleviate transmission congestion through strategic charging and discharging. Consider the same example system described in **Exhibit 50**, on page 109, but analysed over two hours, with and without battery storage on the system. For simplicity, assume no line losses and no efficiency losses from charging and discharging the battery.

Without battery storage, the system operates as follows: in hour 1, generator 1 meets the full 50 MW load. In hour 2, generator 1 serves a 90 MW load and generator 2 serves the remaining 30 MW. Total production costs are (50 MW * ₹7,000/MWh) + (90 MW * ₹7,000/MWh) + (30 MW * ₹10,000/MWh) = ₹12.8 lakh.

The system operates differently with battery storage: in hour 1, generator 1 generates 80 MW, 50 MW of which are used to serve the load and 30 MW of which are charged by the battery. In hour 2, generator 1 generates 90 MW, all of which are used to serve the load. The remaining 30 MW of load in hour 2 are met by discharging the battery. Total production costs are (80 MW * ₹7,000/MWh) + (90 MW * ₹7,000/MWh) = ₹11.9 lakh. The difference in production costs between the two cases (₹12.8 – ₹11.9 = ₹0.9 lakh) is the avoided transmission congestion benefit due to adding battery storage.

Box 5 Illustrative example of transmission congestion (continued)

Exhibit 52 Transmission congestion analysis over a two-hour period



RMI Graphic. **Source**: RMI Analysis

Transmission capacity deferral

Transmission and distribution infrastructure must be designed to meet peak demand, which often occurs during just a few hours each year. As the projected growth in peak demand surpasses the capacity of the grid, investments are required to upgrade equipment and expand infrastructure.[223] BESS offers a mechanism to delay, reduce the size of, or entirely avoid utility investments in transmission system upgrades necessary to meet projected load growth in specific regions of the grid.[224] To effectively address the substantial power demand associated with grid peak periods, BESS chemistries with a favourable power-energy ratio may be preferred for addressing these needs. The value of BESS can be considered the avoided costs of investment in single-function grid assets, transmission wires, poles, and substations. These long-term avoided fixed costs are in addition to the short-term avoided variable costs enabled by alleviating transmission congestion.

Distribution deferral

The distribution sector will be a critical application area for leveraging the full value of BESS in India. Siting BESS assets at the distribution level also enables additional system services that are not available when assets are sited further upstream at generation or transmission points.[225] Understanding how BESS assets can benefit the distribution network, how their performance can be optimised, which conditions make an asset economically viable, and how the existing regulatory and market frameworks can evolve to best assure an efficient and effective electricity system will be essential to deploying and integrating the projected volumes of battery storage required to meet the national goals.

Distribution located storage (DLS) assets can provide the benefits of distribution system capacity deferral at the substation level, particularly in dense urban areas experiencing peak load increases and limited space to expand the distribution system’s physical footprint. Batteries can be used to shift peak load for feeders and distribution substation infrastructure that are currently overloaded or projected to be overloaded in the near term. The distribution transformer and wire upgrades needed to support higher feeder loads may be deferred if batteries can shave the peak load. This is especially valuable in dense urban areas, where space limitations restrict the expansion of substation and distribution infrastructure. DISCOMs and state regulators need to work closely for the timely identification and deployment of the battery project to capture the distribution capital expenditure deferral value.[226]

Deviation avoidance

All DISCOMs are subjected to penalties under the deviation settlement mechanism (DSM). Imbalances between the demand and supply of electricity result in fluctuations in grid frequency, with significant drops leading to blackouts. New DSM regulations introduced in 2022 tie penalties to market rates, the highest of the weighted-average clearing price in the day-ahead market or the real-time market charge across all regions. This reform has led to increased penalties, especially in some states with high renewable resources.[227] DLS in these states can help the DISCOMs effectively balance their portfolios in day-ahead and real-time market operations and reduce potential DSM penalties. States experiencing high VRE growth can consider DLS assets as an option to effectively schedule and operate their energy portfolios and minimise DSM penalties.

Distribution network support services

DLS can also provide an array of other critical power-based services that improve distribution network stability and resiliency, as well as enable VRE generation integration. Advanced inverter real-time control methods enable the accurate control of various quantities beyond mere active power flow, opening the possibility of using BESS for power quality improvement alongside active power exchange.

Perfect power quality means that the voltage is continuous and sinusoidal, with constant amplitude and frequency. Power quality is often described in terms of voltage, frequency, and interruptions. Examples of power quality issues that may impact the distribution network are described in **Exhibit 53** on page 116.

Exhibit 53 Power quality issues in distribution network

Power Quality Issue	Description	Time Scale
Transient Voltage Instability	Short-term voltage instability, associated with rotor angle imbalance, loss of synchronism, or highly stressed high-voltage direct current links.[228]	Milliseconds
Harmonic Distortions	Harmonics are a power quality problem that occurs when currents or voltages have a frequency that is an integer multiple of the fundamental power frequency (50 Hertz, in India). Harmonic distortions are driven by non-linear loads that show an erratic relationship between current and voltage during the alternating period and can cause overheated transformers and tripped breakers.[229]	
Pulse Loads	Some loads draw very high short-term current in an intermittent fashion, which can cause momentary drops in system voltage and frequency.	
Voltage Instability	Long-term voltage instability, associated with high power imports from remote generating stations, a sudden large disturbance, or a large load buildup (such as morning or afternoon pickup).[230]	Minutes

RMI Graphic. **Source:** Saikat Chakrabarti, Notes on Power System Voltage Stability, Department of Electrical Engineering, Indian Institute of Technology Kanpur, 2011, **https://home.iitk.ac.in/~saikatc/EE632_files/VS_SC.pdf**; L. Xaba and S. Chowdhury, "A Comprehensive Review of Harmonic Mitigation Strategies in Power Distribution Systems and Microgrids with Inverter-Based Generation," *Proceedings of the 2024 IEEE PES/IAS PowerAfrica Conference,* Johannesburg, South Africa, (2024): 1–5, **https://doi.org/10.1109/PowerAfrica61624.2024.10759355**; "Causes and effects of harmonics in electrical power systems," Fluke, accessed Feb 11, 2025, **https://www.fluke.com/en-us/learn/blog/power-quality/harmonics-electrical-systems**.

By placing BESS within the distribution network, close to the load, it can respond rapidly to dynamic changes in grid conditions. With a properly designed power conversion system capable of operating at a non-unity power factor, the BESS can source or sink reactive power to stabilise voltage without affecting the overall active power supply.[231] This reduces the need for long-distance transmission of reactive power.

Behind-the-meter BESS

Behind-the-meter (BTM) BESS refers to customer-sited stationary storage systems that are connected to the distribution system on the customer's side of the utility's service meter. This can include commercial, industrial, or residential locations. BTM BESS, along with decentralised renewable energy (DRE) assets and other distribution-level grid assets, are referred to as as distributed energy resources (DERs). Legacy stationary storage applications primarily provided simple back-up to critical services; historically, lead-based batteries were the chemistry of choice for these applications. As the price of lithium-ion batteries declines, a broader range of customer services becomes economically viable, enabling greater adoption.

As lithium-ion prices continue to decline, a wider range of BTM BESS services is becoming economically viable, as detailed in **Exhibit 54**.

Exhibit 54 Behind-the-meter BESS services

Service/Application	Description
Power Quality	Many customers, in particular industrial customers, rely on an uninterrupted supply of high-quality power. These industries, such as manufacturers, may be willing to invest in BTM BESS to ensure grid power remains within very tight voltage or frequency tolerances.
Back Up Power and Reliability/ Uninterrupted Power Supply (UPS)	BTM BESS can provide back-up power at various scales, ranging from sub-second-level power supply for critical industrial operations to 24-hour back-up when paired with an on-site solar PV system.[232]
Customer Cost Savings	• **Demand Charge Reduction:** On-site battery storage systems can be used to manage peak loads and reduce demand charges during periods of highest network charges. • **Time-of-Day Bill Management:** When time-of-day tariffs are implemented, BTM BESS allows consumers to reduce electricity costs by charging the batteries during off-peak hours and discharging during peak time intervals when tariffs are high. • **Retail Arbitrage:** Purchase power in low-price periods and sell in high-price periods on the retail market.[233]
Self Consumption	The excess electricity from distributed generation technologies, such as rooftop solar PV systems, can be stored in BTM batteries and used for local consumption when needed. BTM batteries can help DISCOMs absorb increased variable generation in areas with high VRE penetration, such as rooftop PV systems. Maximising local use of variable generation and minimising grid exports could benefit the system in some cases and help avoid issues related to backflow of variable power.[234]

RMI Graphic. **Source**: Oliver Schmidt and Iain Staffel, *Innovation Landscape Brief: Behind-the-Meter Batteries,* International Renewable Energy Agency (IRENA), 2019, **https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_BTM_Batteries_2019.pdf**; *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value,* Oxford University Press, 2023.

BTM BESS differs from front-of-meter applications on several criteria, including the need for system planners and utilities to develop new management approaches. Some key distinctions of BTM BESS are detailed in **Exhibit 55**.[235]

Exhibit 55 Key distinctions of BTM BESS

Characteristic	Description	Challenge	Solution
Size and Quantity	BTM systems have smaller capacities than utility-scale systems, but there can be more of them	This complicates BTM BESS integration, as utilities may have difficulty processing applications	Well-designed interconnection processes
Siting and Operation	Utility-scale systems are sited and dispatched to meet power system needs. BTM systems are installed and operated to meet customer needs	Customer needs are not necessarily aligned with power system needs	Well-designed compensation mechanisms and other policy instruments can help align interests, ensuring BTM systems are deployed and operated to benefit all system stakeholders
Visibility	System operators and utilities have limited visibility into the BTM system operation (i.e., they only see the difference between customer demand and storage operation)	This can impact planning exercises and regular operating practices	Well-designed interconnection requirements can ensure sufficient metering and telemetry equipment is installed to help utilities; however, the burden these requirements can represent for customers should be carefully considered

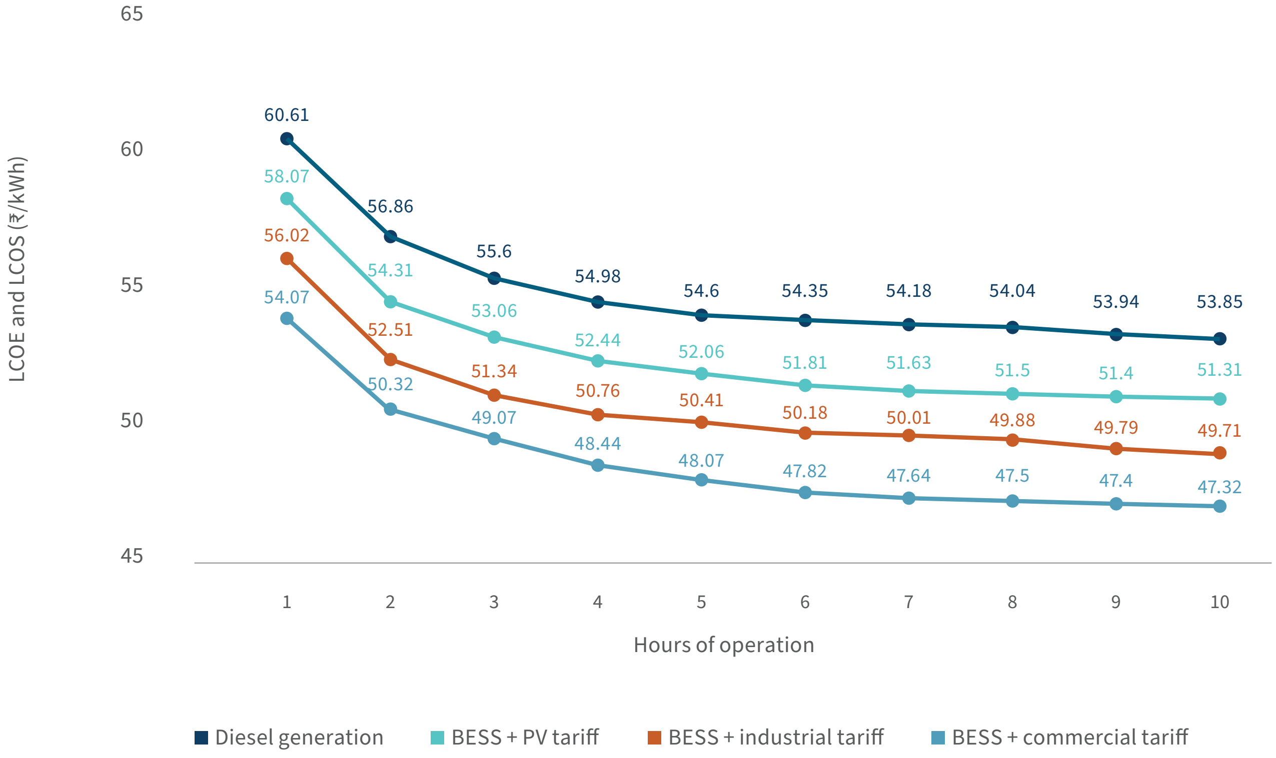
RMI Graphic. **Source:** Thomas Bowen and Carishma Gokhale-Welch, *Behind-the-Meter Battery Energy Storage: Frequently Asked Questions,* National Renewable Energy Laboratory (NREL), 2021, **https://docs.nrel.gov/docs/fy21osti/79393.pdf**.

BESS for commercial and industrial consumers

C&I consumers are critical stakeholders in India's energy landscape, accounting for 36.2% of total power demand in 2021–22. This is anticipated to grow at a CAGR of 8.2% through 2030, reaching an estimated demand of 775.3 billion units.[236] Grid tariffs in India for most C&I consumers exceed ₹7.00/kWh, while RE prices have dropped precipitously.[237] The rise in power demand in India has widened the nighttime peak gap, potentially to 41 GW.[238] As transportation electrification and charging grow, the nighttime peak might rise faster than anticipated, putting pressure on must-run plants and RTC service.

Rapidly declining BESS costs, paired with rising C&I tariffs and reliability risks, open a suite of economic services for C&I consumers in India. Critical infrastructure like telecommunications towers, data centres, and hospitals requires an uninterruptible power supply during outages. Typically, critical infrastructure has relied on lead-acid batteries as temporary backup until either power resumes or diesel generators are turned on. India has over 90 GW of BTM diesel generators primarily used as power backup to cope with frequent power outages. Diesel generators require regular maintenance and have high operating costs, which are especially sensitive to diesel prices. Diesel fuel prices vary across India; however, in many states, they exceed ₹90 per litre, and at times have exceeded ₹100 per litre.[239] While BESS assets have higher up-front costs, they offer lower maintenance and operating costs, protection against fuel price fluctuations, and the ability to provide immediate power backup.[240] The economics of BESS competitiveness against diesel generators will vary depending on a variety of factors, including BESS charging costs (solar tariff, industrial tariff, or commercial tariff) and hours of operation (or back-up per day); see **Exhibit 56.**[241]

Exhibit 56 **Diesel generation set LCOE and BESS LCOS comparison in Tamil Nadu, 2022**



Note: Assumes average LiB pack cost of ₹22,172/kWh and average diesel generator set cost of ₹6,648/kWh; diesel generator set was sized to 128 kW capacity and BESS was sized to 150 kW; solar tariff of ₹3.95/kWh, HT I-A industrial tariff of ₹6.67/kWh, HT-III commercial tariff of ₹8.4/kWh, and diesel price of ₹90/litre.

RMI Graphic. **Source**: *Battery Energy Storage Systems as an Alternative to Diesel Generators: A Comparative Cost Analysis for Tamil Nadu,* Auroville Consulting, 2022, **https://www.aurovilleconsulting.com/wp-content/uploads/2022/06/220801_White-paper_BESS-as-alternative-to-DG_Final-1.pdf**.

Pairing PV generation with BESS generally produces the most cost-effective backup power, while BESS charged from the grid may incur higher costs than incumbent diesel generation. However, lithium-ion pack prices account for the largest share of discovered LCOS. Pack price accounts for 77.1%–89.3% of LCOS, indicating that price declines experienced in India will make lithium-ion BESS increasingly competitive for providing these services.[242] Alternatively, diesel generation is most vulnerable to fluctuations in fuel prices, with variable costs accounting for 87.3%–98.3% of the discovered levelised cost of electricity for backup generation.[243] Increasing diesel prices from ₹90/litre to ₹95/litre results in LCOS increases of 4.8%–5.4%.[244]

Public infrastructure, commercial buildings, and factories are another key C&I subsegment. These users can benefit from using BESS for peak shaving, integration with on-site renewables, self-consumption optimisation, backup applications, and grid services. In international markets where demand charges apply, BESS can reduce energy costs by up to 80%.[245] In India, the value of these services will vary depending on the tariff structure and reliability.

In August 2023, MNRE notified the specifications for the rules on time-of-day (ToD) electricity tariffs. ToD tariffs are price signals that vary over time, being higher in peak periods and lower in off-peak periods. ToD tariffs aim to incentivise a reduction of consumer demand during peaking periods. Arbitrage enabled by BESS can help consumers reduce costs by charging during off-peak periods and discharging during peak periods, shifting demand.

The ToD tariffs notified by MNRE indicate that ToD tariffs for C&I consumers with a maximum demand greater than 10 kW will be effective April 2024 and apply for all non-agricultural consumers by April 2025. The ToD tariff for C&I consumers shall not be less than 1.2 times the standard tariff, and the ToD tariff applies to the energy charge component of the standard tariff. State commissions shall specify the tariff for solar hours and shall be at least 20% lower than the standard tariff for the category of consumers. The duration of peak hours shall not be more than solar hours (as notified by the relevant SERC or SLDC), and solar hours shall be eight hours in a day as specified by the State Commission.[246]

Ultimately, the tariff structure and local incentives will be key determinants of the value of BESS to C&I consumers. Fixed or demand charges are based on the maximum power requirement (measured in kVA or kW) that a business might need and are calculated on either contracted demand (the power capacity agreed upon in the connection agreement) or actual demand (the highest power drawn during a billing cycle). Additional surcharges can include fuel cost adjustment charges, regulatory charges, electricity duty, and power factor penalties or incentives. Tariff structure and incentives can vary widely by state, as exemplified in **Exhibit 57.**[247]

Exhibit 57 Examples of state tariff structures and incentives

State	Tariff Structure[xxiv]
Maharashtra	• Implements mandatory ToD tariffs for commercial consumers above 20 kW • Offers incentives for maintaining power factor above 0.95 • Special rebates for IT parks and data centres • Load factor incentives for consistent power usage
Karnataka	• Progressive slab system with four consumption brackets • Special night-time consumption incentives (10 p.m.–6 a.m.) • Solar rooftop integration benefits • Additional charges for peak hour usage (6 p.m.–10 p.m.)
Gujarat	• Separate tariffs for shopping malls and commercial complexes • Premium tariff for 24/7 power supply guarantee • Special provisions for seasonal businesses • Green energy incentives for renewable adoption
Tamil Nadu	• Voltage-wise tariff differentiation • Special provisions for educational institutions • Door-number-based billing for commercial complexes • Seasonal ToD variations

RMI Graphic. **Source**: "Commercial electricity tariff: 3 components explained," Neufin, 2025, **https://neufin.co/blog/commercial-electricity-tariff-3-components-explained/**.

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xxiv. As of January 2024

Box 6 Neighbourhood BESS in Australia

In addition to providing economic services for C&I consumers, BTM BESS offers opportunities to maximise the benefits of residential or community rooftop solar projects. Neighbourhood or community batteries are an approach to address high up-front BESS costs through shared ownership while unlocking the benefits of a flexible battery asset. Other key benefits include increased network hosting capacity (enabling more rooftop solar), solar energy sharing, improved resiliency, network stabilisation, and environmental and climate benefits.[248] These projects can be BTM, in which case they are charged by a co-located solar system and share the energy with the neighbourhood, or potentially front-of-meter.[249]

The state of Victoria in Australia launched the Neighbourhood Battery Initiative (NBI) in August 2021, with the intent of increasing DERs. The NBI aims to support understanding of the full range of benefits that neighbourhood-scale batteries can provide, as well as overcome barriers to deployment and inform regulatory reforms. The programme aims to support batteries between 100 kW and 5 MW and to enable further rooftop solar by deploying accompanying storage resources to shift load to higher-demand periods. The NBI seeks to explore a range of ownership and operating models, and is open to a variety of entities, including distribution network service providers, third-party market participants, community organisations, or partnerships between such entities.[250] Findings from this initiative are released through the public knowledge hub.[251]

Community solar in India provides a solution to expand clean energy access, especially for low-income households and urban areas where rooftop solar deployment may face space constraints. Enabling multiple households to share a single solar installation helps reduce costs and supports energy equity.[252] Similarly, a residential community (or neighbourhood) battery model may accelerate community solar initiatives while addressing cost and space barriers.

Aggregation and market participation

When many DERs are installed in a community, the benefits can expand beyond individual bill savings and backup power. DERs, including BTM BESS, managed EV charging, distributed generation such as rooftop solar, and demand response, can be aggregated to provide equivalent levels of service to utility-scale systems. Aggregation is the process of combining multiple smaller assets to act as a larger asset for the provision of specific power system services. Aggregation can be important for extending access to additional sources of value for BTM BESS, as it can happen across broad swaths of the power sector, providing energy, peaking capacity, or frequency services to power system operators and wholesale markets. Aggregation can also be concentrated in specific regions of the power sector experiencing issues, such as in non-wire alternatives.[253]

Aggregation of DERs, including BTM BESS and DREs, remains novel; best practices for rules governing DERs are still being developed. Some key considerations include:

- **Technology types:** which technologies or DERs are enabled to aggregate
- **Ownership and aggregation models:** multiple approaches to aggregation have been explored internationally, including VPPs (see **Box 7**, page 124), and distributed energy resource management systems (DERMs)[254]
- **Technical barriers:** coordination and cybersecurity
- **Regulatory barriers:** ambiguity in applicable existing rules or incentives that create uncertainty for customers, developers, aggregators, and other stakeholders

In the United States, the Federal Electricity Regulatory Commission (FERC) issued FERC Order No. 2222 in September 2020 directing independent system operators (ISOs) and regional transmission operators (RTOs) to allow DER aggregations to participate directly in the wholesale markets, allowing DER aggregators to register their resources under one or more participation models or develop participation models that accommodate the physical and operational characteristics of the DER aggregation. Key provisions under FERC Order No. 2222 allow the RTO/ISO to set minimum size requirements, acknowledge the need to avoid double-counting DERs (as DERs may be eligible for both a local utility's programme and wholesale market participation), designate the aggregator (not individual DER) as the point of contact with the RTO/ISO, and establish market rules on coordination across critical stakeholders.

FERC Order No. 2222 also includes directives on information, data, metering, and telemetry requirements to ensure visibility of the entire portfolio, provide settlement and performance data, and enable market operators to maintain situational awareness for dispatching and managing DER aggregation to maintain power system reliability.[255] The provisions outlined in FERC Order No. 2222 can serve as valuable guidelines for international markets, providing a framework for DER aggregation and market participation.

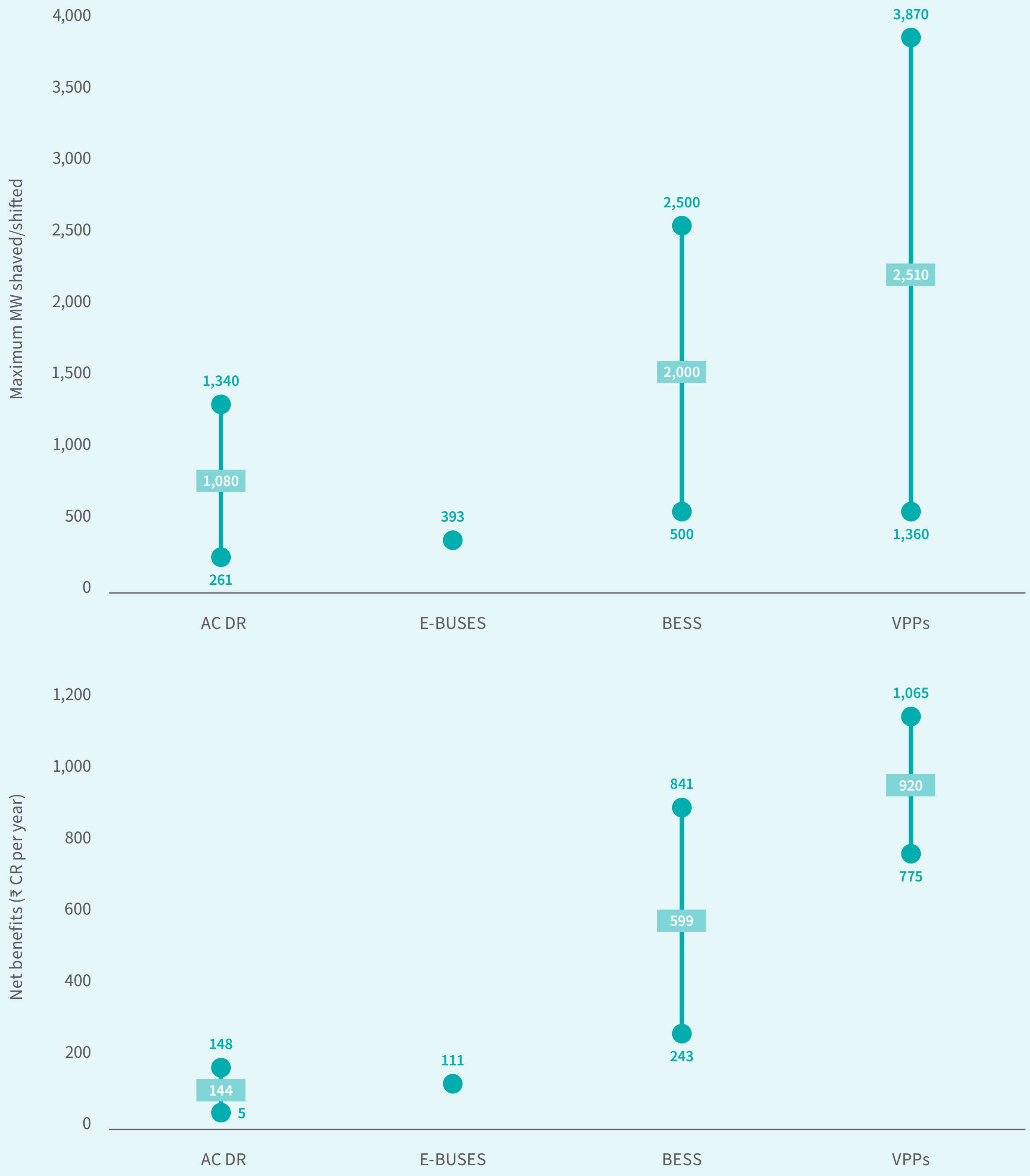
Box 7 Virtual power plants

Virtual power plants (VPPs) are aggregations of DERs that can flexibly balance electrical loads and provide utility-scale and utility-grade services.[256] They can provide utilities and grid operators with cost-effective, reliable, and resilient grid service solutions, while helping customers save on their energy bills. VPPs are emerging as grid resources in many parts of the world.

National Grid's ConnectedSolutions is a pioneering VPP initiative in the United States that aggregates DERs, such as residential cooling demand response (DR), residential batteries, and C&I DR, in a multi-utility programme. This initiative is designed to reduce energy use during peak demand periods and, in turn, reduce total capacity obligation and energy costs. Through the programme, consumers are incentivised to turn their home or business into a network of small, flexible energy resources that are called upon to support the grid. ConnectedSolutions had 34,000 customers representing 310 MW of capacity enrolled at the end of 2020.

The potential exists to capture value through VPP-style aggregation in India. By FY30, RMI projects Delhi could reduce 250–1,350 MW of peak demand through air conditioner demand response (AC DR) programmes, up to 400 MW of demand-shifting potential through managed charging of the electric bus fleet, and 500–2,500 MW of shiftable demand through BESS. Combined as VPPs, these measures could unlock maximum demand reductions of nearly 4,000 MW, about one-third of Delhi's projected peak demand in 2030. Annual net benefits to Delhi utilities could reach a combined benefit of up to ₹1,050 crore (approximately US$118.97 million) for integrated VPPs (see **Exhibit 58**, page 125).

Exhibit 58 FY30 grid flexibility potential and net annual benefits by technology, FY30 for Delhi



RMI Graphic. **Source**: Mohamed Akhtar Ansari et. al, *Transforming Delhi's Power Grid: A Comprehensive Guide to Enhancing Flexibility,* BSES Rajdhani Power Limited, BSES Yamuna Power Limited, RMI, July 2024, **https://rmi.org/insight/transforming-delhis-power-grid/**.

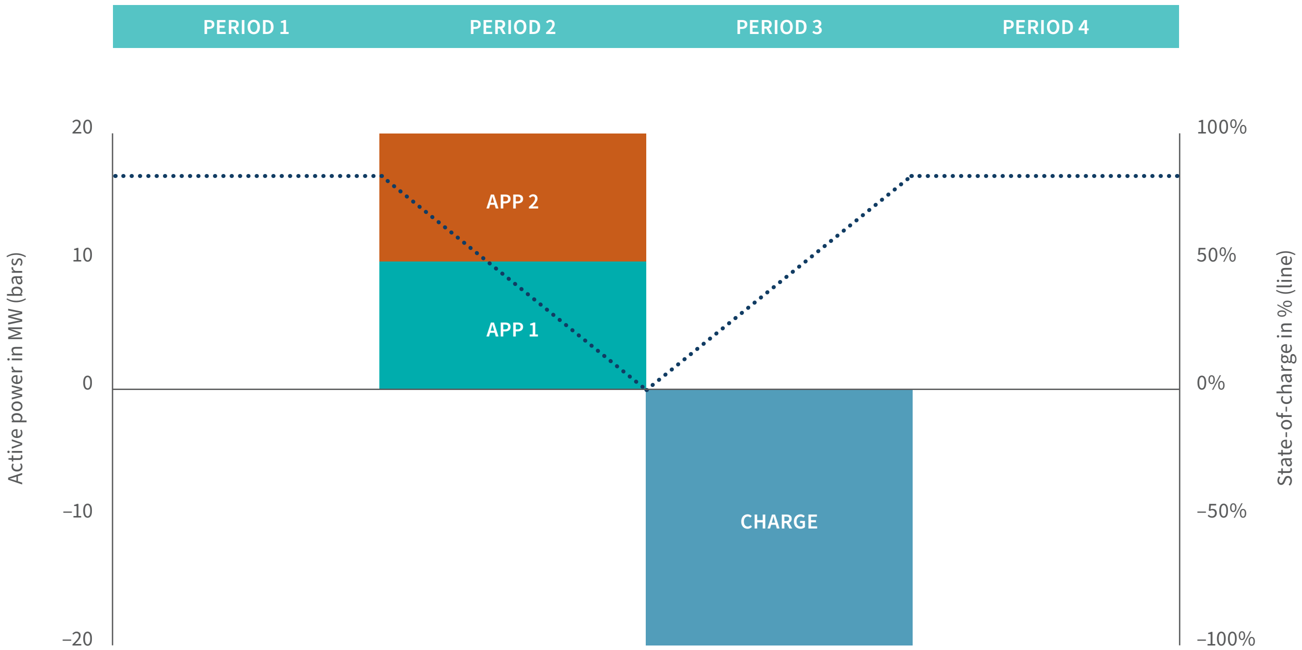
Value stacking

The inherent flexibility of BESS assets allows them to "value stack,"[xxv] to provide and monetise multiple system services, maximising their value to the grid and project developers. Some services are either rarely called for or used infrequently, allowing BESS assets to be designed to provide multiple services and enabling higher overall utilisation.[257] Value stream stacking allows a BESS to improve project economics by capturing the multiple monetary value streams, as enabled by existing policies and regulations. This requires a good understanding of the markets, revenue opportunities, regulations, and an efficient battery management system.[258] Multiple approaches to value stacking are possible, reflecting the service and regulatory participation opportunities and technical considerations (see **Exhibit 59**, page 127).[259] The approach to optimising value stacking must be managed, accounting for technical and performance considerations such as maintaining adequate SoC for the BESS asset to avoid the risk of failing to meet delivery requirements.

[xxv] Sometimes referred to as "revenue stack."

Exhibit 59 Four archetypes of value stacking

PARALLEL STACKING



Description

Power capacity is separated into individual parts. These are provided in parallel to serve different applications. In the above schematic, the 20 MW electricity storage system provides 10 MW to application 1 and 2 each in period 2. As a result, state-of-charge (SOC) reduces from 100% to 0%. The system charges in period 3 to recover SOC from 0% to 100%

Considerations

Operators should not exceed the power committed to the individual applications in order not to compromise any other application contracted for simultaneously.

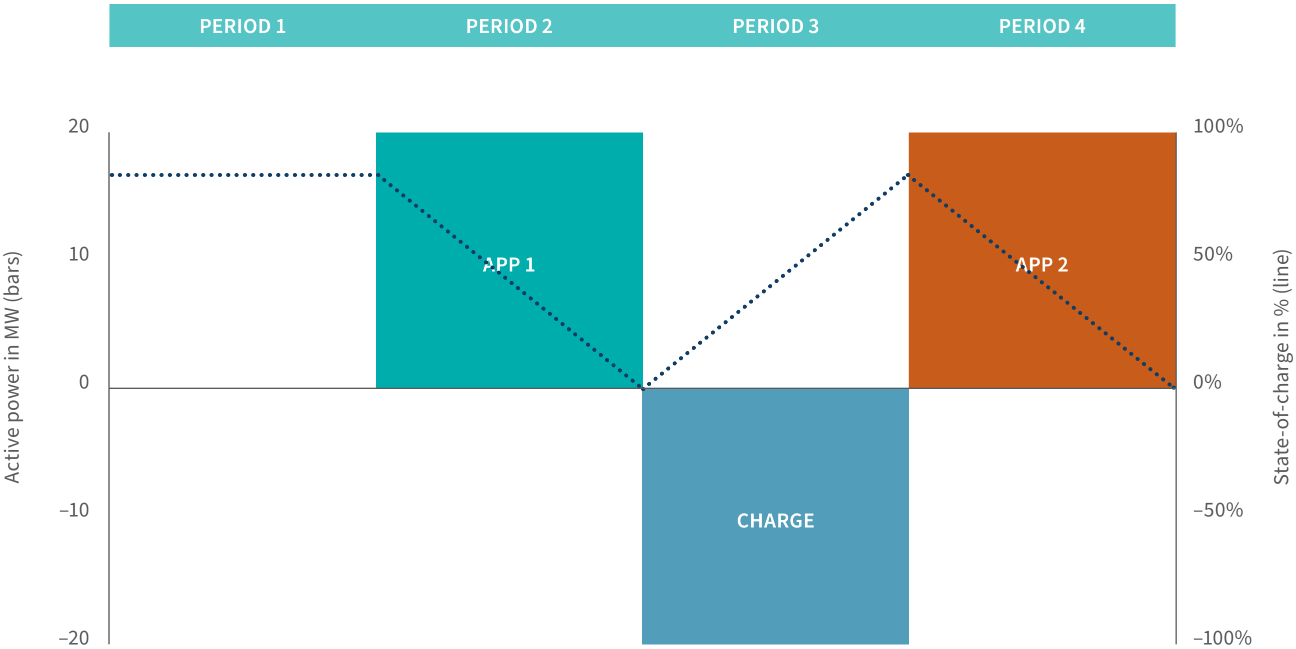
Relevance

Parallel stacking is among the most common types of value stacking. There are numerous examples for various applications across geographies.

RMI Graphic. **Source:** Adapted from Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value*, Oxford University Press, 2023.

Exhibit 59 Four archetypes of value stacking (continued)

SEQUENTIAL STACKING



Description

Power capacity is provided to different applications in different time periods. In the above schematic, the 20 MW electricity storage system provides -20 MW to application 1 in period 2, then charges in period 3 to replenish SOC and then again provides +20 MW to application 2. Depending on the application, the storage system could be rewarded for providing +40 MW in application 2, as its operating point or baseline was -20 MW in the previous period.

Considerations

Operators must manage SOC appropriately to ensure that provision of one application does not affect provision of the other.

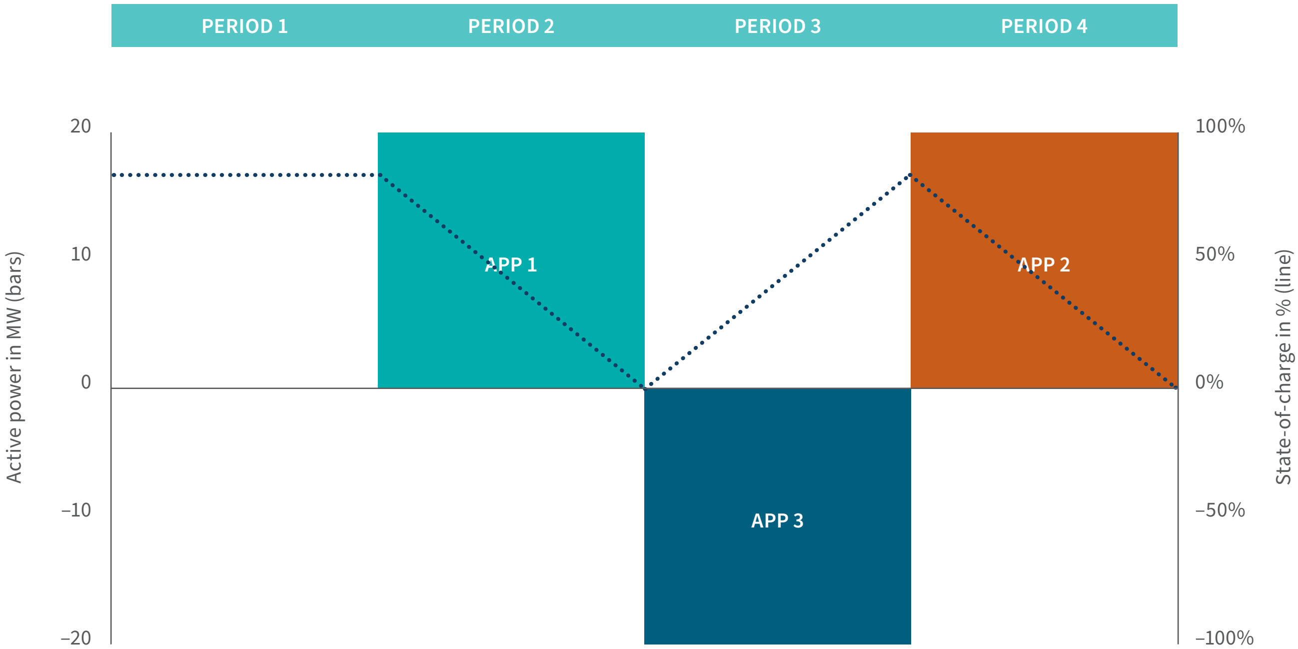
Relevance

Sequential stacking is among the most common types of value stacking. There are numerous examples for various applications in various geographies.

RMI Graphic. **Source:** Adapted from Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value*, Oxford University Press, 2023.

Exhibit 59 Four archetypes of value stacking (continued)

SEQUENTIAL STACKING (OPPOSITE DIRECTIONS)



Description

Power is provided to different applications in different time periods. At least one application is in the opposite direction, so that SOC levels can be managed while being remunerated. In the schematic, the 20 MW storage system provided +20 MW to application 1 in period 2, then -20 MW to application 3 in period 3, which also replenishes SOC. In period 4, +20 MW are provided to application 2 (again, depending on the application, the system could be rewarded for providing -40 MW and +40 MW to applications 3 and 2 respectively based on its baseline operating points in the previous periods).

Considerations

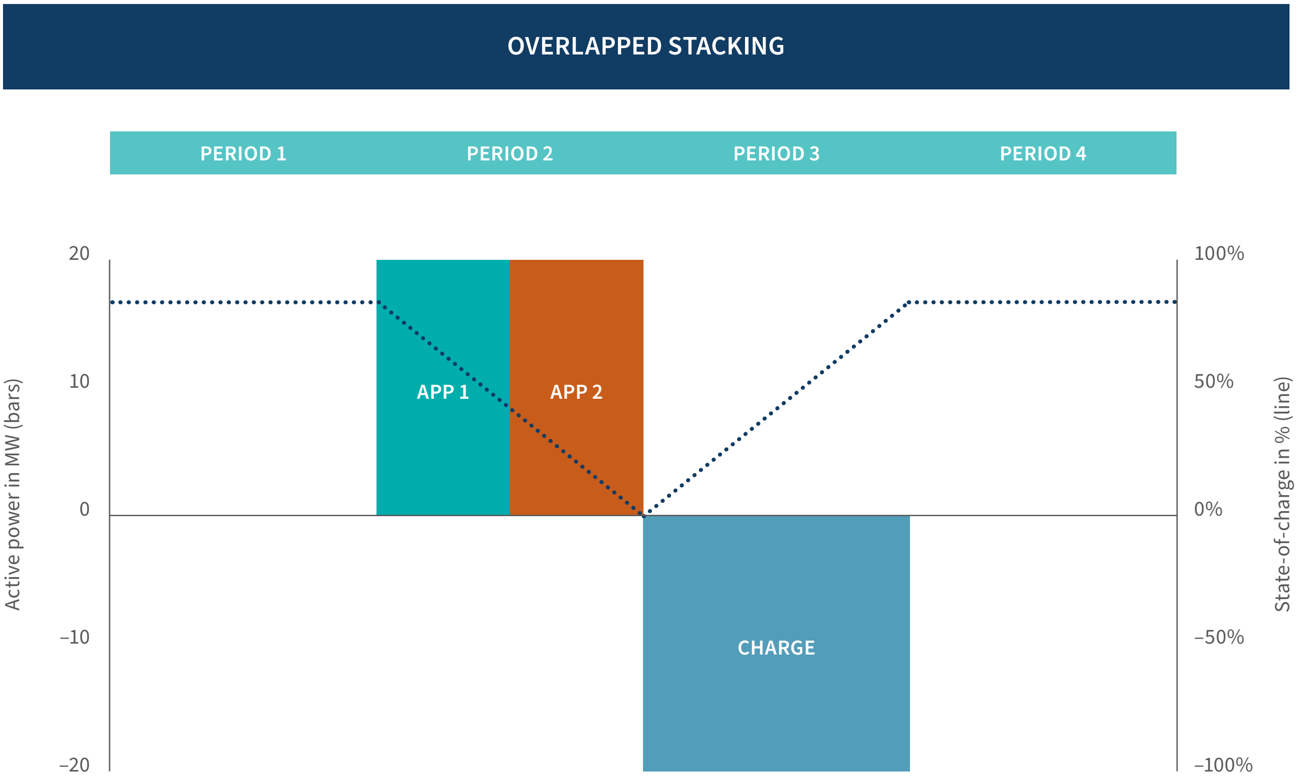
It can be difficult to find two applications with opposite directions that fully enable managing SOC. Often, required power capacity and discharge duration vary strongly between applications. A starting point to identify opportunities would be negatively correlated applications.

Relevance

Opportunities are less common than parallel or sequential stacking.

RMI Graphic. **Source:** Adapted from Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value*, Oxford University Press, 2023.

Exhibit 59 Four archetypes of value stacking (continued)



Description

The same power capacity is provided to multiple applications at the same time. In the above schematic, the electricity storage system is serving its 20 MW power capacity to both applications in period 2. It then charges in period 3 to replenish its SOC.

Considerations

The ability to fulfill requirements of two applications simultaneously may be limited and there are high penalties if contractual obligations are broken. A good starting point to identify opportunities is to look for applications that are positively correlated.

Relevance

Least relevant archetype, because opportunities are rare and regulations (globally) often inhibit providing for alternative applications when power capacity is already contracted.

RMI Graphic. **Source:** Adapted from Oliver Schmidt and Iain Staffel, *Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value*, Oxford University Press, 2023.

Several factors must be considered when operating storage to maximise benefits across value streams:[260]

- Battery operators may co-optimise across multiple services (e.g., energy arbitrage and operating reserves).
- Battery operators must manage state of charge to account for intertemporal constraints and imperfect foresight over future conditions (e.g., discharging energy in one hour may limit the ability of the battery to discharge in subsequent hours).
- Economic results are sensitive to the sizing of the energy storage system in terms of power and energy capacities.
- At large capacities, batteries may be price makers — impacting market prices as a result of their dispatch.
- Battery degradation is an important consideration, and the impact of cycling should be accurately characterised.

In addition to commercial strategy, the BESS operator should also account for related warranty and insurance conditions. Manufacturer warranties may limit the scope of cross-market optimisation, impacting options for revenue diversification and, ultimately, profits. Product warranties typically stipulate that the battery or system has been manufactured, handled, and properly installed. A performance warranty guarantees that the battery will maintain a specific capacity for a specified period. The performance warranty is relevant to operations, as it typically outlines particular constraints (such as temperature range, average SoC or c-rate, cycling frequency, charging rate, and DoD) that the operator must meet. These will be critical considerations when considering the project use case.[261]

Given these limitations, storage operators schedule dispatch using a variety of strategies:

- Operators choose to optimise across all services, a subset of services, customer and utility cases concurrently, or defined scheduling with no optimisation.
- Operators may employ either optimisation, heuristic, or hierarchical dispatch methods.[xxvi]
- Operators employ a variety of advanced forecasting methods to manage state of charge in the face of imperfect foresight into future conditions.
- Operators may set schedules on a day-ahead or week-ahead basis, or they may reoptimise in real-time.

Regulators must consider related issues when determining compensation across multiple value streams:

- Batteries should be compensated for all services provided (e.g., energy arbitrage, transmission congestion alleviation, RA, ancillary services , and network upgrade deferral), including those provided simultaneously.
- Batteries must not be compensated for services that cannot be delivered (e.g., a battery should not be compensated for selling an operating reserve that it could not deliver upon if called).
- Market products should be designed to incentivise storage operations that maximise benefits to the power system at large (e.g., reducing investment and production costs, and meeting other policy goals such as reliability and greenhouse gas mitigation).

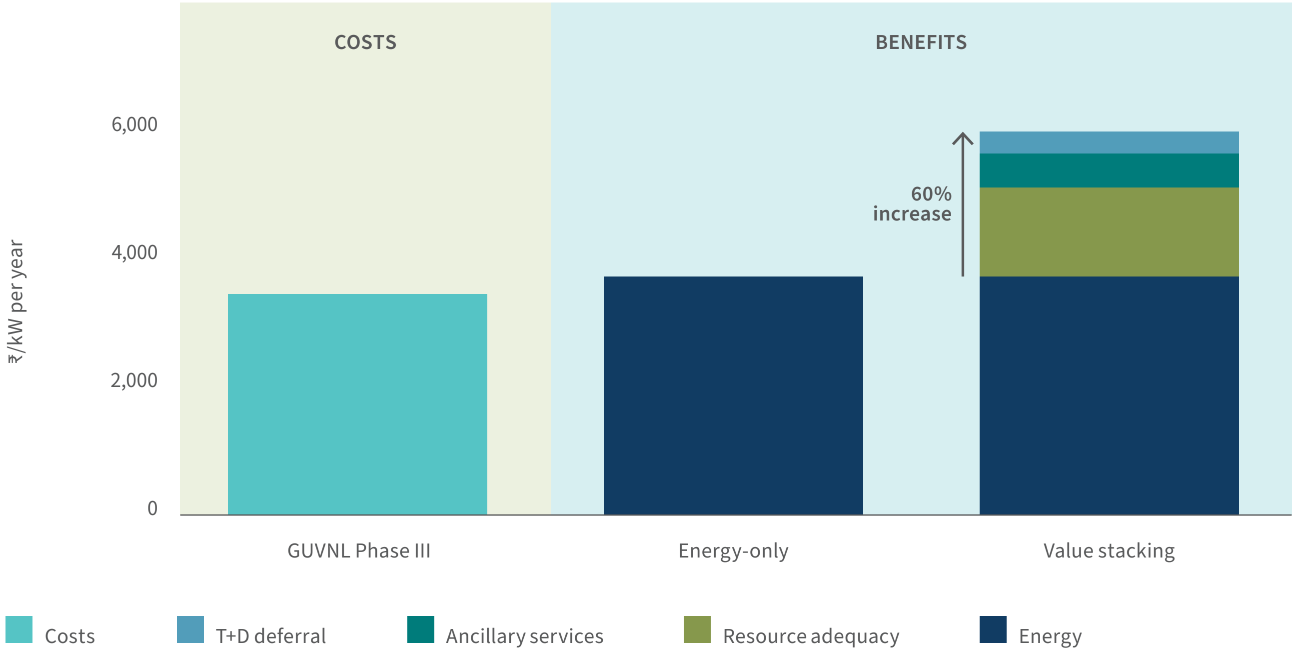
[xxvi] The unit commitment (UC) (deciding which generating units to turn on/off) and economic dispatch (determining power output of each unit online) optimisation problems are solved to minimise the total energy generation cost of the electricity grid. These optimisation problems are often computationally challenging due to several continuous and binary variables along with non-linear technology-specific constraints. Heuristic methods rely on rules or experience-based problem-solving strategies to find near-optimal solutions quickly, rather than mathematically searching for the optimal solution. Hierarchical methods decompose the problem into smaller sub-problems (for example, first solve UC at hourly time resolution and then tackle the economic dispatch problem at sub-hourly resolution) to find mathematical solutions to each sub-problem. Hierarchical methods are more accurate than heuristic methods but can be time-consuming due to rigorous problem-solving algorithms.

Value stack case study

Under today's market rules and regulations, batteries in India are typically only valued for their avoided energy costs. For a market participant, this represents the arbitrage value that a battery operator could earn through charging when wholesale market prices are low and discharging when they are high. For a DISCOM not participating in wholesale markets, it represents the avoided energy costs resulting from shifting generation from high- to low-marginal-cost resources.

In some cases, energy value may be enough to justify investment at today's battery costs. But global examples show that batteries can be co-optimised to deliver value across multiple services simultaneously, including energy, RA, ancillary services, and deferral of transmission and distribution (T+D) infrastructure. By allowing BESS to co-optimise across these value streams and compensating them across the full value stack, India's regulators have an opportunity to greatly advance the grid contributions of existing batteries (see **Exhibit 60**, page 134).

Exhibit 60 Value stack case study cost analysis



Note: Analysis estimates the costs and benefits of a 250 MW/500 MWh BESS, assuming that market rules and regulations are updated to allow for full value stacking. Costs are taken from GUVNL's Phase III tender. The energy value reflects the arbitrage opportunity a 2-hour BESS could have realised had it been dispatched against historical IEX energy prices. Ancillary service value is calculated by assuming the battery could provide ancillary services during the hours it was charged and not dispatched for energy. Ancillary service prices are taken based on historical contracts for Tertiary Reserve Ancillary Services (TRAS). RA and T+D deferral reflect modelled forward-looking values for the Delhi area.[xxvii]

RMI Graphic. **Source**: RMI Analysis

A hypothetical battery project that effectively monetises across arbitrage, RA, ancillary services, and distribution capacity deferral sees a 60% increase in benefits compared to a similar project that provides only energy arbitrage services. Real-world projects may face operational challenges and dispatch complexity, which typically limit them to providing only two or three services. Currently, the full range of these values is not necessarily monetisable in India, hindering project developers' ability to forecast accurate value stacks. Regulators and DISCOMs do not have an agreed-upon methodology for determining the value of transmission and distribution deferral, limiting the ability to forecast and include this value. Not all ancillary service products are open to battery storage, and the TRAS has yet to publish prices, creating opacity for developers. Finally, the RA rules are still being adopted across states, with an unclear timeline for when these values will be realised for battery projects. Regulatory action can enable clear, appropriate value stacking in a system that allows batteries to monetise a full range of services, thereby improving project bankability and incentivising accelerated deployment.[262]

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xxvii. For additional details on ancillary services, resource adequacy, and CAPEX deferral modelling, see **Appendix C**.

Pathways for Incentivising Storage Deployment

Meeting pan-India BESS deployment needs by 2030 will require interventions at multiple stages of the value chain. The existing national framework is an important step toward creating a robust ecosystem for BESS in India. Still, high BESS material costs, low bankability, and lack of stakeholder readiness hinder deployment. While additional steps, such as capital cost subsidies through the expansion of viability gap funding support announced in June 2025, and the RA Framework, will be critical for advancing investments for local system needs, existing regulatory frameworks are inadequate for evaluating the performance and capacity benefits enabled by new flexible energy storage technologies like BESS. Market access and products, along with improved visibility into market values, can help project planners and system integrators better understand battery economics. In addition, further guidance on project planning and tender design can accelerate project development by providing greater clarity on minimum equipment standards and operations.

Accelerating procurement

As grid battery technologies mature and global and domestic costs decline, Indian power sector stakeholders must be prepared to rapidly deploy and integrate high volumes of BESS assets to meet system needs. Stakeholders and developers should have clear guidance on questions related to tender design, operation, and safety that address stakeholder knowledge gaps regarding BESS asset ownership and operation, in anticipation of BESS becoming cost-competitive in India’s market.

Exhibit 61 Near- and medium-term recommendations for accelerating procurement

Near-Term Recommended Actions	Medium-Term Recommended Actions
Provide additional guidance for BESS or hybrid project RFP and tender design: In June 2023, the MoP provided 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,* which aimed to provide a transparent, fair, standardised procurement framework based on open competitive bidding with appropriate risk-sharing between stakeholders to enable procurement of power at competitive prices.[263] While these guidelines set a useful standard for bidding on energy storage projects, additional guidance for RFP design would help procuring entities and developers appropriately plan for bids and projects and avoid conflicts in design and operation. Some key points to be clarified include: • How to specify operational hours of a battery storage project that can maximise flexibility, such as use for value stacking, to avoid auxiliary power costs and minimise degradation • Requirements around certificates or test reports • Developing a standardised list of approved material quality, suppliers, or certificates to avoid utilisation of low-cost, poorly sourced products that create performance or safety risk for the battery project	Align capacity and network planning: As state-level entities implement the RA framework, a process should be developed to align local capacity and national and regional grid network planning. Current system capacity utilisation should be assessed, and DISCOM-level guidelines should be developed to integrate these activities. Lighthouse projects should be undertaken with selected DISCOMs to inform this process, and findings from the Lighthouse projects can be utilised to develop knowledge-sharing materials to socialise the aligned planning process. Concurrently, a transparent tariff and implications on system planning should also be studied by CERC and set by SERCs.

Market development

It is necessary to have reliable revenue streams that appropriately monetise system performance enhancements provided by flexible technologies. Regulatory and market structures should be established that appropriately capture the value of system flexibility and reliability services. These services should encompass energy services, ancillary services, ramping support, flexibility, and capacity; the services should be monetisable with clear price signals to stakeholders to provide greater transparency into project planning and clarity on project bankability. Mature markets with a range of products to meet system needs, both short- and long-term, can create valuable avenues for innovative technologies to compete and attract private investors. Currently, uncertainty around quantifying value streams has hindered project planning and deployment. Both primary and supplementary value streams for DISCOM storage projects face significant process uncertainties and a lack of price data. By appropriately monetising the system benefits provided by flexible technologies, such as BESS projects, regulatory and market entities can bolster robust revenue streams, improve project bankability, and accelerate necessary deployment backed by private capital.

Exhibit 62 Current status and recommendations for market development

Current Status
RA/capacity market While RA guidelines are in place and may serve as an effective signal for determining local BESS needs, DISCOMs' willingness to adhere to them has yet to be proven. Mechanisms to encourage compliance will therefore need to be established. Further, many international power markets hold capacity auctions, which can economically meet system needs and maximise the value of a battery asset. The RA programme in California (valuing capacity) and two capacity market auctions in the UK have been critical to bringing 5 GW and 2.3 GW of storage online, respectively. The Indian power market is yet to evolve to value capacity resources such as BESS.
Ancillary services Historically, India has procured ancillary services through an administered mechanism, but has introduced three ancillary services products: PRAS, SRAS, and TRAS. Despite being well-suited to providing PRAS, battery storage assets are not currently allowed to provide this high-value, fast-response product. Unlike PRAS and SRAS, TRAS are being procured through auction-based mechanisms administered by the power exchanges. The movement-to-market mechanism for procuring PRAS and SRAS needs to be strengthened, with an emphasis on transparency into clearing prices for all ancillary services.
Day-ahead market Trading through the power exchanges for arbitrage enables BESS to help level loads while creating an additional opportunity for battery assets to realise value. Establishing markets that more closely align with production costs enables BESS to improve project economics. Further reforms that similarly capture the actual cost of production may be critical for driving the value of BESS within India.
Other services Opportunity exists to develop procurement mechanisms for other products that will benefit system stability while capturing the value of BESS. In use cases such as black start and voltage support, efforts are needed to clearly enable BESS access to provide these critical services — either through the development of a market or by explicitly allowing BESS to contract for these services. No formal framework currently exists to allow BESS participation.

Exhibit 62 Current status and recommendations for market development (continued)

Near-Term Recommended Actions

Provide additional resource adequacy framework implementation clarity
The RA framework is an important tool for holistic long-term system planning, and CEA is taking steps to guide some DISCOMs through the initial steps of meeting RA requirements, including needs surveys and procurement. As these initial exercises are undertaken, additional guidance on the RA implementation and enforcement mechanisms should be provided. Guidance may include least-cost RA planning strategies to be provided to all DISCOMs. Institutional knowledge building for DISCOM and SERC staff should be initiated to create specific internal staff capability to plan, evaluate, and execute RA assessments. BESS assets should also be explicitly recognised as a capacity resource under the RA framework.

Amend and adopt methodology for calculating capacity credits under the RA framework
CEA released the *Draft Discussion Paper on the Methodology for Capacity Credit of Generation Resources and Coincident Peak Requirement of Utilities under the Resource Adequacy Framework* (Draft Capacity Credit Methodology) in October 2024. Successful implementation of capacity credit and coincident peak requirements hinges on clear, transparent requirements and careful deliberation of key parameters. This draft discussion should be codified with amendments, including, but not limited to:

- Additional clarity on how battery storage capacity credits are calculated, and adoption of SoC-aware capacity credit methodology for storage devices. This metric calculates capacity credit based on SoC rather than storage dispatch during peak demand hours. A storage device receives full capacity credit if it contains sufficient SoC to provide power at its rated capacity during the top-demand hours.

- Assigning capacity credits to FDRE and other hybrid resources. While challenges exist with assigning capacity credits to hybrid resources, the RA benefits of these resources should be considered and provide fair support for additional procurement.

Procure ancillary services (AS products) through market mechanisms
Of the three ancillary services products procured, only TRAS is met through a market mechanism. CERC and GRID-India should shift both SRAS and PRAS to market mechanisms and enable BESS to compete to provide all categories of currently recognised ancillary services.

Publicly report clearing prices for all market products
Publicly available clearing prices will provide market signals to BESS project planners and developers, enabling improved forecasts of project values and optimal operational strategies. This data will enable the identification of the marginal cost of meeting peak power and ancillary services. GRID-India and the power exchanges should work to make clearing prices publicly reported in a standardised format.

Commitment charges should be reconsidered
In ancillary services markets, resources receive a commitment charge for the hours in which they are cleared to supply or withdraw energy, regardless of whether any energy is actually dispatched.[264] Raising the cap on commitment charges will incentivise participation in ancillary markets as BESS can get more value from being available to provide ancillary services for many hours of the day, making it worthwhile to forgo arbitrage revenues during these hours, even when ancillary services are only required infrequently.

Medium-Term Recommended Actions

Develop additional market products
Services such as fast frequency response, voltage support, and black start can be cost-effectively procured through market mechanisms. In addition, products for long-duration arbitrage and capacity can help meet RA projections. Finally, market products can be developed that emphasise the services BESS can provide to the grid, such as fast and flexible ramping support. This is especially important in geographies with high levels of solar generation penetration. CERC, GRID-India, and the power exchanges can collaborate to create and introduce these products.

Addressing load shedding
The high-priced day-ahead market (HP-DAM) failed due to low participation by buyers; many DISCOMs prefer to shed load rather than purchase at higher prices. CERC and the FoR should seek to develop a framework for determining incentives to avoid load shedding that occurred instead of participation in the HP-DAM.

Regulatory reform

As India's power markets develop, flexible technology assets such as energy storage will begin providing services for a range of applications. Energy storage technologies, such as BESS, can be utilised as a non-wire alternative for transmission and distribution network planning, replacing traditional investments and encouraging loss reduction. The need exists for reforming how such services are accounted, especially in dense urban areas where there are space constraints for distribution system infrastructure expansion.

Exhibit 63 Current status and recommendations for regulatory reforms

Current Status
Guidance on transmission and distribution deferral services At present, there is no clear guidance or regulatory framework for using BESS as a distribution system capacity-deferral asset. A streamlined approach is needed to establish its value to the system in terms of financial savings, so that state regulators can appropriately permit revenue realisation through the annual aggregate revenue requirement process.
Time-of-use tariffs Even for established value streams like energy arbitrage and ramping support, enabling policies such as time-of-use (TOU) tariffs can significantly strengthen the value of the flexibility BESS can provide to end-use customers. TOU tariffs are driving the adoption of BTM BESS in international markets (e.g., California). Within India, TOU tariffs have been introduced. Still, implementation in some states is unclear, and the delta between peak and off-peak hours, or between solar and non-solar hours, may not adequately reflect the price differential in supply.
Innovative regulatory frameworks Innovative regulatory frameworks, such as allowing DISCOM-customer co-ownership of BESS assets or performance-based regulation that accounts for non-monetisable services beyond peak procurement, can help incentivise DISCOMs, where appropriate, to invest in innovative technologies. Regulators should develop a deeper understanding of system needs and services where BESS can be a solution. The RIIO (revenue = incentives + innovation + outputs) model explored under the UK system may be a potential model to encourage DISCOMs to meet needs cost-effectively.
Adoption of a clear methodology for state regulators and DISCOMs to assess BESS service value BESS can provide a wide range of services for DISCOMs, including arbitrage, capital expense deferral, system balancing, and other grid services. The cost of these services will vary widely depending on local conditions and needs. However, the lack of agreed-upon evaluation methods creates project approval risk. CERC and state-level regulators should hold a workshop to develop clear, agreed-upon methodologies for calculating a project's value across multiple services.
Uniform technological readiness should be achieved across all state-level entities DISCOMs should adopt governance mechanisms to provide accurate status reports on current communications systems, such as supervisory control and data acquisition (SCADA) systems. By establishing an accurate picture of the level of technological readiness across DISCOMs, a needs assessment can be undertaken and schemes created to ensure that all DISCOMs can integrate software interventions and report data from the distribution network accurately and quickly.
Standardised data disclosure forms should be developed and data reporting mandated by regulations CEA should initiate a stakeholder engagement process to identify critical data, including load profiles, generation, deployment, and substation and feeder-level data. The drive towards a more economic power system will be aided by the data, enabling the quantification of the value of lost load and curtailments. The result can be shared with SERCs through the Forum of Regulators.
DSM penalty disclosure DSM penalties are levied against entities that cause grid deviations. These penalties may be a major incentive for DISCOMs to invest in BESS; however, greater transparency and granularity of deviation data can help identify distribution networks with the highest deviation challenges. Identification of these regions can motivate investment in improved forecasting and DLS.

Exhibit 63 Current status and recommendations for regulatory reforms (continued)

Near-Term Recommended Actions

Software interventions should be deployed to enable optimal BESS operation
As legacy SCADA systems are identified, upgraded, and automated, a roadmap should be created to prepare for integrating software to improve system intelligence. This will require system-level studies on area control errors and frequency deviation. Regulators should then devise and approve grid modernisation programmes to enable the standardisation of communications across DISCOMs.

A publicly accessible central data repository should be created to collect and archive the reported state-level data
Once standardised data reporting forms are developed and reporting is mandated by regulation, state-level entities should regularly contribute data to a centralised repository. A national entity, such as CEA or GRID-India, can maintain the repository.

Institutional knowledge building

BESS assets are also anticipated to be located across the grid: located at generators, transmission, distribution, and behind the meter. Coordination of asset management, both grid-scale and distributed, will require readiness for national- and state-level stakeholders, including DISCOMs, regional load dispatch centres, SLDCs, and the power exchanges. These entities will need to be aware of the range of grid services BESS can provide and to achieve a level of technological readiness and best-practice awareness for battery management. Batteries must be managed across multiple markets, requiring a minimum SoC for participation across markets, and potentially across various owners, such as DISCOMs and C&I end users. Achieving this while reducing risk to the grid will require improved institutional knowledge to enable effective coordination that can maximise the effectiveness of BESS assets.

Exhibit 64 Current status and recommendations for institutional knowledge creation

Current Status

Guidance for BESS operators
As India's power markets develop, battery assets will begin providing services for a range of applications. In the absence of a centralised market operator to set participation standards across uses, regulators should consider creating and providing guidance for battery operators to ensure obligations are met. Guidance should consider best practices for battery management across multiple markets, requiring minimum SoC for participation across markets, or explore the management of battery assets across multiple owners, such as DISCOMs and C&I end users.

Long-term planning for interconnection
Multiple international electricity markets are experiencing lengthy delays in reviewing, approving, and connecting battery assets into the grid due to the high volume of projects. Such connection delays will not be relevant within India until the volume of battery projects increases; however, system operators should be considering connection frameworks to anticipate and avoid potential future delays.

Near-Term Recommended Actions

Institutional knowledge and capability-building programmes should be developed for state-level entities
State-level entities, including SERCs, SLDCs, and DISCOMs, will require additional training and support to address knowledge gaps in BESS project planning, grid services, operations, and contributions to RA. RA planning and BESS's role in meeting RA needs should be aligned with SERC's regulatory evaluation processes. State-level entities should be informed of BESS's capability to provide not only energy but also capacity and non-wired alternative services.

Medium-Term Recommended Actions

A centralised BESS knowledge hub must be established
Learnings from projects across the power system should be compiled into a centralised resource centre maintained by the MoP. This will enable the creation of benchmarks for project evaluation and provide all stakeholders with access to best practices in project planning, construction, and operation.

Conclusion

India has the opportunity and goal to ensure reliable electricity access and accelerate industrialisation. Growth in electricity generation is fundamental to maintaining robust economic development. The country has set an ambitious target of meeting 50% of the installed electricity generation capacity from non-fossil fuel sources by 2030, underpinning the ambitious climate targets set by the government.[265]

As electricity demand continues to grow, with peak demand outpacing projections, and VRE capacity constitutes a larger share of the generation mix, greater volumes of energy storage will be required across the electricity system to maintain a stable, resilient, and cost-effective grid. By 2030, more than 60 GW of storage will be needed, of which an estimated 42 GW is likely to be provided by battery storage. Innovations in BESS technology and declining global costs have made this technology an attractive solution, able to provide numerous values to system operators, transmission, and distribution utilities. The GoI has taken important initial policy and regulatory steps, but rapid deployment will require further actions to operationalise the regulatory framework. However, additional work is required to ensure that storage projects are able to maximise the value and reduce risks of cancellation or hindered bankability.

BESS assets bring improved flexibility and reliability to India's electricity grid, but traditional regulatory frameworks for determining system investments are inadequate for evaluating these qualities. The recommendations in this report are derived from stakeholder consultations, learnings from international markets, and rigorous analysis. By enhancing the ability for storage assets to fairly compete to provide the wide range of services required to maintain the grid, India can meet its rapidly growing needs in a transparent and economic manner. In addition, greater access to markets and improved visibility into market values can help project planners and system integrators better understand the battery economics. Growing electricity demand and increased VRE integration are increasing risk of grid instability and driving the need for ancillary services, which fast-responding BESS assets are well-suited to economically provide.

In dense urban areas such as Delhi, where distribution infrastructure faces congestion risk and challenges to meet growing peak demand, local BESS assets can provide critical capacity value that can defer capital expenses for new costly additions to the distribution network and improve system efficiency. However, new technology requires improved learnings for all stakeholders, including central and state regulators, DISCOMs, load dispatch centres, project developers and operators, and local institutions such as fire departments. Roadmaps for enabling BESS technology to provide services beyond arbitrage must be designed and implemented — including resource adequacy, ancillary services, and deferred capital expenses — and stakeholders must have clarity on how to manage BESS assets in a manner that can balance stacking these values with safe operation.

Global partnerships and learning from international markets can help guide India to effectively deploy this novel technology in a manner that minimises risk and maximises value. With these strategic actions and partnerships, India can turn it's grid — the largest in the world — into a major asset for continued economic growth and become a global leader for the clean energy transition with lasting benefits for the country and the world.

Appendices

Appendix A: National level needs for grid storage

As India aims to achieve 50% of non-fossil fuel generation capacity installed by 2030, grid storage technologies are needed to integrate the country's emerging renewable-rich grid.[266] The latest studies estimate that, at the national level, between 60 GW and 90 GW (252–380 GWh) of grid storage will be required by 2030. There are varied storage estimates across studies, with estimates from the PSP and BESS at different levels. The Optimal Generation Mix 2030, by the CEA, has the highest estimate of 19 GW (128 GWh) of PSP capacity coming online by 2030. This is because of the MoP's recent focus on supporting PSP deployment in India.[267] The CEA 2023 study estimates 42 GW (208 GWh) of BESS needs. The NREL 2021 study estimates the highest need for the BESS technology at 84 GW (304 GWh) by 2030 and estimates 6 GW (76 GWh) of PSP needs by 2030.[268]

The primary driver of grid storage needs is integrating increasing amounts of VRE, mainly solar and wind technologies, to meet rising electricity demand. A combined VRE (solar and wind) capacity of 92–450 GW is expected to come online by 2030. **Exhibit A1** summarises the grid storage needs and VRE projections by 2030 across these national studies.

Exhibit A1 National-level needs of grid storage and likely VRE capacity by 2030

Study Name	2030 Storage Needed (GW/GWh)	PSP (GW)	BESS (GW/GWh)	VRE GW (solar+ wind split)
CEA 2023	60 GW (336 GWh)	19 GW (128 GWh)	42 GW (208 GWh)	392 GW (292 S + 100 W)
LBNL 2021 — Least-Cost Case	63 GW (252 GWh)		63 GW (252 GWh)	449 GW (307 S + 152 W)
NREL 2021 — Reference Case	90 GW (380 GWh)	6 GW (76 GWh)	84 GW (304 GWh)	450 GW (250 S + 200 W)

RMI Graphic. **Source:** RMI Analysis

All these studies use state-of-the-art grid modelling called capacity expansion modelling (CEM). Given future electricity demand and other system constraints, CEM predicts the optimal generation and storage resource mix. For example, CEM considers the costs of new generation technologies, storage technology prices, technical specifications, and current and future transmission network topologies to determine optimal levels of new generation and storage investments. Although the basic modelling construct is similar across these studies, the system topology, transmission network, technology costs, and other input assumptions often vary, leading to different conclusions about the need for new grid storage.

Appendix B: Lithium-ion battery chemistries and component materials

Lithium-ion batteries include key components: anode, cathode, electrolyte, and separator. When determining the combination of suitable material and chemical structure for LiB, regulators, project developers, and manufacturers must consider a range of factors. The chosen chemistry should account for ageing, material degradation processes, safety concerns such as operating temperature, performance metrics (cycle life, DoD, and charge/discharge current rates), material accessibility and cost, extraction impacts, social costs, and energy security concerns. Lithium-ion batteries have been commercially available for well over a decade, with traditional chemistries including nickel-manganese-cobalt (NMC) and lithium iron phosphate (LFP). However, recent research is aimed at developing new high-capacity anodes, cathodes, electrolytes, and separators. This appendix will provide an overview of LiB chemistries, materials available for these components, and their relative performance considerations.

Lithium-ion chemistries

Referring to a suite of technologies, LiBs have emerged as the dominant market force due to their high energy density and rapidly decreasing costs. Though prices and specifics vary by chemistry (and some batteries use multiple types of lithium-ion cells in concert to balance different advantages and disadvantages), the general chemistry, design, and characteristics of popular types are covered in **Exhibit A2** on page 146.[269]

Exhibit A2 Commercial lithium-ion batteries

Cathode Metal Composition[270]	Pros	Cons	Applications	Major Developments
Lithium cobalt oxide (LCO)	• High energy density and moderate load capabilities • Acceptable cycle life	• High proportion of cobalt (increasingly cost-restrictive; issues in the supply chain and sustainable mining concerns) • Poor heat resistance and safety	Popular for consumer electronics (phones, laptops, and wearable products)	• DuPont has partnered with Steinerfilm and Polaris Battery Labs to use LCO cathodes to test innovations for other battery components, demonstrating 26% higher energy density.[271]
Lithium nickel cobalt aluminium oxide (NCA)	• High energy and power density • Good cycle lifetime	• Poor thermal energy management and safety issues • High cost per kWh	Popular in EV powertrains, including Tesla	• Panasonic announced plans to start mass production of 4680 NCA cells for Tesla, which are five times bigger but up to 10%–20% cheaper than their current NCA cells.[272]
Lithium manganese oxide (LMO)	• Excellent power discharge and maximum load • Fast charging capability • Good thermal stability and safety	• Low energy density • Low cycle life	Used in EV designs with a hybrid battery pack, in combination with NMC batteries, LMO's high-power discharge allows better acceleration performance	LMO batteries are used in a few EVs, such as the first generations of Nissan Leaf, because of its high reliability and relatively low cost.[273] But due to lower cell durability than competing technologies, uptake has been limited.
Lithium iron phosphate (LFP)	• Low cost • Thermally stable • Excellent cycle life, fast-charging capability • Uses easy-to-source minerals • Flat voltage discharge curve	• Lower energy density than NMC batteries	• Increasingly being considered as a replacement for NMC in low/mid-range EVs (including electric buses) with improvements in pack-level energy density • Common use in stationary applications for grid-scale storage	• Reliance New Energy Ltd. announced plans to acquire Lithium Werks BV, an expert in LFP cell and module manufacturing.[274] • Tesla announced a transition from NCA batteries to LFP for their standard range models in 2021; deployment for stationary applications is also expected in the future.[275] • CATL and BYD announced the cell-to-pack (CTP) design for LFP batteries in 2020, which allows energy density up to 140 Wh/kg.[276]
Lithium nickel manganese cobalt* (NMC) *NMC622	• High energy density • Increasingly being optimised to achieve lower cobalt proportions, thus mitigating supply chain concerns and lowering costs	• Reliance on cobalt • Poor thermal performance and safety	• Chemistry of choice currently for EVs	Industry players (LG Chem, Samsung SDI, etc.) expect to move to high energy density NMC-811 from currently popular NMC-532/611 as price premiums decline. GODI Energy India reported the first batch of domestically manufactured NMC-21700 cells in January 2022.[277]

Exhibit A2 Commercial lithium-ion batteries (continued)

Anode Metal Composition	Pros	Cons	Applications	Major Developments
Lithium titanate oxide (LTO)[278]	- Extremely long cycle life (~ 7,000) - Excellent thermal management and safety - Fast charge/ discharge capabilities	- Low energy density - Higher costs	- Used in stationary grid storage - Used in specific applications, such as medical devices	Leclanché, one of the world's leading energy storage solutions companies, has deployed 100 MWh of stationary storage projects with LTO batteries around the world.[279]

RMI Graphic. **Source:** RMI Analysis

LiBs are witnessing rapid growth in this decade, spurred by the global transition in the mobility and power sector. As adoption of LiBs goes mainstream, many startups and established battery manufacturers are developing advanced LiBs with improved performance and lower costs. These advanced LiBs have identified new manufacturing processes, cell design factors, and new battery components to enhance the performance and efficiency of legacy LiBs. Advanced LiBs will play a key role in accelerating further uptake of LiBs globally. Leading advanced battery technologies are covered in **Exhibit A3** on page 148.

Exhibit A3 Advanced lithium-ion batteries

Cell Schematic	Pros	Cons	Applications	Major Developments
Lithium sulphur	• Higher specific energy and power discharge compared to conventional LiBs • High tolerance for extreme temperatures • Uses low-cost and easily disposable input material	• Low cycle life and longevity	• Truck and bus electrification	• Industry expects LiS technology evolution for specialist, high-performance applications. • Research groups at Monash University and the University of Michigan have reported advancements at laboratory scale in membrane/interlayer materials that can allow higher cycle life.[280]
Solid state	• High thermal and impact safety since the liquid electrolyte is replaced by a solid • Reduced dendrite growth issues extend service lifetime • High specific energy and low cost	• Cycle life is highly dependent on the specific anode-cathode mix (currently less than 1,000 cycles) • Not commercially viable currently; expected to reach mass market in 3–5 years	• Long-range EVs	• Samsung SDI announced the construction of a solid-state pilot line in South Korea; Nissan has plans to mass-produce proprietary solid-state batteries by 2028 at US$75/kWh pack targets.[281,] • Solid Power is already producing 20 Ah solid-state batteries in low-volume batches.[282] • Volkswagen is possibly planning for EVs with solid-state batteries as soon as 2025, using QuantumScape's technology.[283]
Lithium air	• Very high theoretical energy density • Uses abundant, low-cost materials for electrodes, offering a lower bill of materials	• Technology still in R&D stage, currently limited by low efficiency and poor cycle life	• Residential storage, EVs	• Technology still in R&D phase (advanced materials research).

Exhibit A3 Advanced lithium-ion batteries (continued)

Cell Schematic	Pros	Cons	Applications	Major Developments
Lithium carbon	• Combines the benefits of traditional LiBs with capacitors – good energy/power density and fast recharging • Promises low carbon footprint • Low cost, relatively abundant materials • Not susceptible to thermal runaway; does not need external cooling system	• Technology is in a very early stage, with a limited number of makers	• EVs (especially 2/3-wheelers) where fast charging can add value	• Allotrope Energy announced this technology for long-range and fast charging use in the last-mile delivery segment (electric two-wheelers) in partnership with Mahle Powertrain.[284]
Semi-solid	• Design eliminates the need for binder material, making the cell cheaper and lightweight • Storage capacity not limited by battery size (as in flow batteries) • Promises safer performance than incumbent battery technologies	• Technology not expected to be commercialised before 2025 • Currently faces issues with electrode separators, R&D in solid electrolyte material with sufficient electrical conductivity	• Can be tailored for specific applications (e.g. stationary storage, EVs)	• 24M announced the advanced semi-solid manufacturing process in 2015 and, since then, has struck strategic partnerships with Kyocera (residential storage solutions), Volkswagen, as well as Lucas TVS to set up production capacity in India.[285]

RMI Graphic. **Source:** RMI Analysis

Anode materials

The anode is the negative electrode for the LiB. Early lithium-metal or lithium-alloy anodes suffered from capacity loss due to reactions between the anode and the solvent electrolyte and dendritic growth that could penetrate the separator. Dendritic growth would create an electrically conductive pathway, leading to a short circuit and triggering a thermal runaway, potentially causing the battery to catch fire. Subsequent research focused on replacing lithium-metal anodes with alternative lithium-intercalation compounds to enhance cell cycle life and safety. **Exhibit A4** presents a selection of anode materials.[286]

Exhibit A4 A selection of anode materials developed for LiB

Material	Description	Theoretical capacity (mAh g^{-1})	Assessment
Carbonaceous			
Hard carbons	Composed of small, disordered graphitic rains with nano to micro-scale voids between them, which result in small isotropic volume expansions and permit the accommodation of Li+ ions.	200–600	Good working potentials, less columbic efficiency. Li+ ions are accommodated in the inter-layers of the grains and can supplant intercalation and deintercalation of Li+ ions in electrode materials during charging. Less-graphitised carbon materials have higher life cycles due to the many lattice defects pinning the graphite grains and layers together, making it tougher for less-graphitised carbon materials to be exfoliated. The pinning and exposure of large numbers of edge planes increase the density of the electrically resistive solid–electrolyte interphase (SEI), reduce ionic conductivity, and ultimately impair performance.
Carbon nanotubes (CNTs)	Composed of graphene sheets rolled into cylindrical tubes with diameters typically around a few nanometres and lengths of several micrometres.	1,115	Relatively low cost, high voltage hysteresis. High electrical and thermal conductivities, superior mechanical properties, and desirable chemical properties make them attractive materials for energy conversion and storage applications. Studies indicate CNTs have good lithium absorption rates, ion diffusion rates, and intercalation/de-intercalation rates, but properties are dependent on morphology and structure.
Graphene	A carbonaceous material consisting of a honeycomb framework of sp^2 carbon atoms arranged and bonded into a two-dimensional sheet with a single-atom thickness.	780–1,115	Safe to operate and high capacity. Properties like large surface area, superior mechanical strength, high electrical conductivity, good charge mobility, and ionic transport make graphene a good anode material. It has good chemical stability and mechanical strength, combined with flexibility that allows for use in a variety of forms for various applications.
Graphene nano-flakes		165	Good charging for 80 cycles.
Graphene-like graphite	The morphology and crystal structure of graphene-like graphite are quite similar to those of graphite.	673	Good stable discharge capacity.

Exhibit A4 A selection of anode materials developed for LiB (continued)

Material	Description	Theoretical capacity (mAh g^{-1})	Assessment
Titanium oxides			
LiTi4O5		176	Low cost and safe, but low capacity
TiO2		320	High power capacity, low energy density, and good service life cycle
Alloy/de-alloy			
Germanium	Alloy material with high lithium capacity and high electronic conductivity, greater than silicon.	1,623	High energy density, but large fading, and low life cycle. Hampered by higher cost and large volumetric changes during lithium insertion and de-insertion. However, nanometer-scale structures could handle volumetric changes more easily than bulk structures.
Silicon oxide		1,562	High capacity and density, safe, but suffers from fading
SiO_2/CNT/ graphene		260–723	Good initial discharge, but drops
Tin (Sn)		992	Good charging, but suffers from fading
SnO_2		510	Good charging for 50 cycles
Metal Oxides			
CoO, $Co3O_4$, CuO, Cu_2O, $CR2O_3$, $Fe2O_3$, $Fe3O_4$, MoO_2, MoO_3, NiO, RuO_2, etc.		500–1,200	High capacity, energy, low cost, and eco-friendly; poor cycle life, unstable SEI formation, poor columbic efficiency, and increased hysteresis issues

RMI Graphic. **Source**: Triana Wulandari, et al., "Lithium-based batteries, history, current status, challenges, and future perspectives," *Battery Energy,* Vol. 2, Issue 6, November 2023, **https://onlinelibrary.wiley.com/doi/10.1002/bte2.20230030?msockid=3b9c5269bcfc61a52c764416bddd60ac**.

Cathode materials

Exhibit A5 Available cathode materials for LiBs

Material Structure	Theoretical Capacity (mAh g^{-1})	Comments
Layered		
$LiCoO_2$	274	High operating voltage (~4 V) but suffers from fading at high temperatures and voltages.
$LiNiO_2$	275	High operating voltage (~3.8 V), less expensive than Co, has higher reversible capacity and higher electrical conductivity compared to LCO.
$LiMnO_2$	285	Cooperating voltage (~3.3 V), Mn is less toxic and cheaper than both Co and Ni, but its capacity rapidly fades with cycling, and its layered structures change to manganese spinel.
$LiNi_{0.33}Mn_{0.33}Co_{0.33}$ **$LiNi_{0.7}Co_{0.3}O_2$** **$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$** **$Li(Ni_{1-x-y}Co_xMn_y)O_2$**	~280	Composites doped with Ni, Mn, or Al with surface coatings have improved thermal stability, performance and life cycles.
Spinel		
$LiMn_2O_4$	148	Low cost, reversibility, high lithium-ion and electrical conductivity, and eco-friendly nature of Mn suffer from capacity fading.
$LiMn_2O_4$ + dopants	~142	Doping with Al, Co, and Cr improved cycle capacity retention.
$LiAl_xMn_{2-x}O_4$		
Olivine		
$LiFePO_4$	170	Good stability performance, but suffers from low electrical conductivity, low ionic conductivity, and low energy density.
$LiCoPO_4$	167	Lower electrical conductivity than $LiFEPO_4$, but nanocomposites have displayed high-rate capabilities and improved performance compared to $LiFEPO_4$.

RMI Graphic. **Source**: Triana Wulandari, et al., "Lithium-based batteries, history, current status, challenges, and future perspectives," *Battery Energy*, Vol. 2, Issue 6, November 2023, **https://onlinelibrary.wiley.com/doi/10.1002/bte2.20230030?msockid=3b9c5269bcfc61a52c764416bddd60ac**.

Appendix C: Battery value-stack modelling methodology

Ancillary services modelling details

RMI has prepared models to determine the value of services provided by a theoretical battery project to evaluate how these services can be stacked. Modelling assumptions for ancillary services offered in India are listed in **Exhibit A6** on page 153.[287]

Exhibit A6 Ancillary services modelling assumptions

Framework	Value stream	Details	Assumptions	
Value stack — currently monetisable (accounted in showing viability gap)	Tertiary Reserve Ancillary Service (TRAS)	We assumed the remaining battery capacity after daily arbitrage is available for TRAS. There is a lack of price transparency and of data on the frequency of TRAS deployment. The NRPC has published price data for the day-ahead, real-time, and emergency TRAS markets for a three-week period in August/September 2023 (weeks 19, 20, and 21). There was no publicly available data on dispatch frequency, but we learned from discussions with stakeholders that TRAS is required daily during peak seasons. The battery is conservatively assumed to have sufficient charge for dispatch for 60% of available hours each day. 3.5% escalation rate assumed.	**Reference Scenario** **For 67% of the year:** Average emergency compensation margin (TRAS up minus TRAS down): ₹3.2/kWh. Average day ahead and real-time commitment charge: ₹0.2/kWh. Batteries have been dispatched to TRAS every day, as the need for TRAS for emergencies at lower margins is evident in all weekly reports.	**High Revenue Scenario** **For 25% of the year:** Average day-ahead compensation margin (day-ahead TRAS up minus average energy DAM price): ₹11.7/kWh. Day-ahead TRAS at higher margins is needed during peak seasons. **For 42% of the year:** Average emergency compensation margin from Reference scenario: ₹3.2/kWh Average day ahead and real-time commitment charge of ₹0. 2/kWh.
Value stack — that could be monetisable by 2025 with clarity on prices and rules (not included in viability gap analysis)	SRAS	Lack of price transparency, and how a storage asset could get committed. Storage use for SRAS is supporting early adoption in other international markets (UK and California), where batteries used for SRAS do not also participate in arbitrage due to the frequency of dispatch for SRAS. Price data averaged from NRPC and ERPC weekly reports.	Compensation charge of ₹3/kWh, Performance incentive of ₹0.7/kWh; Assuming the battery is used entirely for SRAS as a stand-alone value stream, revenues account for 50% of the battery cost.	

RMI Graphic. **Source**: RMI Analysis

Stand-alone SRAS

We assume that batteries used for SRAS do not participate in arbitrage, owing to the frequency of dispatch for SRAS — a pattern consistent with other markets. SRAS providers receive compensation for up-regulation and incur a drawl or charging cost for down-regulation. SRAS providers also receive a performance incentive for responding on time to SRAS control signals, which varies based on the provider's performance.[288] Public data on system requirements (prices and times when service is generally required) for SRAS up and down services was not available, so we conservatively estimated that the battery would have sufficient charge levels to provide SRAS up or down services in 60% of hours and would provide equal amounts of both services.

Arbitrage and TRAS

Generally, only TRAS up (injecting supply) is seen in day-ahead and real-time markets, where the supplier is compensated for providing this service. However, there are emergencies where TRAS down (drawl) is needed, and the participant is charged for drawing energy. We assume the remaining battery capacity after participation in arbitrage is available for TRAS. Providers receive a compensation charge for providing TRAS up reserves, and a commitment charge for being available to provide reserves.[289] Again, we conservatively assume that the battery would have sufficient charge to provide TRAS in 60% of available hours, due to a lack of data on the times of day when the service would likely be needed.

Resource adequacy and transmission and distribution deferral

Avoided generation capacity/RA value

If state regulators adopt the MoP's Guidelines for Resource Adequacy Planning Framework for India, and the Forum of Regulators' model RA regulations by 2030,[290] Delhi utilities will be responsible for meeting planned reserve margin requirements and procuring for capacity obligations, either through building new generating resources or securing bilateral contracts. Given that the modelling for this report shows relatively high reliance on market purchases for energy in 2030, the generation capacity value was estimated using avoided bilateral contracts. To estimate the value of generation capacity per kW-year for each grid flexibility measure, we need three parameters: the price of capacity per bilateral contract, the grid flexibility measure's capacity accreditation, and the transmission and distribution losses avoided by securing capacity from demand-side resources rather than traditional generators. To estimate the price of capacity, we use a net cost of new entry (CONE) methodology.[291] We calculate the net CONE as the capital cost and fixed O&M cost for a resource built in 2030, minus its net revenues in the energy market, as simulated in our production cost model. We compared net CONE values for open-cycle and combined-cycle gas turbines and found the combined-cycle gas turbine to have a lower net CONE, and therefore to be the expected marginal capacity resource. The net CONE of the combined cycle is ₹2,793/kW-year.

Exhibit A7 Net CONE estimation for open-cycle gas turbine (OCGT) and combined-cycle gas turbine (CCGT)

	OGCT	CCGT
Capital cost (₹/kW)	50,000	34,700
Capital cost (₹/kW-year)	5,508	3,823
Fixed O&M (₹/kW-year)	1,800	2,900
Gross CONE (₹/kW-year)	7,308	6,723
Net energy revenues (₹/kW-year)	2,335	3,930
Net CONE (₹/kW-year)	4,973	2,793

RMI Graphic. **Source**: Capital cost and fixed O&M per the *CEA First Indian Technology Catalogue.*[292] Authors levelised to an annual cost using the CEA assumed lifetime of 25 years and a 10% WACC. Net energy revenues are estimated by RMI.

Capacity accreditation per resource is tabulated below. Four-hour batteries are given full capacity credit, in accordance with the methodology utilised in California.[293] Since AC DR and e-bus load reductions are fixed, capacity credits are calculated based on the coincidence of demand reduction with the top 20 net peak load hours of the year. This methodology is widely accepted as a high-quality approximation for more complex probabilistic accreditation analyses, such as effective load-carrying capacity.[294] VPP credits are calculated based on the sum of capacity credits across measures.

Transmission and distribution losses are assumed to be 8%, based on the most recent aggregate technical and commercial losses reported for Delhi utilities in PFC India's *Report on Performance of Power Utilities 2021–2022.*[295]

Exhibit A8 Capacity accreditation by resource

Resource	Capacity Credit
4-hour storage	100%
AC DR — low	29%
AC DR — mid	40%
AC DR — high	35%
e-Bus	12%
VPP — mid	72%
VPP — high	78%

RMI Graphic. **Source**: RMI Analysis

Distribution deferral value

We calculate the distribution deferral value by estimating each resource's contribution to avoid distribution circuit investments, such as transformer upgrades. We assume going forward distribution investments of ₹500 per kW-year, based on the midpoint of costs estimated in Energy, Environment, and Economics Inc. (E3)'s *Regulatory and Business Case for Distributed Energy Resources in India.*[296] We assume that batteries can be dispatched to reduce the distribution-coincident peak (i.e., fully, they earn 100% capacity credit for distribution deferral). To calculate the contribution of AC DR programmes to distribution deferral, we count the ability of AC DR to reduce total annual system peak demand. Implicitly, we are making the simplifying assumption that Delhi system-wide peak demand and distribution-circuit level peak demand are coincident. In the low-participation casepeak demand is not reduced; in the mid-participation case, it is reduced by 553 MW; and in the high-participation case, by 944 MW. These correspond to capacity credits of 0%, 87%, and 70%, respectively. We assume that the e-bus managed charging programme provides no distribution deferral value, owing to the costs of upgrading the distribution system to accommodate bus depots.

The value assumptions used for this report were initially developed for RMI's report *Transforming Delhi's Power Grid: A Comprehensive Guide to Enhancing Flexibility,* published in July 2024.[297] These assumptions and values have been adopted to create a value stack projection for this report.

Appendix D: FDRE modelling methodology

The modelling methodology for FDRE involves formulating and solving an investment cost minimisation problem by taking a developer-centric approach. The mathematical formulation is given in **Exhibit A9**.

Exhibit A9 FDRE mathematical formulation

Sets and indices:		
$t \in \mathscr{T}$	Hours, $t \in \{1,2,3, \ldots, 8760\}$	
Parameters:		
$\bar{p}t$	Solar capacity factor at time *t*	[-]
$\bar{w}t$	Wind capacity factor at time *t*	[-]
d_t	Electricity demand at time *t*	[MW]
cp	Cost of installing a PV plant	[₹/MW]
cw	Cost of installing a wind plant	[₹/MW]
cs	Power cost of BESS	[₹/MW]
ce	Energy cost of BESS	[₹/MWh]
M	Penalty for curtailment	[₹/MW]
Variables:		
P^{max}	Installed solar capacity	[MW]
w^{max}	Installed wind capacity	[MW]
S^{max}	Installed storage power capacity	[MW]
SE^{max}	Installed storage energy capacity	[MWh]
E_t	Energy stored in storage at time *t*	[MWh]
PD_t	Discharging power for storage at time *t*	[MW]
PC_t	Charging power for storage at time *t*	[MW]
C_t	Generation curtailed at time *t*	[MW]
X^c_t	Binary: 1 if BESS charging at time *t*, 0 otherwise	

Objective function:		
Minimise	$cp \cdot P^{max} + cw \cdot W^{max} + cs \cdot S^{max} + ce \cdot SE^{max} + M \sum C_t$	
Subject to:		
Supply-demand balance	$P^{max} \cdot \bar{p}t + W^{max} \cdot \bar{w}t + PD_t = d_t + PC_t + C_t$	$t \in \mathscr{T}$
Charging limit	$0 \leq PC_t \leq S^{max} \cdot Xtc$	$t \in \mathscr{T}$
Discharging limit	$0 \leq PD_t \leq S^{max} \cdot (1 - Xtc)$	$t \in \mathscr{T}$
State of charge tracking	$E_t = E_{t-1} + PC_t - PD_t$	$t \in \{2,3, ...,8760\}$
State of charge limit	$0 \leq E_t \leq SE^{max}$	$t \in \mathscr{T}$
Initial state of charge	$E_1 = 0$	

The objective function minimises total investment cost and penalises curtailment to avoid overbuilding capacity. The demand-supply balance constraint ensures that the addition of RE generation and BESS dispatch equals the addition of electricity demand, BESS charging load, and curtailment (if present) for all time periods. Constraints on charging, discharging, and SoC limits provide an operating envelope for BESS. A binary variable ensures that BESS is not simultaneously charging and discharging at any time. SoC tracking estimates the amount of energy stored in the BESS, based on its SoC from the previous time period, charging, and discharging. The above constraints are solved for each hour of the year. Note that the model makes simplifying assumptions, such as perfect foresight (i.e., RE capacity factors are assumed to be known for the entire year at hourly resolution). The model neglects BESS's charging and discharging efficiency and variable operations and maintenance costs for operating RE generators and BESS. The price of electricity is estimated based on the following expression,

$$\text{Price} = \frac{\sum i \in tech \; ci}{n \cdot \sum t \; dt}$$

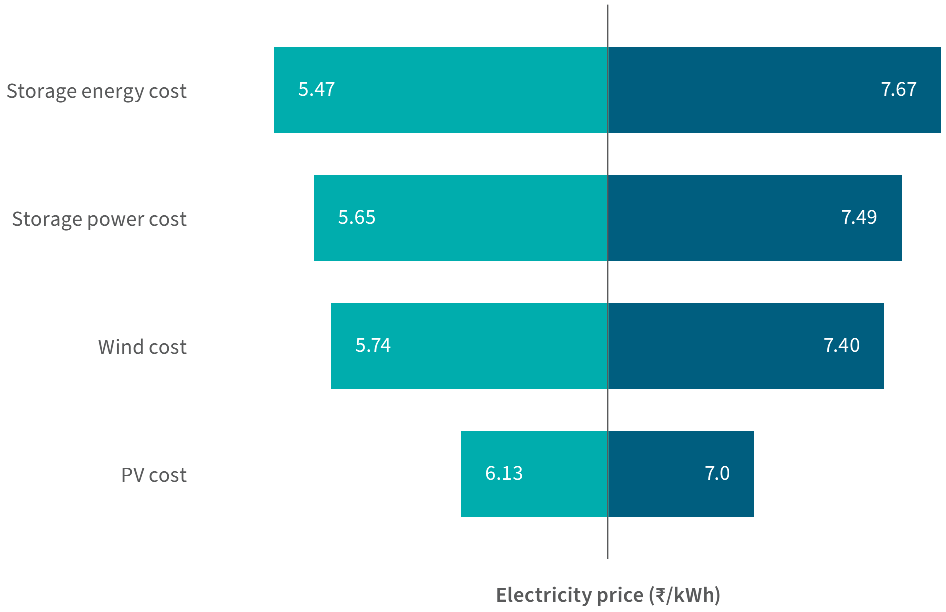
where, 'c_i', 'n', 'd_t', represents the installation cost of technology in Indian rupees (₹), lifetime of technology in years, and electricity demand in MW at time t, respectively. Values of parameters used in the analysis are tabulated in **Exhibit A10** on page 159.

Exhibit A10 Values and parameters in FDRE analysis

Solar installation cost (₹ crore/MW)	4.5
Wind installation cost (₹ crore/MW)	6.0
BESS energy cost (₹ crore/MWh)	2.4
BESS power cost (₹ crore/MW)	8.0
Lifetime (years)	25

The sensitivity analysis for Gujarat Peak Guarantee FDRE (see **Exhibit A11**) shows that the electricity price is most sensitive to the BESS energy cost. Sensitivity analysis is conducted by varying one parameter at a time by 50% and observing its effect on the electricity price. For example, the Gujarat FDRE electricity price is ₹7.67/kWh when the BESS energy cost is ₹3.6 crore/MWh. The cost of solar installation has the least impact on electricity prices. This indicates that the storage energy and power costs need to be reduced to reduce electricity prices.

Exhibit A11 Tornado chart for Gujarat FDRE with BESS



RMI Graphic. **Source**: RMI Analysis

Appendix E: Solar + storage cost methodology

We estimate delivered energy costs for co-located (this is how you have written it earlier in the report) solar + storage facilities using data on stand-alone solar and storage costs and assumptions about cost savings from co-location. The table below shows estimated delivered energy costs for four configurations: 100 MW PV; 100 MW PV + 10 MW/20 MWh BESS; 100 MW PV + 25 MW/50 MWh BESS; and 100 MW PV + 50 MW/100 MWh BESS. We assume that inverter, transformer, and grid connection costs are fully shared between the solar and storage components of the project. Since the solar component is always larger in MW than the storage component, adding incremental storage is assumed not to incur additional inverter, transformer, or grid connection costs beyond those already borne by the solar component. So, for example, the inverter costs for 100 MW PV and 50 MW BESS are equivalent to the inverter costs of 100 MW PV.

Exhibit A12 Cost breakdown for co-located solar and storage

		100 MW PV	100 MW PV + 10 MW/20 MWh BESS	100 MW PV + 25 MW/50 MWh BESS	100 MW PV + 50 MW/100 MWh BESS
Solar cost (crore/year)	[1]	61.5	61.5	61.5	61.5
BESS cost (crore/year)	[2]	0	4.5	11.2	22.3
Cost savings from co-location (crore/year)	[3]	0	1.5	3.6	7.3
Hybrid system costs (crore/year)	[4] = [1] + [2] – [3]	61.5	64.5	69.0	76.6
Hybrid system annual net generation (GWh/year)	[5]	201.1	199.2	196.5	192.0
Cost of delivered energy (₹/kWh)	[6] = ([4] * crore)/([5] * kWh per GWh)	3.1	3.2	3.5	4.0

Notes: Solar costs are estimated using the ₹3.06/kWh price discovered in SECI's 2024 600 MW allocation and an assumed capacity factor of 23%.[298] BESS costs are estimated based on the ₹3.72 lakh/month price determined in GUVNL's 2024 Phase III tender.[299] Savings from co-location are calculated assuming that the per-MW inverter, transformer, and grid connection costs are the same for solar and storage. Per-MW inverter and transformer and grid connection costs are estimated using data from CEA's Indian Technology Catalogue,[300] which shows that inverter costs make up 15% of capital costs for solar, and transformer and grid connection costs account for 10% of capital costs for solar. Of the total solar costs, 95% are capital costs and 5% are FOM. Hybrid system net generation values are estimated from RMI analysis of cost-optimal dispatch, assuming a 23% capacity factor for solar and 86% RTE for battery storage.

RMI Graphic. **Source**: RMI Analysis; "SECI Allocates 600 MW Solar in India at ₹0.036/kWh," *pv magazine,* December 25, 2024, **https://www.pv-magazine.com/2024/12/25/seci-allocates-600-mw-solar-in-india-at-0-036-kwh/**; "Gensol Wins Phase III of GUVNL's 250 MW/500 MWh Standalone BESS Tender," *ETN News,* June 12, 2024, **https://etn.news/energy-storage/gensol-wins-battery-energy-storage-bidding-gujarat-urja-vikas-nigam**; *Indian Technology Catalogue: Generation and Storage of Electricity,* Central Electricity Authority (CEA); Danish Energy Agency (DEA); and COWI, 2022, **https://cea.nic.in/wp-content/uploads/irp/2022/02/First_Indian_Technology_Catalogue_Generation_and_Storage_of_Electricity-2.pdf**.

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