Indo-German Energy Forum

Gap Analysis for Deployment of Grid-Scale Storage Technologies in India

Study by:

Customized Energy Solutions
Analyze · Simplify · Implement

IESA
India Energy Storage Alliance

On behalf of:

नवीन एवं नवीकरणीय ऊर्जा मंत्रालय
MINISTRY OF NEW AND RENEWABLE ENERGY
सत्यमेव जयते

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Imprint

Commissioned on behalf of
Ministry of New and Renewable Energy (MNRE), Govt. of India
Ministry for Economic Affairs and Energy (BMWE), Govt. of Germany

Commissioned by
Indo-German Energy Forum Support Office (IGEF-SO)
c/o Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
1st Floor, B-5/2 Safdarjung Enclave
110029 New Delhi, India
Email: info@energyforum.in
Website: www.energyforum.in
Tel.: +91 11 4949 5353

Study by
Customized Energy Solutions (CES)
Website: www.ces-ltd.in
Email: indiainfo@ces-ltd.com
Tel: +91 020 27714000

India Energy Storage Alliance (IESA)
Customized Energy Solutions Pvt. Ltd.
A-501, G-O Square, Aundh-Hinjewadi Link Road
Wakad, Pune 411057, India
Website: www.indiaesa.info
Email: contact@indiaesa.info
Tel: +91 96997 19818

Authors
Bhupesh Verma (CES)
Debi Prasad Dash (CES)
Bhushan Khade (CES)
Bindu Madhavi (CES)
Vijay Bokade (CES)

Advisors/Reviewers
Kumar Abhishek (IGEF-SO)
Fynn Mertner (IGEF-SO)
Moritz Schmidt (IGEF-SO)
Siegrun Gansch (IGEF-SO)
Madhuri Negi (IGEF-SO)

Version: April 2024
Design and Layout: Indo-German Energy Forum Support Office (IGEF-SO)

Table of Contents

List of Figures

List of Tables

Abbreviations

ACC	Advanced Chemistry Cell
BEMS	Battery Energy Management Systems
BESS	Battery Energy Storage Systems
BHEL	Bharat Heavy Electricals Limited
BNEF	Bloomberg New Energy Finance
BRPL	BSES Rajdhani Power Limited
CEA	Central Electricity Authority
CES	Customized Energy Solutions
CERC	Central Electricity Regulatory Commission
C&I	Commercial and Industrial
DISCOM	Distribution Companies
DoD	Depth of Ddischarge
EMS	Energy Management System
EPC	Engineering Procurement and Construction
ESS	Energy Storage Systems
ESO	Energy Storage Obligations
EV	Electric Vehicles
FAME	Faster Adoption and Manufacturing of Hybrid and Electric Vehicles
GoI	Government of India
GSI	Geological Survey of India
GST	Goods and Services Tax
GTG	Greening the Grid
GUVNL	Gujarat Urja Vikas Nigam Ltd
IESA	India Energy Storage Alliance
IEGC	Indian Electricity Grid Code
KREDL	Karnataka Renewable Energy Development Limited
LAB	Lead Acid Batteries
LCO	Lithium Cobalt Oxide
LTO	Lithium Titanate Oxide
LCOE	Levelized Cost of Energy

LCO	Lithium Cobalt Oxide
LCOS	Levelized Cost of Storage
LDES	Long Duration Energy Storage
LFP	Lithium Ferro (Iron) Phosphate
LIB	Lithium-ion Battery
LiS	Lithium Sulfur
LMO	Lithium Manganese Oxide
LNMO	Lithium Nickel Manganese Oxide
LiOH	Lithium Hydroxide
MNRE	Ministry of New and Renewable Energy
MSEDCL	Maharashtra State Electricity Distribution Company Limited
MW	Mega Watt
NaS	Sodium Sulphur
NCA	Nickel Cobalt Aluminium
NESM	National Energy Storage Mission
NLDC	National Load Despatch Center
NMC	Nickel Manganese Cobalt
NPACC	National Programme on Advanced Chemistry Cell
NTPC	National Thermal Power Corporation
OPEX	Operational Expenditure
O&M	Operations and Maintenance
PCKL	Power Company of Karnataka
PGCIL	Powergrid Corporation of India Limited
PLI	Production Linked Incentive
PNNL	Pacific Northwest National Laboratory
POSOCO	Power System Operation Corporation Limited
PPA	Power Purchase Agreement
PRAS	Primary Reserve Ancillary Service
PSP	Pumped Storage Projects
RE	Renewable Energy
RPO	Renewable Purchase Obligations
RTC	Round-the-Clock

RTE	Round Trip Efficiency
R&D	Research & Development
SCADA	Supervisory Control and Data Acquisition
SECI	Solar Energy Corporation of India Limited
SERC	State Electricity Regulatory Commissions
SRAS	Secondary Reserve Ancillary Service
SERL	Sustainable Environergy Research Lab
SOC	State of Charge
TRL	Technology Readiness Level
UAV	Unmanned Air Vehicles
USAID	United States Agency for International Development
VGF	Viability Gap Funding
VRE	Variable Renewable Energy
VRFB	Vanadium Redox Flow Batteries

Key Findings

- There is a significant potential for BESS deployment in India. An analysis by the IESA estimates that the projected cumulative energy storage installation in the country is expected to be 110GWh by the year 2030 under the best-case scenario. The key drivers for BESS deployment are performance improvements, cost-effectiveness, grid modernization, ancillary services, policy, and regulatory support.

- Among the existing BES technologies, Lithium-ion chemistry is more prevalent as it offers better performance characteristics regarding energy and power density, cycle life, safety, etc. Technologies like flow batteries, sodium-based batteries, and zinc-based batteries are also emerging as they can be sized according to the requirements, have lesser performance degradation, and are economically viable.

- In the last ten years, battery storage technology prices have been reduced by ~90%, with a significant reduction in LiBs. These batteries are expected to decline further in the coming years. A battery cost comprises the significant cost share in a BESS; hence, reducing battery prices will significantly impact BESS costs and the overall levelized cost of storage (LCOS). Based on the estimations by BNEF, the LCOS for large-scale batteries with four-hour storage capacity in India is approximately 184 $/MWh for the year 2023, whereas considering the technological advancement in the battery energy storage technologies, the projected LCOE for the year 2030 is approximately 99 $/MWh.

- The country has seen significant growth in the tenders released by various central and state agencies, such as SECI, NTPC, MSEDCL, KREDL, GUVNL, etc., for storage integration in renewable projects. The storage capacity requirement for these tenders varies from 5 MWh to 2 GWh with a requirement of a 2-hours to 6-hour duration of the energy storage systems. The need for projects above 4-hour duration is expected to increase post-2026, with larger penetration of renewables on the grid. Also, up to 4-hour duration tenders are won by BESS technology while above 4 to 8-hour duration are presently being allotted to pumped hydro projects.

- There has been a significant push for the large-scale deployment of BESS in grid applications; however, several challenges must be addressed at the deployment and manufacturing level, such as higher costs (capital and operating), reliability, environmental issues, degradation, etc. Some of the key deterrents in the large-scale deployment of BESS are discussed below. The prevalent LIB technology poses several challenges in terms of manufacturing, supply chain, technology policy, etc, in the country. Addressing these challenges will facilitate the large-scale deployment of advanced chemistry battery technologies in the country.

1 Introduction

India has pledged ambitious commitments to reach 500 GW of non-fossil fuel-based energy capacity by 2030 and boost the share of renewables in installed capacity generation to 50%. Wind and solar energy are already among the most affordable renewable energy sources. However, integrating substantial amounts of renewable energy while ensuring grid stability is extremely difficult because of their inherently variable, unpredictable, and intermittent character. Flexible Energy Generation is the key to meeting India's constantly changing energy needs to engage in assets with the capacity to offer Base Load and Peak Power both economically and efficiently. The intermittent nature of Wind and Solar energy poses challenges to operators in managing the grid balancing and stability with the increased variability of renewable energy.

Grid-scale storage technology will be vital in achieving India's net zero emission targets. It plays a significant role in integrating renewable energy (RE), storing excess energy, balancing and grid stability, reliability, ancillary services, providing flexibility of power systems, etc. Among the existing storage technologies (pumped hydro, thermal storage, compressed storage, etc.), battery energy storage (BES) is preferred due to advantages like compactness, rapid response, smaller gestation period, flexibility in installation, etc. Lithium-ion chemistry is more prevalent within the BES technologies as it offers better performance characteristics regarding energy and power density, cycle life, safety, etc. Technologies like flow batteries, sodium-based batteries, and zinc-based batteries are also emerging as they can be sized according to the requirements, have lesser performance degradation, and are economically viable.

As per the IESA estimates, the country would require around 110 GWh of energy storage to fulfil the primary requirement of RE integration and grid applications by 2030. To meet these targets, and facilitate a large-scale BESS deployment in the country, it is important to examine the critical bottlenecks in manufacturing and deployment of BESS and recommend solutions to address these gaps/bottlenecks. This study examines the existing BEBS technologies, deployment status, and challenges (w.r.t supply chain, manufacturing, technology, deployment, policy, regulations, investment landscape, etc.). This study also covers new battery technologies with respect to their technology readiness and identifies suitable suggestions and recommendations considering its potential and deployment in the Indian market.

There are detailed sections in the report that describe:

- Potential of BESS technology in grid applications.
- Classification of existing BESS technologies and overview of their performance characteristics.
- Existing costs (capital and operations) and future cost projection trends in BESS deployment.
- Status of energy storage tenders in the country with specific details.
- Challenges in the existing manufacturing and deployment ecosystem for BESS.
- Existing policy and regulatory scenario for BESS deployment.
- Recommendations and the way forward.

2 Status of Existing Battery Storage Technologies Deployed Globally and in India

With advancements in technology in terms of performance and safety improvement in lithium-ion technology, as well as rapid cost reductions, there has been a surge in the adoption of stationary energy storage and electric vehicles. This adoption of lithium-ion batteries (LiBs) was important for the initial transition to a clean energy system, putting the electricity and transportation sectors on a path to full decarbonization. Given the development of lithium-ion technologies, it has become a huge market opportunity for batteries to serve a variety of new end uses that were previously technically or commercially not feasible. The key drivers for greater adoption and deployment of energy storage systems in India are mentioned below in Figure 1.

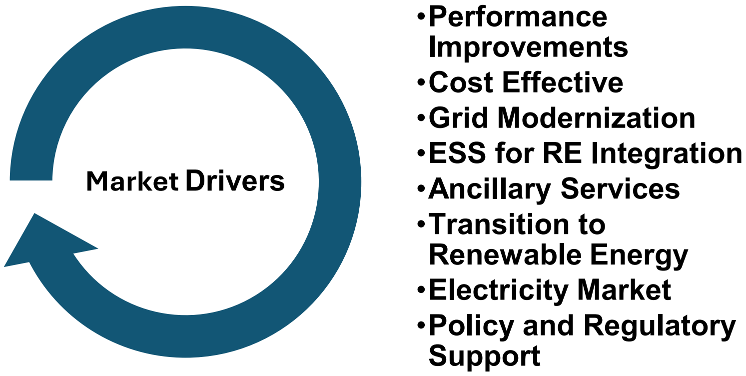

Figure 1: Market drivers for deployment of energy storage systems

Different battery technologies may appeal to various use cases, such as long-duration storage (essential for a 100% renewable energy system), ground and maritime transportation, commercial and industrial applications, and commercial and cargo aviation. Despite showing signs of considerable promise, some of these developing technologies face substantial challenges before reaching the technological readiness levels or manufacturing scale required to emerge as viable alternatives to existing lithium-ion technology.

Lithium-ion batteries (Lithium Iron Phosphate (LFP), Nickel Cobalt Manganese (NMC), Lithium Cobalt Oxide (LCO), etc.) have emerged as a key battery technology for major battery applications. These batteries have a longer cycle life than regular lead-acid batteries, but the fundamental reason for their widespread use is their high energy density.

Along with lithium-ion batteries, additional battery technologies such as metal-air, solid-state, and lithium-sulfur batteries have advanced in technology, but these are still being researched. This was partly due to a hundredfold increase in manufacturing during the same time. Battery cell and pack performance are critical factors that equipment manufacturers consider when developing their supply chains. Battery cell and pack manufacturing in India must meet minimal application-specific performance parameters specified by domestic and export customers. Long-term competitiveness with global manufacturers requires that Indian manufacturers produce cells and packs that are competitive to those of existing global suppliers and continue to do so. The performance indicators for the cells and packs will depend on the application and set by the worldwide market. Various battery technologies and their commercial and R&D stages are mentioned in Figure 2.

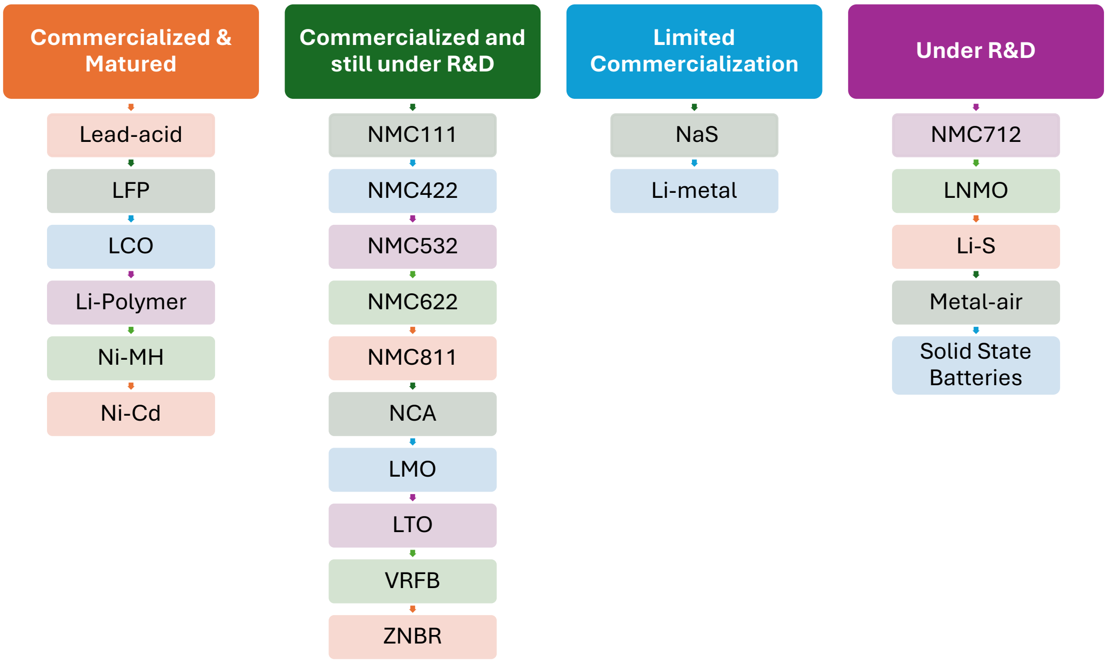

Figure 2: Stages of key battery technology and its status

2.1 Comparison of Common Cell Chemistries

Electrochemical energy storage has significantly evolved in terms of performance characteristics (energy density, power density, cycle life, safety, etc.) in the last decade. Figure 3 provides a schematic representation of the evolution of performance characteristics of various electrochemical storage technologies.

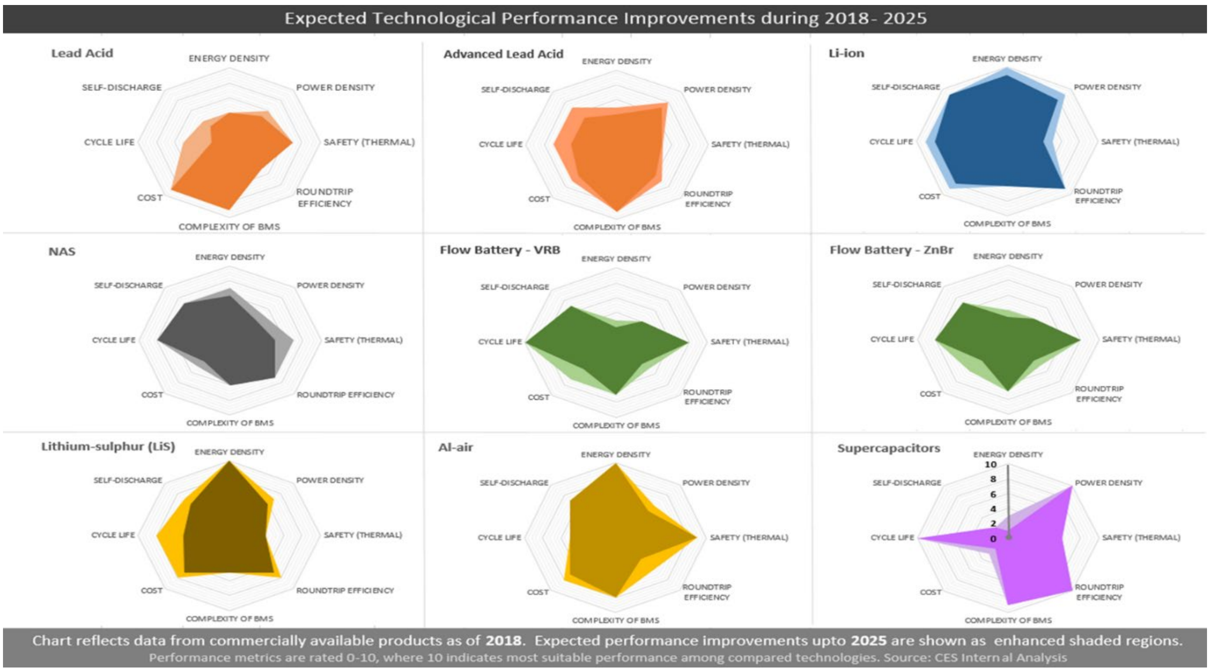

Figure 3: Evolution of electrochemical energy storage technologies

By virtue of their high energy density and rapidly reducing costs, LiBs have emerged as the dominating market force, including a range of technologies. Though prices and specifications fluctuate between chemistries, the strengths, weaknesses cases of the respective chemistry are provided in Table 1.

Table 1: Lithium-ion batteries – strengths, weakness, and use cases

Battery technology	Strengths	Weakness	Use Cases
Lithium cobalt oxide (LCO)	• High energy density and moderate load capabilities • Acceptable cycle life	• High proportion of cobalt (increasingly cost-restrictive; issues in supply chain and sustainable mining concerns) • Poor heat resistance and safety	• Consumer electronics (phones, laptops, and wearable products)
Lithium nickel, cobalt aluminium oxide (NCA)	• High energy and power density • Good cycle life	• Poor thermal energy management and safety issues • High cost per kWh	• EV powertrains, including Tesla
Lithium manganese oxide (LMO)	• Excellent power discharge and maximum load • Fast-charging capability • Good thermal stability and safety	• Low energy density • Low cycle life	• EV designs with a hybrid battery pack
Lithium ferro (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	• EVs • Stationary applications for grid-scale storage
Lithium nickel manganese Cobalt (NMC)	• 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	• EVs
Lithium titanate oxide (LTO)	• Extremely long cycle life (~7,000 cycles) • 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

Emerging technologies are those in which manufacturers invest commercially to meet projected growth in battery demand through 2030. Even though some of these technologies have been around for a while, recent advances have improved performance and reduced costs enough to make them acceptable for commercial deployment, and they constitute a significant innovation when compared to lead-acid, nickel metal hydride, and other older battery technologies.

As incumbent LiB chemistries rely significantly on rare materials such as lithium, cobalt, nickel, and graphite, India necessitates the development of other emerging technologies. Despite some recent discoveries of these materials in India, there are currently few domestic suppliers of these commodities and no control over the supply chain. The reliance on imports, whether of minerals or cells, provides an energy security issue that might obstruct the economic development of the energy storage market. Domestic cell manufacturing capacity development will necessitate significant investments in innovative technologies that either capitalise on abundant resources in India, minimise scarce resources, or enable the successful implementation of circular economic principles through reuse and recycling. Alternative and enhanced cell chemistries will be critical to meeting India's expanding storage requirements. These include technologies that make the best use of rich Indian resources, such as sodium ion, aluminium air, liquid metals, and zinc hybrid are provided in Table 2 below.

Table 2: Other emerging technologies – strengths, weaknesses, and use cases

Battery technology	Strengths	Weakness	Use Cases
Sodium Sulphur (NaS)	• High energy and power density • High-round-trip efficiency • Fast response • Low input material costs; cost competitive with traditional LiBs • Long life cycle • Fast-discharge capabilities • No self-discharge • Uses environmentally safe materials	• Low-cycle stability • Rapid capacity fading in the initial cycle • Safety concern due to high working temperature	• Power quality • Renewable Integration • Congestion relief • Long-duration storage
Vanadium redox flow batteries	• No energy-to-power ratio constraint • High power and voltage delivery performance • Extreme design flexibility • High-life cycle which does not depend on DoD • Adjustable power rating • Limited self-discharge • Rapid response time	• Low specific energy • Requires special housing for thermal safety • Poor energy-to-volume ratio • Heavyweight • Limited for stationary storage application	• Ramping requirement • Peak shaving • Time shifting • Frequency regulation • Power quality
Lead acid or Advanced lead-acid	• High maturity • Low cost • High efficiency • Excellent safety feature	• Low power and energy density • Less reliable • Lower cycle life • Sustained degradation due to sulphation on electrode plates	• Load leveling and regulation • Grid stabilization • Back-up power • Energy time shift
Sodium ion	• Low material cost for sodium, more abundant and sustainably sourced	• Currently in the commercialization phase, has not achieved scale	• Grid-scale storage

	• Allows easy and safe transport without loss of performance • Low tendency for dendrite growth on charging	• Relatively lower energy density and cycle life performance	
Zinc air	• High theoretical energy density • Higher safety performance compared with incumbent LiBs • Low-cost materials for the electrodes allow for lower overall manufacturing cost	• Technology has not reached mass market penetration; currently expensive to manufacture rechargeable zinc-air batteries • India has limited zinc reserves	• Small consumer electronics • Potential use in long-duration storage
Aluminium air	• High theoretical energy density, lightweight • Easily recyclable cell raw material • Not susceptible to thermal runaway • India has abundant aluminium reserves	• Technology still in the early R&D stage • Typically nonrechargeable, so battery replacement stations need to be built out if the technology achieves commercialisation	• Long-range EVs and unmanned air vehicles (UAVs)
Supercapacitors	• Very high cycle life • Good specific energy • Low input material costs; cost competitive with traditional LiBs • Uses environmentally safe materials	• High temperatures required for operation raise safety concerns and require special housing • Currently, high system costs	• Fast-response grid support applications • Medical devices and consumer electronics

Table 3 provides the performance characteristics of various BESS such as Efficiency, Lifespan, technological maturity, applications etc.

Table 3: Storage Technologies based on Duration, Maturity and Applications

Energy Storage System Attributes	Li – Ion	NaS	Flow Batteries
Round trip Efficiency	80-90%	75-80%	70-75%
Life span	10-15 years	10-15 years	Up to 20 years
Development & Construction Period	6 months - 1 year	6 months - 1.5 year	6 months - 1.5 year
Maturity of Technology	Commercial	Commercial	Early to moderate
Applications	Power quality, Frequency regulation	Time shifting, Frequency regulation, RE integration	Peak shaving, Time shifting, Frequency regulation, RE Integration

2.2 Market penetration

As per National Electricity Plan [1] issued by Central Electricity Authority in May 2023, a detailed study has been carried out to assess the capacity addition requirement to meet the projected demand (Table 4 and Table 5) in the years 2026- 27 and 2031-32 for various scenarios:

1. Higher Demand Scenario
2. Higher Battery Energy Storage System (BESS) Cost Scenario
3. Conservative Scenario (Based on the historical trend of construction time in capacity addition)
4. High Hydro Scenario (accelerated Hydro and PSP addition)

Table 4: Likely Installed Capacity by end of 2026-27 in Different Scenarios (in GW)

Scenario	Base Case	Higher Demand	Higher BESS Cost	Conservative Scenario	High Hydro
Hydro [2]	52.4	52.4	52.4	52.3	54.0
PSP	7.4	7.4	7.4	7.4	13.0
Small Hydro	5.2	5.2	5.2	5.2	5.2
Solar	185.6	185.6	185.6	174.6	185.6
Wind	72.9	72.9	72.9	61.4	72.9
Biomass	13.0	13.0	13.0	13.0	13.0
Nuclear	13.1	13.1	13.1	10.1	13.1
Coal + Lignite	235.1	235.1	235.1	235.1	235.1
Gas	24.8	24.8	24.8	24.8	24.8
Total	609.6	609.6	609.6	583.9	616.7
BESS (GW/GWh)	8.7/34.8	22.8/91.2	8.7/34.8	13.5/54	2.1/8.4

Table 5: Likely Installed Capacity by end of 2031-32 in Different Scenarios (in GW)

Scenario	Base Case	Higher Demand	Higher BESS Cost	Conservative Scenario	High Hydro
Hydro [3]	62.2	62.3	62.3	57.7	65.7
PSP	26.7	26.7	29.1	24.9	31.8
Small Hydro	5.4	5.4	5.4	5.4	5.4
Solar	364.6	364.6	364.6	338.6	364.6
Wind	121.9	121.9	121.9	92.1	121.9
Biomass	15.5	15.5	15.5	15.5	15.5
Nuclear	19.7	19.7	19.7	16.9	19.7

1 https://cea.nic.in/wp-content/uploads/irp/2023/05/NEP_2022_32_FINAL_GAZETTE-1.pdf

2 Excl. Hydro imports from neighbouring countries

3 Excl. Hydro imports from neighbouring countries

Coal + Lignite	259.6	262.6	261.2	254.6	259.0
Gas	24.8	24.8	24.8	24.8	24.8
Total	900.4	903.4	904.5	830.5	908.4
BESS (GW/GWh)	47.24/236.2	66.78/333.9	42.85/214.25	67.04/335.2	38.71/193.55

Based on the India Energy Storage Alliance (IESA) report titled, "India Stationary Energy Storage Market Overview Part I - Front-of-the-Meter 2022 – 2030" [4], which covers energy storage applications for grid-scale renewable energy integration, DISCOM-side integration, and ancillary services. In a significant boost to the grid-scale energy storage market, in March 2022, the Ministry of Power notified new guidelines on procuring BESS and energy storage obligations for DISCOMs. In addition, viability gap funding for 4,000 MWh of BESS projects in the country was announced in the 2023 budget.

RE integration accounts for a major share of energy storage projects being deployed and under development in the country. Modhera is the first RE integration project completed in Gujarat; it comprises 6 MW solar with 7 MW/19.2 MWh of BESS.

The DISCOM-side ESS ranges from a few kWh to 10 MWh for applications such as peak load shifting, distribution deferral, and energy arbitrage. Apart from this, the ancillary services market is yet to pick up in India due to a lack of supportive policies and regulations benefiting end users. SECI pilot project of 500 MW/1000MWh standalone BESS to be implemented in Rajasthan had mentioned a specific share of power to be given to NLDC & POSOCO for grid ancillary services. Currently, no ESS project has been deployed specifically for ancillary services applications in the country.

Key contributors to this market are grid-scale renewable integration (contributes nearly 85%) and DISCOM-side ESS (almost 10%) during 2021-2030. While RE integration is predominantly a policy-driven market, clear techno-commercial benefits drive the DISCOM-side ESS market. The intermittent nature of renewable power needs to be amply supported with storage technology to ensure a firm and reliable power supply to the grid. Considering this, IESA estimates that, the projected cumulative energy storage installation in India will be 110 GWh by 2030 under best case scenario. IESA made a detailed analysis of various scenarios, considering the best case [5], base ,case, [6] and worst case [7]. The annual year-wise stationary energy storage market potential from 2021 to 2030 under various scenarios is given in Figure 4.

---

4 https://indiaesa.info/resources/industry-reports/4355-india-stationary-energy-storage-market-overview-part-i-front-of-the-meter-ftm-2022-2030

5 In best case scenario, it is assumed that the country installs renewable power closer to the national RE targets 2030, and policies lacking in the market and awaiting approval are sanctioned.

6 In base case, the business as usual scenario is considered, the growth rate of the market in past 3-4 years is studied and expected to follow similar trend into the future. Existing policy framework supports till end of forecast period.

7 In worst case, the market is expected to follow a low growth path, due to impact of COVID-19 and unsupportive policies which leads to RE addition by 2030 to be around 50-60% of the target.

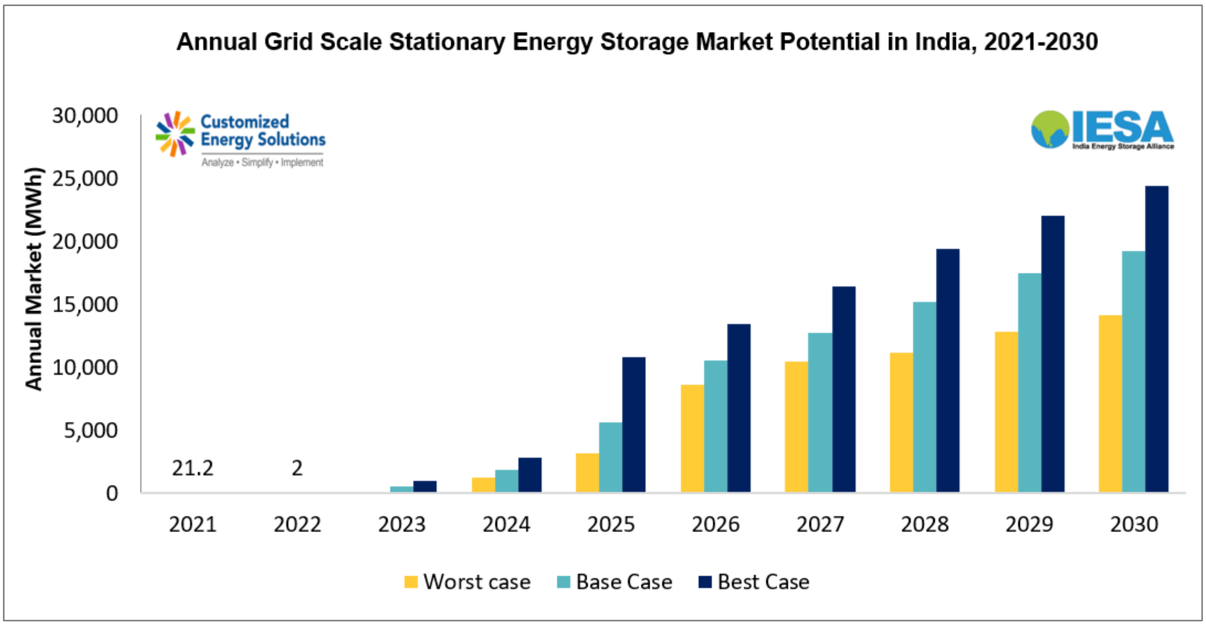

Figure 4: Annual Stationary Storage Market Potential, India, 2021-2030 [8]

2.3 BESS Pilot Projects in India

The battery energy storage system (BESS) has many dimensions to consider while also benefiting many stakeholders. Multiple pilot projects demonstrating a combination of different technologies and varied applications are necessary to assess the full potential of BESS in the Indian context. A BESS at the distribution level may give cumulatively larger benefits to the electrical system than explicit benefits visible from the viewpoint of DISCOM. Some of the pilot projects in India, along with their major findings and lessons learned, are presented below.

Pilot Project 1			
Pilot Locations	Applications	Battery Chemistries	Technical Characteristics
10 MW/10MWh BESS in Rohini, Delhi	• DSM, Frequency regulation, Peak shaving and Reactive Power Control	Lithium Nickel Manganese Cobalt Oxide (NMC)	• Design capacity: 10 MWh/ 10 MW • Maximum discharge rate: 1 C • SOC range: 10-99%
Key Findings	During FY 2020/21 (till August 2020), the operation of BESS for DSM application saved a significant sum (approx. INR 22 lakh). Furthermore, after operating the system for 13 instances, the reactive power control mode resulted in a voltage improvement of 2.51%.		

8 Source: CES-IESA Analysis

Pilot Project 2			
Pilot Locations	Applications	Battery Chemistries	Technical Characteristics
500 kWh BESS at PGCIL facility in Puducherry	• Energy time shift, Frequency Regulation	Lithium ferro-phosphate (LFP) and Advanced Lead Acid	• Design capacity: 398 kWh (LFP); 691.2 kWh (Adv. Lead-acid) • Usable capacity: 357 kWh (LFP); 384 kWh (Adv. Lead acid) • Discharge rate: 2C
Key Findings	As the utilisation rate is an important aspect when considering revenue streams from BESS operation, the systems have been built to support diverse grid-level applications. Furthermore, a few other applications could be introduced to the control topology of battery energy management systems (BEMS) to cover all possible financial consequences in revenue generation. In this regard, USAID collaborated with PGCIL, and the total staked value of BESS for providing various services to the grid and the local Transmission & Distribution network will be examined through its Greening, the Grid (GTG)-RISE initiative. This collaborative work aims to leverage investments and expand the pilot project's reach while also evaluating other functions.		

Pilot Project 3			
Pilot Locations	Applications	Battery Chemistries	Technical Characteristics
410 kWh BESS pilots at multiple locations under BRPL licensee area in Delhi	• Peak shaving (cat.-A) • Reliability improvement (cat.-B) • Energy time shift (cat.-C)	Lithium ferro-phosphate (LFP)	• Design capacity: 288 kWh (cat.-A), 216 kWh (cat.-B), 72 kWh (cat.-C). • Discharge rate: 1C (cat.-A), 2C (cat.-B), 1 C (cat.-C). • SOC range: 15-95%
Key Findings	The customizable EMS is one of the important features of this pilot, which will leverage distribution utility to demonstrate more than one application at each site to maximise the utilisation of BESS and increase the benefits earned from the system, as the project is focused on technology demonstration and further research. The system will be linked to the utility's existing SCADA system through an appropriate communication protocol, allowing the system to monitor and control from both central and locally situated control stations.		

Pilot Project 4			
Pilot Locations	Applications	Battery Chemistries	Technical Characteristics
1 MWh BESS pilot at BHEL's R&D center in Hyderabad	• Ramp rate control, Capacity Firming	Lithium ferro-phosphate (LFP), Advanced Lead-acid and Vanadium redox flow battery	• Design capacity: 516 kWh (LFP), 584 kWh (adv. Leadacid) and 273 kWh (flow battery) • Discharge rate: 1C (LFP), 0.3 C (Adv. • Lead acid), 0.25 C (flow battery)

Key Findings	The designed BESS complies with all applicable national/international requirements, including anti-islanding protection, grid harmonics, grid interconnection, and overall system safety. The system is also intended to work in various grid-level applications such as reactive power control mode, peak load shaving, load levelling, frequency regulation, and power quality improvement through EMS configuration.

2.4 Cost Comparison

Over the past ten years, there has been a 90% decrease in the price of battery storage technologies, spearheaded by Li-ion battery chemistries. The development of VRE integration in power systems has been further under consideration by these declines. Installed capital, operating, and decommissioning costs comprise the three main cost components of the BES system. The cost of the storage block, the storage balance of the system, the storage system, control and communication, system integration, EPC, project development, and grid integration are all included in the installed capital costs. The costs related to fixed operations and maintenance (O&M), variable O&M, round trip efficiency (RTE) losses, warranty, and insurance are included in the operational costs. Decommissioning costs also cover disconnecting, disassembling/removing, cleaning up the site, recycling, and disposal, as shown in Figure 5.

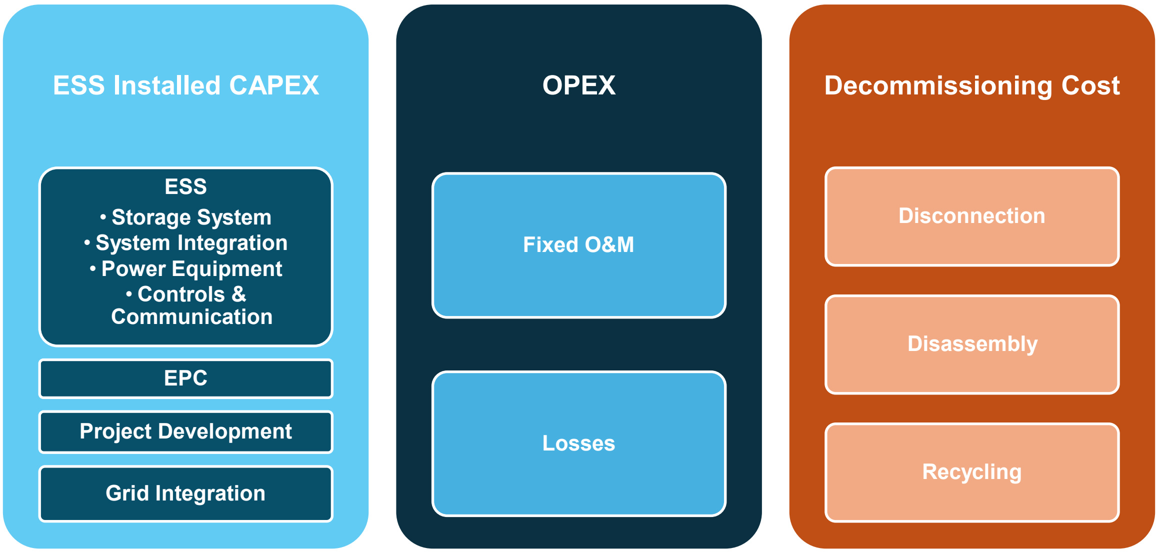

Figure 5: Energy storage subsystems

The prices are summarised in Table 6 below for the most popular battery chemistries, including lithium-ion iron phosphate (LFP) batteries, lithium-ion nickel manganese cobalt (Li-NMC) batteries, lead-acid batteries (LAB), vanadium redox flow batteries (VRFB), Zinc batteries with a capacity of 10MW for 4 hours of storage.

Table 6: Component-wise installed capital cost and operating cost for various BES technologies [9]

Parameters	Units	LFP Batteries		Li-NMC batteries		LAB		VRFB		Zinc batteries	
		2021	2030	2021	2030	2021	2030	2021	2030	2021	2030
DC Storage Block	($/kWh)	173.67	113.64	205.28	134.33	235.07	221.13	263.42	218.95	239.33	191.47
DC Storage BOS	($/kWh)	40.38	30.15	39.37	29.4	47.01	35.11	52.68	39.34	45.17	40.65
Power Equipment	($/kW)	73.05	64.62	73.05	64.62	133	117.65	133	117.65	73.05	64.62
Controls & Communication	($/kW)	7.75	5.78	7.75	5.78	7.75	5.79	7.8	5.82	7.75	5.78
System Integration	($/kWh)	46.66	39.59	52.78	44.78	43.92	37.26	52.55	44.59	41.99	35.63
EPC	($/kWh)	56.18	47.67	63.53	53.9	48.95	41.53	60.58	51.4	50.56	42.9
Project Development	($/kWh)	67.42	57.2	76.23	64.68	61.52	52.2	69.66	59.11	60.67	51.48
Grid Integration	($/kW)	24.81	21.05	24.81	21.05	24.81	21.05	25	21.21	24.81	21.05
Total Installed Cost	($/kWh)	410.7	311.11	463.58	349.95	477.86	423.35	540.34	449.55	464.13	384.99
	($/kW)	1643	1244	1854	1400	1911	1693	2161	1798	1857	1540
Fixed O&M	($/kW-year)	4.59	3.89	5.11	4.34	6.44	5.5	6.66	6.03	22.14	18.79

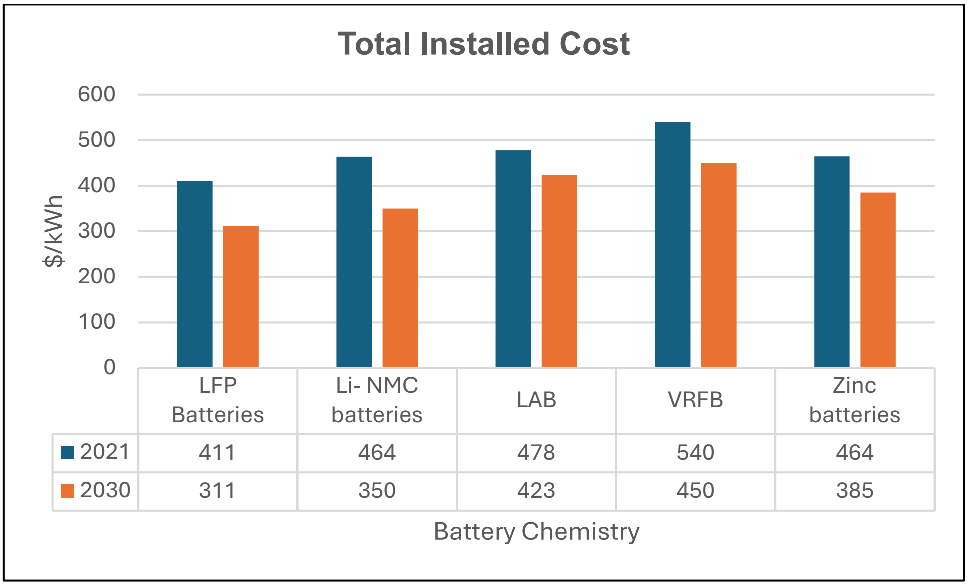

Figure 6: Total installed cost of ESS for various battery chemistry ($/kWh) [10]

The overall lifetime cost of an investment in an electricity storage system divided by its cumulative delivered electricity is the levelized cost of storage (LCOS). It reflects the internal average price at which energy can be sold for the investment's net present value to be zero (i.e., its revenue requirement). It is thus equivalent to the levelized cost of electricity (LCOE) concept for generation technologies. The LCOS for storage and LCOE for generation technologies can be directly compared; however, distinct ideas of providing power and

[9] Pacific Northwest National Laboratory (PNNL)

[10] Pacific Northwest National Laboratory (PNNL)

subsequent variances in cost calculation methods necessitate using separate classifications. The LCOS method's applicability for comparing storage systems for certain applications and generation technologies. As per BNEF 2023 report, the LCOS for large-scale batteries with four-hour storage capacity in India is approximately 184 $/MWh for the year 2023, whereas considering the technological advancement in the battery energy storage technologies, the projected LCOE for the year 2030 is approximately 99 $/MWh. The year-wise projection of the LCOE is mentioned in Figure 7.

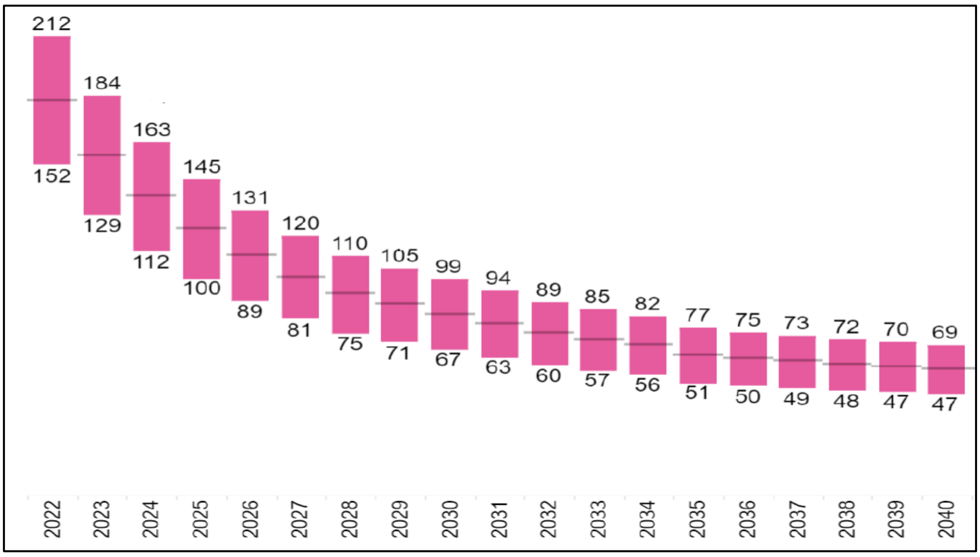

Figure 7: Projected levelized cost of storage with 4 hrs of storage in India (in $/MWh)[11]

2.5 Estimated Cost Curve Development and Potential Capacity Deployment

The possibility of deploying battery energy storage capacity is affected by several variables, such as technology improvements, cost reductions, policy assistance, market demand, and grid requirements. Based on the usability and scale of energy storage installations, significant categories are mentioned below.

- *Utility-Scale Energy Storage:* Utility-scale energy storage is the term used to describe large-scale battery installations used for grid-level tasks such as balancing power supply and demand, boosting grid dependability, and incorporating renewable energy sources. Utility-scale energy storage has a huge deployment potential, which is anticipated to increase significantly over the next several years. By 2030, utility-scale battery storage may have a capacity of several hundred gigawatt-hours (GWh) to terawatt-hours (TWh), according to several studies and estimates.

- *Commercial and Industrial (C&I) Energy Storage:* Commercial and industrial energy storage systems are often implemented by firms, industrial facilities, and universities to optimize energy use, lower peak demand prices, and provide backup power. There is also a sizable deployment potential for C&I energy storage. By 2030, there may be installations of tens to hundreds of gigawatt-hours of C&I energy storage, according to estimates.

[11] Source: BNEF 2023

- *Residential Energy Storage:* Residential battery backups and other residential energy storage systems are growing in popularity due to issues including solar PV integration, energy self-consumption, and backup power during outages. It is anticipated that as costs continue to drop and more households switch to renewable energy sources, the deployment potential for residential energy storage will increase.

- *Off-Grid and Remote Area Applications:* Battery energy storage is especially essential for off-grid and rural area applications, with little to no access to reliable electricity. Applications like isolated communities, islands, mining operations, and communication infrastructure are among them. Battery energy storage can offer dependable and sustainable power to millions of people globally, although its deployment potential in off-grid and remote locations relies on the particular energy requirements of each place.

The estimated cost curve development of different battery technologies can vary depending on factors such as technology maturity, production scale, research and development investments, market demand, and economies of scale. Based on the type of chemistries and technology, major battery technologies are mentioned below.

- *Lithium-Ion Batteries:* Lithium-ion batteries are predominantly used in portable devices and electric vehicles (EVs), so they have emerged as the industry standard. With the recent advancement in the deployment of BESS projects, Li-ion batteries play a crucial role in the transition to energy storage. Through technological breakthroughs and greater manufacturing volume, the price of lithium-ion batteries has been gradually falling over the past ten years. The price per kilowatt-hour (kWh) is predicted to fall from approximately $1,100 in 2010 to about $137–$187 in 2020. According to projections, the kWh price might drop to $62–$100 by 2030.

- *Solid-State Batteries:* As a developing technology, solid-state batteries have the potential to outperform lithium-ion batteries in terms of energy density, safety, and charging speed. They are, however, still in the early stages of development and are not yet widely accessible in the market. Solid-state battery prices are expected to drop as the technology develops and production ramps up.

- *Lithium-Sulphur Batteries:* In addition to lithium-ion batteries, lithium-sulfur (Li-S) batteries are a promising new technology that may offer greater energy density at cheaper costs. Li-S batteries are still in the research and development stage, and it will likely be a decade before they are commercially available. Li-S battery cost estimations range widely, though some speculate they could reach an average of $80-$150 per kWh by 2030.

- *Flow Batteries:* Flow batteries are a rechargeable technology that operates by pumping two externally stored electrolyte solutions across the electrochemical cell. They are ideally suited for stationary energy storage applications. Although flow battery prices have been falling, they are still substantially higher than those for lithium-ion batteries. Costs for flow batteries can range from $150 to $500 per kWh, depending on the precise chemistry and size of deployment.

- *Sodium-Ion Batteries:* Sodium-ion batteries are considered a potential alternative to lithium-ion batteries as they utilize more abundant sodium as the charge carrier. Sodium-ion batteries are still in the early stages of development, and it is uncertain if they will be commercially viable. However, according to predictions, the cost of sodium-ion batteries could fall below $100 per kWh with technological breakthroughs and economies of scale.

However, it's important to consider that these cost projections could change as battery technologies develop, and elements like supply chain dynamics, material costs, manufacturing techniques, and policy support may greatly impact future cost curves for various battery technologies.

2.6 Ongoing projects and tenders

The ongoing projects and tenders issued by various agencies like SECI, NTPC, etc., and other state government agencies like MSEDCL, KREDL, GUVNL, etc., are the major force behind most energy storage integrated with renewable tenders. The status of the projects and tenders issued by the various agencies are mentioned in Table 7.

Table 7: Status Energy storage projects and tenders in India

Tendering Authority	Location	RE (MW)	Storage Type	Energy Storage (MW/MWh)	Winning Bids	Tender Status Results announced
SECI	PAN India	1200	Technology Agnostic	150 MWh (ReNew Power)	Greenko (900 MW, Peak Tariff : ₹ 6.12/unit) ReNew Power (600 MW, Peak Tariff: ₹6.85/unit)	Jan 2020
SECI	PAN India	400	Technology Agnostic	100 MWh*	ReNew Power (₹ 2.9/unit)	May 2020
SECI	Ladakh	20	Electrochemical	20 MW/50MWh	Tata Power (Project Cost: ₹ 386 Crore)	Aug 2021
SECI	Chhattisgarh	100	Electrochemical	40 MW/120 MWh	Tata Power (Project Cost: ₹ 945 Crore)	Dec 2021
SECI	Rajasthan	NA	Electrochemical	500 MW /1000MWh	JSW Energy (₹ 10.84 lakhs/MW/year)	Aug 2022
NTPC	PAN India	NA	Technology Agnostic	500 MW/3000 MWh	Greenko (₹ 27.9 lakhs/MW/year)	Dec 2022
MSEDCL	Maharashtra	250	Technology Agnostic	750 MWh*	Solar Generating Hours (₹ 2.42/unit) Ayana Renewables – 150 MW & NTPC Renewable – 100 MW (₹ 9/kWh - Non-Solar Generating Hours)	Dec 2022
GUVNL	Gujarat	500	Technology Agnostic	X/2MWh (X is the contracted capacity of the project)	-	Tender Issued (Aug. 22)
SECI	PAN India	1200	Electrochemical	Min 1200 MWh	-	Tender Issued (June 22)
KSEB	Kerala	NA	Electrochemical	10MW/20MWh	Hero Future Energy (₹ 11.25 lakhs/MW/month)	July 2022

NTPC	Gujarat	-	Electrochemical	Min 0.25MW /1.2MWh	NA	Tender Issued (Nov. 22)
KREDL	Karnataka	2	Electrochemical	4.5 MWh	NA	Tender Issued (Dec. 22)
GSECL	Gujarat	35	Electrochemical	57 MWh	L&T (Project Cost: ₹ 335 Crore)	Tender Issued (Sept. 21)
SECI	Kaza	2	BESS	1MWh	Extended	Tender issued (Feb 2023)
PCKL	Karnataka	-	PHP	1GW, 8 GWh	Greenko-700MW (₹14.76 Mn/MW/Yr) JSW - 300MW (₹14.75 Mn/MW/Yr)	Tender issued (Feb 2023)
RUVNL	Pan India	1200	Technology Agnostic	6-hour duration	Extended	Tender issued (March 2023)
NTPC REL	Pan India	-	Technology Agnostic	1500/9000MWh	Extended	Tender Issued (May 2023)
RUMSL	12 sites in MP		PHP	13800 MW	-	Tender issued (May 2023)
SJVNL	PAN India	1500	Technology Agnostic	Firm and Dispatchable RE	Extended	Tender issued (June 2023)
SECI	PAN India	500	Technology Agnostic	Firm & Dispatchable RE - I	-	Tender issued (July 2023)
NTPC - REL	PAN India	-	PHP	2000MW – 6 hrs of storage	-	Tender issued (July 2023)
SECI	PAN India	500	Technology Agnostic	Firm & Dispatchable RE - II	-	Tender issued (July 2023)

As per the projects mentioned in the above table, the location of projects in the state-specific tenders are for the same state and tenders issued by central agencies is PAN India. The 2-hours to 6-hour duration of the energy storage system was witnessed in the tenders. The need for projects above 4-hour duration is expected to increase post-2026, with larger penetration of renewables on the grid. Also, up to 4-hour duration tenders are won by BESS technology while above 4 to 8-hour duration is presently allotted to pumped hydro projects. The major application with respect to requirements mentioned in the tenders are:

- Round-the-clock (RTC) power supply with a renewable energy project, where solar, wind, or hybrid project is stipulated to supply power for 12 to 24 hours which can be assured with the use of ESS.
- Assured peak-power supply from a solar, wind, or hybrid power plant for 4 to 6 hours daily, which requires using an ESS.
- Stand-alone storage is used for multiple applications in which the number of discharge cycles per day is stipulated, and the tendering authority decides the application. The schematic representation of the process is provided in Figure 8.

Peak Tariff

- Bidders need to quote tariff in terms of INR/Unit for providing energy during peak hours of the day.
- Bidders are provided flat tariff as per bid document in case of power supplied during non-peak hours

Round the Clock Tariff

- Bidders need to quote tariff in terms of INR/Unit for providing power supply throughout the day.

Project Cost

- Bidders quote the total project cost expected to be utilized for setting up of the project

Capacity Charge

- Bidders quote bid in form of capacity charge i.e., INR/MW in terms of monthly or annual basis as per applicable case.

Figure 8: Financial Model – Bid Type

2.7 Investment Landscape and Project Financing

The investment landscape for battery energy storage projects in India has gained momentum in recent years. Incorporating renewable energy sources, maintaining grid stability, and addressing peak demand challenges are all made possible by BESS. Some key aspects of the investment landscape for energy storage projects in India are mentioned below.

Government Policies and Support: The Government of India has launched several programs and initiatives to encourage battery energy storage projects. The Ministry of New and Renewable Energy (MNRE) has implemented initiatives like the National Energy Storage Mission (NESM), the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, and the National Programme on Advanced Chemistry Cell Battery Storage (NPACC) - Production Linked Incentive (PLI), which provides financial incentives and subsidies for achieving manufacturing capacity of 50 GWh of ACC and five GWh of "Niche" ACC.

Project Financing: Financing battery energy storage projects in India can be accomplished in various ways. The Indian government provides subsidies, grants, and tax incentives to encourage investment in energy storage. Furthermore, international institutions, development banks, private equity firms, and venture capitalists are investing significantly in the Indian energy storage sector.

Partnerships and Collaborations: Domestic and international enterprises are creating partnerships and alliances to access the Indian battery energy storage market. Joint ventures are prevalent among technology suppliers, project developers, and utilities, allowing for knowledge sharing, risk sharing, and access to a more extensive customer base.

Ancillary Services and Business Models: Various ancillary services markets, like frequency regulation, peak shaving, and load shifting, can be served by battery energy storage projects. These services generate revenue for project developers and investors, making the business case more appealing. Furthermore, new business models, such as battery leasing or energy-as-a-service, are emerging that minimize upfront investment costs and enhance market acceptance.

Grid Integration and Regulations: India has set ambitious targets for implementing renewable energy, particularly solar and wind power. Battery energy storage devices are critical for integrating intermittent renewable energy sources into the grid, regulating unpredictability, and assuring grid stability. As the use of renewable energy expands, so does the need for battery energy storage projects, creating significant investment opportunities. The regulatory framework in India is changing to make integrating BESS into the grid easier. The Central Electricity Regulatory Commission (CERC) and the State Electricity Regulatory Commissions (SERCs) are developing regulations, tariff structures, and market procedures to allow battery energy storage projects to operate in the electricity market.

Electric Vehicle (EV) Charging Infrastructure: With the government's push for electric transportation, the development of EV charging infrastructure is gaining traction in India. Battery energy storage devices can help the fast-charging infrastructure by providing peak shaving and load management capabilities. Investing in BESS for EV charging infrastructure provides grid support and revenue generation prospects.

Technology Development and Manufacturing: India has been building domestic battery manufacturing skills to reduce reliance on imports and increase cost competitiveness. Investing in battery technology development and production facilities allows for capitalising on the growing demand for batteries in the energy storage sector.

2.8 Existing policies and regulations in India favoring a market for large-scale storage applications.

The development of policy and regulatory framework for energy storage increased since 2018 in India. Both central and state governments have identified the importance of energy storage and have included it as part of various policies for developing renewable energy projects with or without energy storage. The overall development in policies and regulations in India in the past decade is given in Figure 9.

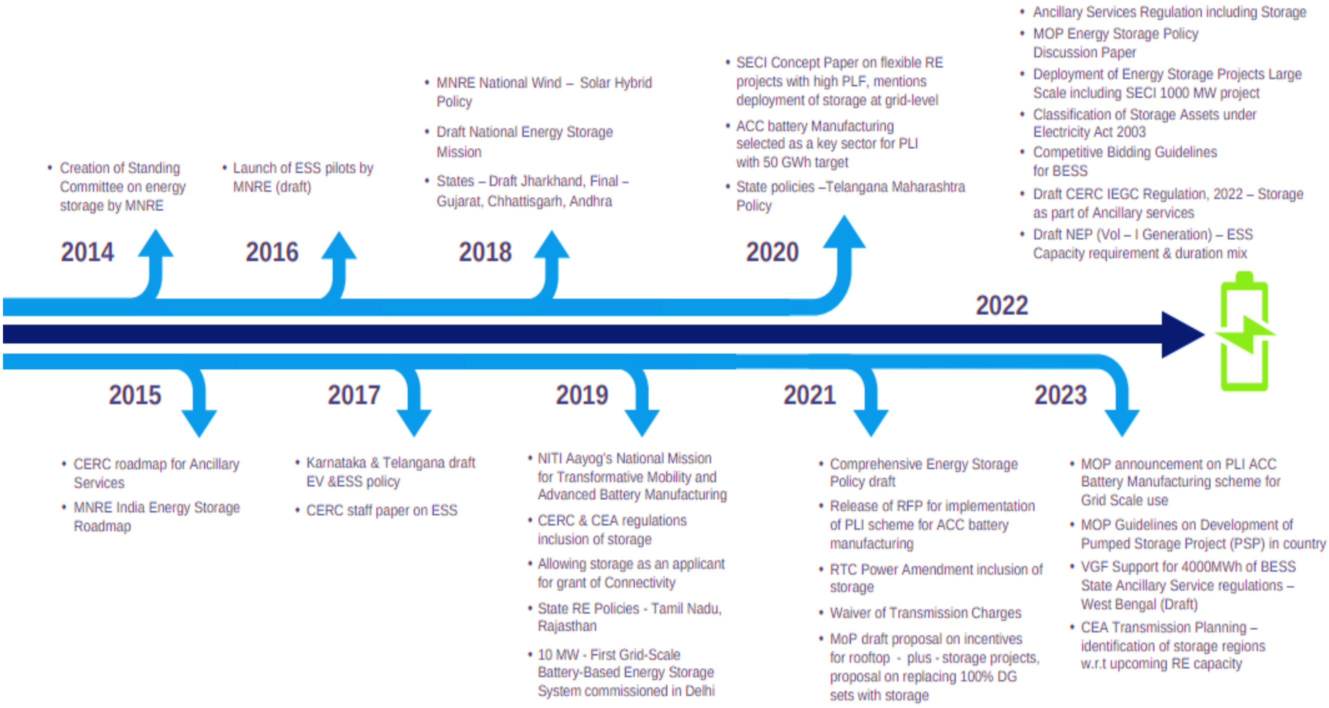

Figure 9: Status of Energy Storage Policies and Regulations in India[12]

Ministry of New and Renewable Energy (MNRE), with the issue of the National Wind Solar Hybrid Policy, paved the way for RE + Storage projects pipeline in India. This policy has provided a framework for promoting large-scale grid-connected wind-solar PV hybrid systems for optimal and efficient transmission infrastructure and land utilization, reducing the variability in renewable power generation and achieving better grid stability. As per the policy, energy storage can be added to the hybrid project to reduce RE integration issues and ensure firm power availability for a particular period. To reduce the cost of power procurement and meet the requirement of Round the Clock (RTC) power, MNRE had issued guidelines for tariff-based competitive bidding for procurement of RTC power from grid connected RE projects complemented with power from any other source or energy storage.

For the development of the solar wind sector, Ministry of Power (MOP) issued scheme for bundling expensive solar power with the cheaper thermal power. The risk associated with solar and wind has been brought down through measures such as green energy corridor, standardized PPA with tenure of 25 years to provide financial stability. Such de-risking measures helped bring down the RE tariff aiding rapid development. However, the intermittent nature of RE and the low utilization of transmission systems need to address. MOP has issued tariff-based competitive bidding guidelines for procurement of firm and dispatchable power grid connected RE projects and ESS. The guidelines ensure a steady and predictable supply of RE power to the DISCOM while addressing the intermittent nature of RE power and the availability of transmission infrastructure. The guidelines aim to increase the transparency, competition, and procurement of RE power optimally to reduce the cost of power purchase and to meet the RPO and ESO targets of DISCOM. Based on these guidelines recently, tendering authorities have started inviting tenders for firm and dispatchable power under tariff-based competitive bidding.

MOP has issued an order to waive inter-state transmission charges on the transmission of the electricity generated from RE sources, including storage projects up to June 30, 2025, for 25

---

12 Source: CES – IESA Analysis

years from commissioning date. The intention behind these guidelines is to give necessary push for development of energy storage capacity and make it cost-effective by reducing tariffs. Post 2025 these charges shall be increased periodically. MOP has also clarified that ESS shall be accorded status based on its application area, i.e., generation, transmission, and distribution energy storage; defined under sub-section (50) of Section 2 of the Electricity Act, 2003. ESS can be developed, leased, and operated by a generating company, transmission licensee, distribution licensee, system operator, or standalone service provider. The ESS will have the same legal status as of generation, transmission, or distribution asset making eligible to be a de-licensed activity and availing all the benefits as per the prevailing policies or regulations. Some of the key polices and regulations that can impact present growth of energy storage is highlighted in Figure 10.

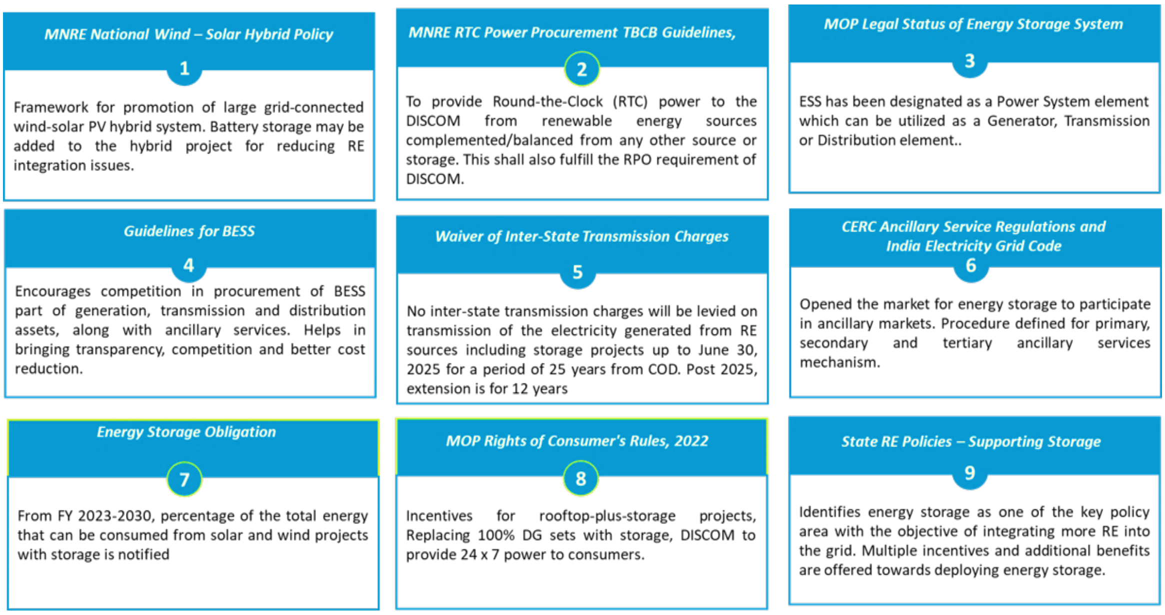

Figure 10: Key Policy & Regulations supporting India's ESS Plans [13]

To boost the installation of the energy storage system and reduce the cost of storage, MOP introduced the trajectory for Energy Storage Obligation (ESO) up to 2029-30. The ESO will be calculated in energy terms and considered fulfilled only when 85% of the energy stored in the Energy Storage System (ESS) is procured from renewable energy sources annually. This obligation is to be adhered to by all states to develop the energy storage capacities within the states. In the wake of this, state authorities are issuing tenders for developing ESS projects to contribute towards fulfilling the obligation.

In a recent development, CERC has issued the final Indian Electricity Grid Code (IEGC) Regulations 2023 and included storage as a part of Ancillary service. Energy storage can be crucial in deploying ancillary services because of its quick response, such as primary, secondary, and tertiary reserve ancillary services. The primary reserve is where the maximum quantum of power comes into service through the governor action of the generator or any other source in the event of a sudden change in frequency. Primary Reserve Ancillary Service (PRAS) should start immediately when frequency deviates beyond permissible limits and complete its obligation in 45 seconds, sustaining up to 5 minutes. The secondary reserve is the maximum quantum of power that can be activated through secondary control signal and provided by generating station or an entity having energy storage resources, or an entity capable of providing demand response. The secondary Reserve Ancillary Service (SRAS)

[13] Source: CES – IESA Analysis

provider shall state responding to the SRAS signal within thirty seconds and be capable of providing the entire obligation in fifteen minutes, sustaining up to thirty minutes. Tertiary Reserve is procured by the National Load Dispatch Centre (NLDC) from the generating station, an entity with energy storage resources, or an entity capable of providing demand response connected to intra or interstate transmission systems. Central Electricity Authority (CERC) issued Ancillary Service regulations in 2022, which provided procedures for deploying secondary and tertiary ancillary services.

The Optimal Generation Mix for 2029-30 (Version 2.0) report was published by CEA with the objective of finding out the optimal generation mix to meet the projected regional peak electricity demand and electrical energy requirement in the year 2029-30. Accordingly, the energy storage capacity of 60.63 GW (18.98 GW PSP and 41.65 GW BESS) is required by 2029-30. Whereas the National Electricity Plan (Volume – I, Generation) issued by Central Electricity Authority (CEA) provides source-wise, including the ESS capacity addition plan for 2022-27 & 2027-32. As per the National Electricity Plan projections, the energy storage capacity of 16.13 GW/82.37 GWh with PSP-based storage of 7.45GW capacity and 47.65 GWh storage and BESS-based storage of 8.68 GW/ 34.72 GWh is required by the year 2026-27. The storage capacity requirement increases to 73.93 GW (26.69 GW PSP and 47.24 GW BESS) with storage of 411.4 GWh (175.18 GWh from PSP and 236.22 GWh from BESS) by the year 2031-32.

The Ministry of New & Renewable Energy (MNRE) has planned to invite bids for 50 GW of renewable energy capacity per year for the next five years, from Fiscal Year 2023-24 to Fiscal Year 2027-28. These annual tenders for ISTS (Inter-State Transmission) connected renewable energy capacity will also involve the installation of at least 10 GW of wind power capacity every year. The MNRE's bidding trajectory enables power procurers, especially distribution companies, to properly manage their RE procurement strategies. The bid trajectory will boost the country's RE manufacturing industry by signaling the demand for their equipment. Furthermore, the Ministry has announced a quarterly bid plan for FY 2023-24, which includes bids for at least 15 GW of renewable energy capacity in each of the first and second quarters of the fiscal year (April-June 2023 and July-September 2023, respectively), and at least 10 GW in each of the third and fourth quarters of the fiscal year (Oct-December 2023 and January-March 2024, respectively).

Pumped hydro storage is a mature technology for construction capabilities and operation. However, there needed to be a regulatory framework available to track and monitor the development of these projects. To address this concern, MoP has issued guidelines for developing Pumped Storage Projects (PSP) in India. The guideline is focused on the mode of allotment of project sites, the timeline for start of construction work, and exemptions provided for pumped hydro plants. The guideline identified a separate category for off-stream PSP to fast-track the environmental and forest clearance to reduce the gestation period of these plants.

Strong policy support is required for framing regulations, standards development, and integration of storage with renewable energy projects to support the effective implementation of storage technologies. MOP had introduced Viability Gap Funding (VGF) for 4000 MWh BESS projects. The guidelines for disbursement of VGF are under draft stage and are expected to be released soon. Similarly, reducing the GST rate of batteries and their components is important to bring down the cost of BESS to make it competitive concerning other technologies.

Key Recommendations:

- The Government of India 2018 announced the creation of the National Energy Storage Mission to facilitate large-scale integrated electric storage and to set up a national portal on energy storage projects for knowledge, cost-benefit analysis, and know-how on manufacturing. However, this draft was never finalized. Even the committee formulated in the year 2020 for framing the comprehensive storage policy has been in the draft stage for a long. It is important to have a central policy for covering the entire technology spectrum under ESS, which should cover requirements, planning of both long-duration and short-duration storage applications, and having phase-wise development targets and strategies.

- Multiple documents/plans from authorities target planning are varying. Many of the documents mention that the plan may vary based on BESS pricing. To give the right signal to the industry, it's essential to define storage requirements and strategies to achieve these targets.

- The major issue with states in active storage adoption is because of awareness of BESS, its applications, and its advantages. Apart from imposing storage obligations, it is equally important to set targets at states, and create awareness, including the findings of storage requirements as part of policies. Any support required for the states in this direction must also be explored. The BESS application's value staking is another important aspect that needs to be addressed.

- Financial/Investment planning is an important factor for developing any emerging technology growth in any country. National Electricity Planning should also cover phase-wise requirements of ESS duly considering technology growth and investment planning to achieve the set targets. That will ensure long-term investment signals to different technology providers.

- BESS has been proven around the globe as technology to be used for Long Duration Energy Storage (LDES) applications. Hence it is important to start concentrating on LDES technologies development happening around the globe and include these technologies as part of planning and works towards the growth of these technologies.

- In addition to norms on power quantum, it shall be the duty of every supply licensee to ensure power quality (covering voltage, harmonics, frequency, surges, etc.) as prescribed by the relevant authority. The licensee shall be allowed to offer different qualities at different prices, subject to regulatory approval and meeting a minimum power quality as mandated. We need to create a power quality benchmark and monitor power quality across the grid so that consumers know the power quality issues and improvements can be monitored systematically.

2.9 Challenges in the Lithium-ion Battery Manufacturing Ecosystem

Lithium-ion chemistry is more prevalent within the BES technologies as it offers better performance characteristics regarding energy and power density, cycle life, safety, etc. The Lithium-ion battery manufacturing value chain has six stages (mining to recycling). Figure 11 provides a schematic representation of the Lithium-ion battery supply chain levels. The upstream level of the supply chain includes the mining and processing ores into critical metals. The middle stream consists of the materials that can further be processed for applications in cathode, anode, electrolyte, and separator. The downstream level comprises the production of cells, battery pack, and recycling of used batteries.

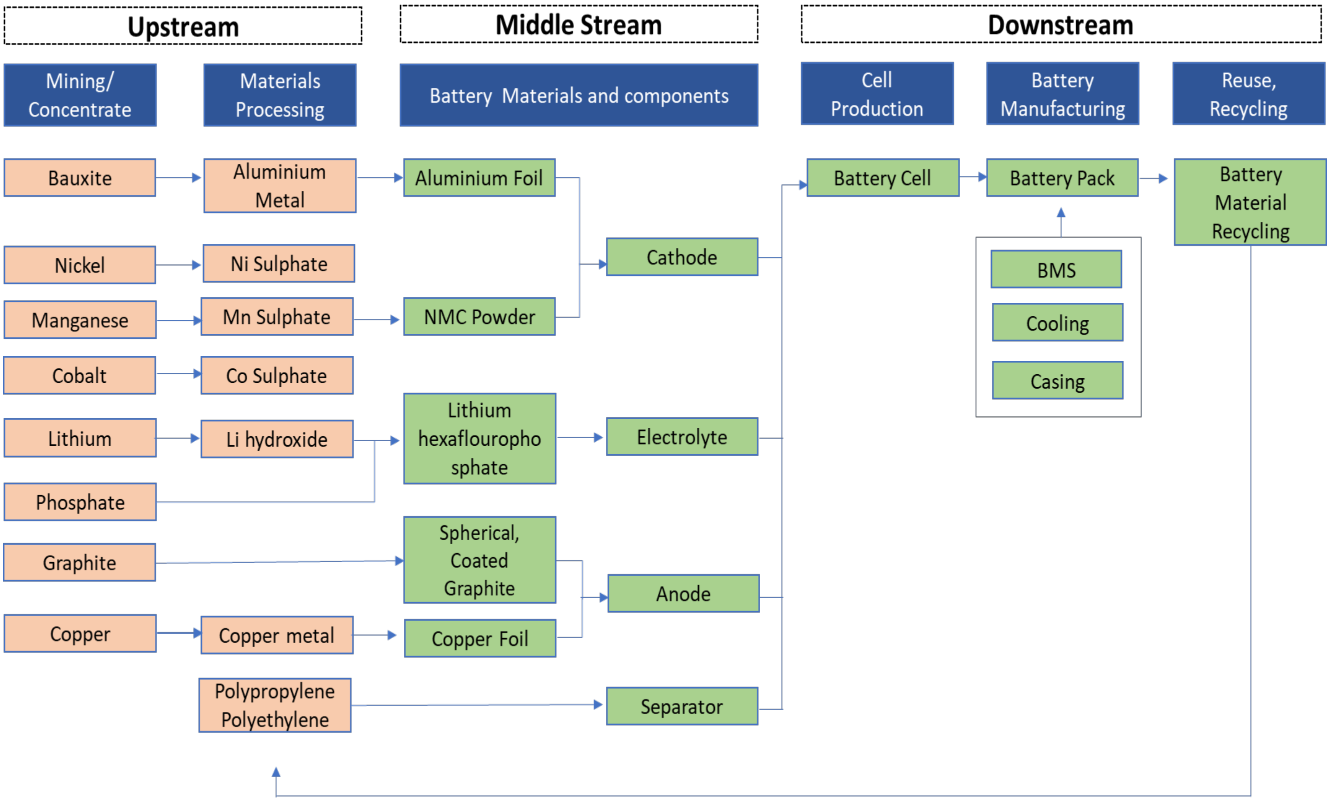

Figure 11: Lithium-ion battery supply chain

2.9.1Current Manufacturing Ecosystem in India

The domestic battery manufacturing industry is growing significantly to cater to the domestic and global demand for Advanced chemistry cell (ACC[14]) batteries. The government of India's (GoI) national program on ACC production-linked incentive (PLI) scheme is a great starting point for developing the domestic battery manufacturing ecosystem. With the recent progress in the ACC PLI scheme, three companies have signed the PLI agreement for a capacity of 30 GWh and are all set to build their plants. A remaining 20 GWh capacity is yet to be allocated. This makes a cumulative 50 GWh manufacturing capacity for ACC targets by 2027. Further, the GoI is introducing another PLI scheme to manufacture 50 GWh ACC batteries for power sector applications. The PLI scheme has provided a great impetus to the battery manufacturing ecosystem players. In addition to the capacity awarded under the PLI scheme, more than 10 companies plan to set up their ACC gigafactories without any PLI benefit. Figure 12 provides the details of upcoming and planned ACC gigafactories in India. The announced capacity for these gigafactories ranges between 5 GWh to 20 GWh with a mix of LNMC and LFP technologies.

[14] It is Lithium-ion battery technology significantly.

Figure 12: Upcoming and Planned ACC gigafactories in India

The cell-active materials/component manufacturing ecosystem is developing significantly to support the domestic cell manufacturing industry[15]. Figure 13 provides an overview of the components that Indian players are developing. Currently, manufacturing of the below-mentioned components is at various stages of development (planning, pilot scale, commercial scale). As the manufacturing ecosystem advances, by 2025 and 2030, the industry envisages achieving large-scale manufacturing capacities to cater to the growing demand for ACCs.

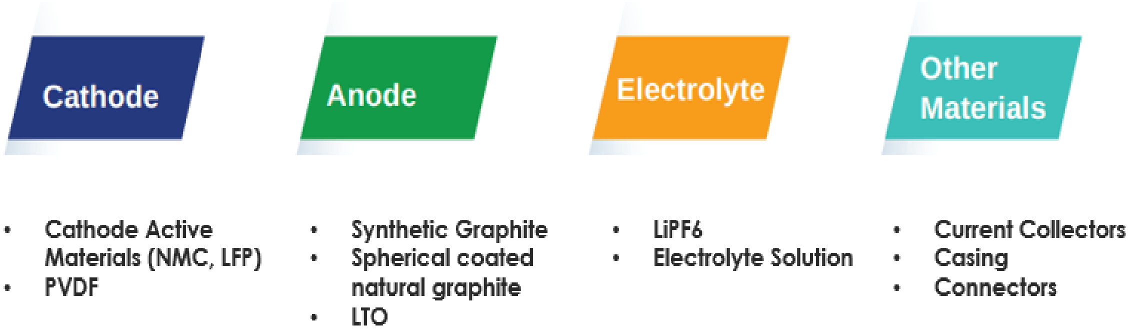

Figure 13: Current Manufacturing Status in India

The key industry players involved in manufacturing various cell-active materials are provided in the Figure 14 below. As mentioned earlier, these are at different stages of development.

15 These inputs were collected from Industry players through a primary survey or one-on-one interactions.

Component	Company
Anode Material	epsilon carbon; Himadri; NEOGEN CHEMICALS LTD.; TIRUPATI GRAPHITE; PCBL
Cathode Materials	BASF We create chemistry; ALTMIN; epsilon carbon; 50Hertz Creating Balance; NEOGEN CHEMICALS LTD.; VRINDA Li-iON Batteries
Electrolyte	GFL GUJARAT FLUOROCHEMICALS VALUE THROUGH GREEN CHEMISTRY; NEOGEN CHEMICALS LTD.; NAVIN FLUORINE INTERNATIONAL LIMITED
Cathode Binder	GFL GUJARAT FLUOROCHEMICALS VALUE THROUGH GREEN CHEMISTRY
Aluminum Foil	ADITYA BIRLA HINDALCO

Figure 14: ACC Component manufacturing player in India

2.9.2 Lithium Deposits in India

Lithium-ion batteries and the associated energy storage capacity are crucial for India to achieve its greenhouse gas emission reduction targets. As of August 2023, the Ministry of Heavy Industries notes, that the investment in manufacturing and overall value addition of Advanced Chemistry Cells (ACCs) in India is negligible, and almost all domestic demand is still met through imports.[16] This is mainly because until recently there was no domestic availability of raw material such as Lithium in India. However, in February 2023, Lithium inferred resources of 5.9 million tonnes were discovered in Jammu & Kashmir.[17] This makes India the 7th largest lithium resource in the world, after Bolivia, Argentina, the US, Chile, Australia and China.[18]

In August 2023, the Parliament passed the Mines and Minerals (Development and Regulation) Amendment Bill, 2023, to attract private sector investment in exploring the resources and to speed up the exploration process.[19] Through this amendment, the Central Government has been empowered to exclusively auction mining lease and composite license for 24 critical minerals such as Cobalt, Graphite, Lithium, Nickel, Tantalum, Titanium etc. The objective of this amendment is to increase the exploration and mining of critical minerals and ensure self-sufficiency in the supply of critical minerals which are essential for the advancement of many sectors, including high-tech electronics, telecommunications, transport, defence, etc. These

16 Indian Ministry of Heavy Industries on Lithium-Ion Batteris, Posted On: 08 AUG 2023 4:13PM by PIB Delhi, pib.gov.in/PressReleaseIframePage.aspx?PRID=1946679

17 Indian Ministry of Mines, Posted On: 09 FEB 2023 7:19PM by PIB Delhi, Press Information Bureau (pib.gov.in)

18 Economic Times: Lithium Reserves countries: Countries with largest lithium reserves. Here's the list | EconomicTimes (indiatimes.com)

19 Indian Ministry of Mines, Posted On: 02 AUG 2023 5:10PM by PIB Delhi, Press Information Bureau (pib.gov.in)

are also vital to power transition to a low-emission economy, and the renewable technologies that will be required to meet the 'Net Zero' commitment of India by 2070.[20]

On 29th of November 2023, the Ministry of Mines launched the e-auction of critical and strategic minerals. In the first tranche auction process, the Ministry has identified 20 blocks of critical and strategic minerals spread across seven states—Bihar, Gujarat, Jharkhand, Odisha, Tamil Nadu, Uttar Pradesh, and Chhattisgarh and the union territory of Jammu & Kashmir. Among these mineral blocks, 16 will be auctioned as a grant of Composite Licence, and four will be auctioned as a grant of Mining Lease. The critical and strategic minerals include the blocks of Lithium, titanium, bauxite (aluminous laterite), glauconite, nickel, chromium, potash, copper, graphite, manganese ore, molybdenum ore, phosphorite, platinum group elements, and rare earth elements. The entire process will be completed in 103 days from the day of the auction launch.

The auction of these blocks aims to create a steady supply of these minerals, thus reducing India's reliance on imports and ensuring a more secure and resilient supply chain. The process from exploration to recovery will take time, but in the future, it will fulfil the aspirations of the domestic ACC battery manufacturing plan, complementing the Aatmanirbhar Bharat mission and catering to the export market. Additionally, the refining and material processing industry is being developed faster to fulfil the domestic and cater to the export opportunities. The discovered lithium reserves have the potential to achieve the ambitious goals of deploying Advanced Chemistry Cell (ACC) batteries in stationary energy storage applications and e-mobility in India.

To be noted: Several press releases in May 2023 announced the discovery of large lithium deposits in Rajasthan. However, the Geological Survey of India terms that these reports are 'baseless'.[21]

2.9.3 Challenges in the Current Ecosystem

This section highlights the challenges with technology, raw materials, policy, and regulations for upstream supply chain development. Details are discussed as follows.

Raw Material: Indian ACC manufacturers import most cathode and anode active materials from China and other countries. It involves a variety of critical battery materials (Li, Co, Ni) that are limited to a few countries. The growing demand for ACC batteries globally may influence the prices of critical minerals, and it can ultimately impact the supply chain and cell manufacturing industry. India has resources and reserves for Li, Co, Ni, and Mn; however, further exploration of the feasibility of mining and processing is needed to strengthen the supply chain of critical battery materials.

The challenges associated with raw materials are listed below.

Cathode active materials- Given that the materials processing industry is yet to develop in the country, so to fulfil the aspirations of domestic manufacturing in the short-term, the Cathode materials for NMC-based chemistries will be fully imported, whereas for LFP-based battery chemistry, there is a possibility of significant value addition domestically by 2030.

Anode Materials- Presently, synthetic anode material can be produced indigenously; however, with the growing demand for batteries and other applications, there can be a

---

20 Ministry of Mines, Posted On: 13 DEC 2023 4:15PM by PIB Delhi, pib.gov.in/PressReleaseIframePage.aspx?PRID=1985839

21 The Economic Times, May 09 2023, GSI terms reports on large lithium reserves found in Rajasthan as 'baseless' - The Economic Times (indiatimes.com)

shortage of coal tar (precursor material), and the industry might have to import petroleum coke from countries like the USA and the EU. Also, due to the limited availability of natural graphite and mining restrictions in India, natural graphite may have to be imported in the long term.

Electrolyte- The precursor materials, such as Lithium carbonate (Li_2CO_3)/ Lithium Hydroxide ($LiOH.H_2O$), Solvents for the electrolyte solution, yellow Phosphorous, and Fluorspar are fully imported due to unavailability in India.
Current Collectors: The technical know-how for anode and cathode current collectors (copper foil and Aluminium foil) needs to be built in the country. A few companies plan to set up battery-grade aluminium and copper foil in India.
Similarly, the manufacturing base for separators and other chemicals still needs to be developed. However, some companies are considering the domestic manufacturing of these components in the coming years.

Technology/Equipment: The key equipment/machinery used in cell and component manufacturing is imported presently. For instance, the equipment used in manufacturing cathode materials (kilns, furnaces, and milling), anode materials (Milling & Shaping, coating, finishing), electrolytes, etc., is imported.

Manufacturing: The manufacturing capabilities for upstream/intermediate-level supply chain components are at various stages of development (planning, pilot scale, commercial) in the country. A few players have started building giga-level manufacturing plants, and others are planning to put up or expand the existing manufacturing capacities. It will take a few years' time to establish a large-scale manufacturing ecosystem in the country.

Skilled Manpower: The ACC manufacturing ecosystem is developing, and technical know-how currently needs to be improved in the industry. Battery manufacturing is a complex process requiring skilled manpower to operate the equipment. Therefore, technical collaborations with global players are needed.

Other Challenges

- The initial cost of technology (capital investment) is higher in specific components.
- Manufacturing of some components is highly working capital intensive.
- Taking environment clearances is a lengthy process and eventually delays the projects.
- Issues in taking loans from banks—banks require confirmation of orders in case of funding requirements for significant expansions. Since the customers are still establishing themselves in this industry, getting those guaranteed offtakes to get bank loans is difficult.
- Huge investment is required for R&D.
- Delays/Uncertainty in getting land approvals for a project set-up.

2.9.4 Challenges in the BESS Deployment

There has been a significant push for the large-scale deployment of BESS in grid applications; however, several challenges must be addressed, such as higher costs (capital and operating), reliability, environmental issues, degradation, etc. Some of the key deterrents in the large-scale deployment of BESS are discussed below.

Higher cost of BESS: Cost is the most critical factor considered while deploying the BESS. Sizing BESS to cater to the longer-duration needs increases the capital and operating costs. The primary factors for the higher costs could be the type of battery technology (chemistry), applications, geographical locations, maintenance requirements, etc. Further other factors, such as degradation of batteries, power losses, state of charge, etc., significantly impact the costs. The battery costs for advanced chemistry cell technology are projected to reduce considerably in the coming years; therefore, the BESS deployment is envisaged to be economical in the long term.

Power Quality Concerns: The key objective of BESS integration with the grid is to ensure the reliability and steadiness of power transmission. However, there are issues with the power quality that can affect the overall distribution network performance. The most common power quality problems include voltage sag and swell, overvoltage, undervoltage, voltage unbalance, frequency deviation, etc. There is a need to develop techniques to improve the power quality by improving the voltage imbalance.

Battery Degradation and Aging: Battery degradation and aging significantly impact the overall BESS cost. A battery consists of different chemicals/materials, and different batteries have a different lifespan. The main performance characteristics of an efficient BESS are fast charging, slow discharging, and a longer lifetime. However, the calendric (In idle conditions, the chemical agents of the battery are active due to the temperature and voltage, causing a constant degradation of the battery) and cyclic degradations (caused by the charging and discharging rates of the battery) take place in a battery. To overcome this issue, it is necessary to consider optimizing DoD, charging, and discharging during the design of the batteries. Further, ambient temperature is to be maintained to reduce the degradation of electrodes.

Environmental Impact: The batteries used in energy storage pose environmental issues during various stages of their lifecycle (mining, production, operation, and afterlife). Some metals, such as lithium, nickel, and cobalt, are hazardous. These materials need appropriate treatment; otherwise, they can contaminate the environment and harm human health. There is a need to develop environmentally benign battery technologies and create a sustainable framework to treat the waste batteries' afterlife. An average cost of recycling LFP batteries is around $2-$3.

Lack of standardization: Safety testing, certification, and inspection guidelines based on relevant standards and codes are required to ensure battery energy storage systems' safety, security, and sustainability. System-level certification is essential to enable more secure and reliable power plant installations. However, MNRE has issued guidelines for the procurement and utilization of BESS, which majorly focuses on the relevant codes and standards for safety. Moreover, there is a need for operational and performance-based standardization along with timely inspection for the smooth and efficient operation of BESS.

Policy and Regulatory Conditions: The policy and regulatory framework for BESS deployment in India is evolving. A clear roadmap to direct the scope and scale of energy storage is crucial for investments. Delay in the signing of PAA could be one of the major challenges considering the rising cost of the system.

Other mandatory conditions for BESS Site selection

- The site should be large enough to accommodate a BESS system and its associated equipment.
- Land Acquisition for the BESS projects play an important role to setup the complete system along with its grid integration.
- Should be accessible for construction and maintenance transportation.

- Should be in areas free from extreme weather conditions such as flooding, high wind, earthquakes, etc.
- Factors such as the shape (which can affect the layout of BESS) of the site and topography (a gentle slope would minimize the cost of grading) must be considered, as they can impact the cost of BESS deployment.
- Soil condition must support the weight of BESS and associated equipment. Further, it should be free from any contaminants.
- It should comply with the zoning (industrial or commercial applications) and permitting requirements.

3 New Battery Technologies & Estimated Cost Development

3.1 Flow batteries

Redox flow batteries (RFBs) or flow batteries (FBs)—the terms are sometimes used interchangeably—are innovative technology providing a bidirectional energy storage system by utilising redox active energy carriers contained in liquid electrolytes. RFBs pump negative and positive electrolytes via energized electrodes in electrochemical reactors (stacks), storing and releasing energy as needed. Flow batteries, with the potential of cheaper, more reliable energy storage, are poised to transform the way consumers like residential, commercial, and industrial power their appliances, embarking on a new era of sustainable energy. Given their liquid form, RFBs have unique properties such as decoupling energy and power, scalability, and possible cost-effectiveness. RFBs are well suited for various applications, including utility-scale energy storage, microgrids, renewables integration, backup power, and remote/off-grid power. The following are some important commercial developments in this field.

- A 100-MW/400-MWh VFB system, the largest of its kind in the world in Dalian in northeast China in 2023 by Rongke Power Company
- A 7-MW/30-MWh VFB system will be installed by Invinity Energy Systems on the National Grid in the United Kingdom
- ESS, Inc., in the United States, ended 2022 with nearly 800 MWh of annual production capacity for its all-iron flow battery.
- China's first megawatt iron-chromium flow battery energy storage demonstration project, which can store 6,000 kWh of electricity for 6 hours, was successfully tested and was approved for commercial use on February 28, 2023, making it the largest of its kind in the world.
- Australia-based Redflow Limited has 2-MWh zinc-bromine RFBs at Anaergia's Rialto Bioenergy Facility in San Bernardino County, CA.
- E22 commissioned the first vanadium redox flow battery. It was acquired by the Indian state-owned enterprise Bharat Heavy Electricals Limited (BHEL) in Hyderabad, India. It will provide 50 kW of power and has a storage of 200 kWh of energy for a period of four hours.

Table 8 provides the component-wise installed capital and operating cost for VRF batteries for different storage back-ups.

Table 8: Component-wise installed capital cost and operating cost of Vanadium redox flow battery[22]

Parameters	Units	VRFB 10 MW, 4 hours		VRFB 10 MW, 8 hours	
		2021	2030	2021	2030
DC Storage Block	($/kWh)	263.42	218.95	219.27	182.25
DC Storage BOS	($/kWh)	52.68	39.34	43.85	32.75
Power Equipment	($/kW)	133	117.65	133	117.65
Controls & Communication	($/kW)	7.8	5.82	7.8	5.82
System Integration	($/kWh)	52.55	44.59	42.03	35.67
EPC	($/kWh)	60.58	51.4	48.41	41.08
Project Development	($/kWh)	69.66	59.11	55.68	47.24
Grid Integration	($/kW)	25	21.21	25	21.21
Total Installed Cost	($/kWh)	540.34	449.55	429.97	357.06
	($/kW)	2161	1798	3440	2857
Fixed O&M	($/kW-year)	6.66	6.03	10.27	9.09

3.1.1 Experience in India and involvement in research

In 2021, exploration by the Geological Survey of India (GSI) found reserves of Vanadium in Arunachal Pradesh, India. Concentrations of vanadium have been found in the palaeo--proterozoic (era) carbonaceous phyllite rocks in the Depo and Tamang areas of Papum Pare district in Arunachal Pradesh. There are various other potential sites in various districts in Arunachal Pradesh. India is a significant consumer of vanadium but is not a primary producer of this metal. As per a GSI survey, in 2017, India consumed 4% of the total global production of Vanadium. A few of the startups, projects, and initiatives in India are mentioned below:

- Delectrik, India based start-up company, starts commercial production of containerized RFB200 series Flow Battery systems. The first set of units is getting ready for dispatch to the US and Australia.
- VFlowTech is a Singapore-based long duration energy storage solutions provider manufacturing low-cost and efficient modular vanadium redox flow batteries, already started limited manufacturing and deployment in various countries and interested in manufacturing and deployment in India.
- VRB Energy is exploring large-scale deployment in India and currently has a presence in India.
- Researchers at the Indian Institute of Technology, Madras, developed a vanadium redox flow battery (VRFB) in June 2022 through a project funded by ONGC Energy Centre Trust and the Pudukkottai-based company High Energy Batteries.
- IIT team successfully demonstrated 1kW/10kWh VRFB using solar power charging. More than 300 cycles (each cycle takes about three days) have been completed using

22 Pacific Northwest National Laboratory (PNNL)

solar charging. The developed VRFB can operate at a high current density with 80-85 percent efficiency.

- IIT Delhi's Sustainable Environergy Research Lab (SERL) at the Department of Chemical Engineering is actively working on Vanadium Redox Flow Battery (VRFB) technology. Recently, a VRFB based charging station, especially designed under the Smart Campus Initiative of the Institute, was inaugurated on the campus. The project is on hold at the current stage.

3.1.2 Challenges and Risk Mitigation Measures for greater deployment in India

The high capital expense required for RFB deployment creates a significant obstacle for large-scale deployments in India. Furthermore, mining, scaling, and managing the energy storage system and pilot projects necessitate substantial investment in industrial processes and project development, requiring more cost and time. The technologies that deliver reasonably meaningful impacts at relatively low investment levels, such as improvements in the battery metrics and materials, improving domestic recycling, supply chain analytics, power performance, and system design and packaging, is an emerging pattern. Investment in these innovations and those in separators/membranes would result in significant LCOS reductions at low investment levels.

The challenges and risks related to the supply chain and its associated risk mitigation aspects are discussed below:

- Currently, an ion-conducting membrane, called 'Nafion,' is used in the VRFB stack. This constitutes nearly 20 per cent of the system cost. Nafion is a high-performance polymer that is primarily manufactured by The Chemours Company. Chemours, a spin-off from DuPont, is a chemical company that produces a wide range of chemical products. While Chemours has manufacturing facilities in various locations worldwide, the production of Nafion is primarily concentrated in the United States. As it is a proprietary polymer with limited manufacturing around the globe, alternative polymers are being researched for suitable applications in VRB stacks; in India, IIT Madras is working on cost-effective ceramic-hydrocarbon-based porous membranes for VRB Applications.
- Bipolar plate impacts the complete systems, as far as total dimensions, total weight, thermal and electrical properties of the stack, and thus of the system are determined by the bipolar plate technology. Graphite composite-based bipolar plates are manufactured using highly filled compounds. They contain fillers like graphite and other electrically conductive carbons incorporated in polymers performing as a gluing binding matrix. Compounding, and molding processes, which can be injection molding, compression molding or continuous extrusion, are very sensitive to process parameters and need to be carefully controlled. At present, VRFB technology is import-dependent on these electrodes from Europe. Domestic VRFB technology companies remain dependent on the import of these electrodes in the short term. However, in the mid to long time, this presents an opportunity for Indian manufacturing to cater to this demand locally and acquire the related technology.
- Some common chemicals and additives used in VRFB are battery-grade Sulphuric acid and De-ionized water. These chemicals and additives pose very minimal supply chain risks, as there is sufficient domestic manufacturing to support the demand locally in the mid and long-term.

- About 8-10 tonnes of Vanadium is required per kWh of VRFB storage, current less than 50% of vanadium supply has been localized in India, and VRB technology companies have to rely on imports from South Africa and China for their requirement. Although exploration studies are underway by the GSI, secondary sources of vanadium leg slag from aluminium processing are being explored by VRFB companies to mitigate supply dependencies.

The key challenges and risks related to the manufacturing and scaling up of VRFB are discussed below:

- *Electrode fabrication:* VRFBs require the fabrication of electrodes with high surface area and excellent electrochemical properties, accounted for the manufacturing process to maximize performance and durability. Achieving consistent electrode quality across large-scale production can be challenging.
- *Membrane Production:* VRFBs utilize ion-exchange membranes to separate the positive and negative electrolytes while allowing ion transport. Manufacturing these membranes with the required parameters is crucial for optimal battery performance. Developing cost-effective and reliable production methods for these membranes is a challenge.
- *Vanadium Electrolyte Management:* VRFBs employ a vanadium-based electrolyte, which needs careful management during manufacturing. Vanadium ions can undergo precipitation or cross-contamination, reducing the battery's efficiency and capacity. Maintaining the appropriate vanadium concentrations and preventing impurities in the electrolyte is critical.
- *Cost Reduction:* VRFBs have shown potential for large-scale energy storage applications, but their current manufacturing processes contribute to high costs. Streamlining production methods, optimizing material usage, and improving overall manufacturing efficiency are critical to reducing the cost per kilowatt-hour and enhancing the commercial viability of VRFBs.

The significant risk mitigation aspects related to the manufacturing and scaling up of VRFB are discussed below:

- *Process Optimization:* Conduct thorough research and development to optimize the manufacturing processes for VRFB components such as electrodes, membranes, and stack assembly.
- *Automation and Robotics:* Incorporating automation and robotics technologies in manufacturing can improve efficiency, accuracy, and consistency.
- *Standardization and Modular Design:* Developing standardized manufacturing protocols and specifications for VRFB components can streamline production and enhance consistency. Modular design principles for VRFB systems allow for easier assembly, maintenance, and scalability.
- *Research and Development Investments:* Continued research and development efforts are essential to overcome manufacturing challenges. Investing in research initiatives focused on improving manufacturing techniques, developing new materials, and enhancing process efficiency can lead to breakthroughs in VRFB manufacturing.

3.2 Other Chemical Battery Technologies

The maturity and technology readiness level (TRL) assessment is critical for tracking technology evolution and evaluating investment risks, impediments, and commercial scale-up measures. Technological advancement and commercialization are hardly linear processes.

Despite the demand and momentum behind various energy storage technologies, some may face roadblocks and uncertainties along their development and demonstration paths. The electrochemical energy storage technologies with their TRL and other important parameters are mentioned below in Table 9.

Table 9: Energy Storage technologies – Technology Readiness Level and Parameters

Storage Technology	Technology Readiness Level (TRL)	Storage Duration (Hrs)	System size (MW)	Energy Density (Wh/Kg)	Calendar Life (Years)	Cycle Life (Cycles)
Lithium Iron Phosphate (LFP)	9	Upto 8	10 to 100	160-180	10-16	2,500-3,000
Nickel Manganese Cobalt (NMC)	9	<6	10 to 100	270-300	10-13	1,500-2,000
Vanadium Redox Flow (VRF)	9	Upto 10	Upto 100	Upto 35	10-20	15,000-20,000
Sodium Ion (Na-ion)	7	Upto 10	10 to 100	100-160	10-15	More than 3,000
Aluminium Air (Al-air)	7	Upto 20	Upto 10	1,300	-	-
Zinc Based Batteries (ZBB)	8	2 -100	Upto 10	65-500	10-25	1,000-12,500
Sodium Sulphur (NaS)	8	Upto 6	Upto 10	110	15	4,500-5,000
Iron Air (Fe-air)	7	Upto 100	Upto 10	600	30	Upto 10,000

4 Conclusions and Way Forward

The BESS plays a critical role in the large-scale deployment and realizing the full potential of renewable energy, thus achieving the net zero goal. The government of India has introduced several policy and regulatory measures to support in large-scale deployment of BESS in grid applications. As discussed in the sections above, there are challenges at manufacturing and deployment level of BESS. The following recommendations[23] can help overcome these challenges and facilitate the deployment of BESS technologies in the country.

At Manufacturing Level:

- Indian ACC manufacturers import most cathode and anode active materials from China and other countries. Developing an upstream value chain will fulfill the mandate of ACC PLI and reduce import dependency.
- India has resources and reserves for Li, Co, Ni, and Mn. Further exploration and examining the feasibility of mining and processing can help India strengthen the supply chain of critical battery materials.

23 These recommendations are compiled from the inputs received from the industry players through primary survey or one-on-one interactions.

- The companies engaged in manufacturing ACC components/materials (cathode, anode, electrolyte, separator, current collectors, etc.) should be provided special incentives to bring cost competitiveness and promote indigenous manufacturing.
- Loans with lower interest rates and longer tenure can be provided. Provided the importance of ACC batteries in realizing the net zero emissions goals, financing can be considered under priority sector lending.
- Import duty exemption:
  - Raw materials: The critical materials to manufacture these precursor materials are imported. Therefore, a duty exemption on the imports of raw materials/minerals will be helpful during the initial years of operations.
  - Import of capital equipment for raw material production.
- Government can facilitate collaborations with countries to support sourcing critical minerals/materials and technology for manufacturing.
- Support domestic manufacturing by levying duties on imported products (semi-finished/finished goods)
- To promote a circular economy in the battery manufacturing value chain.
- To promote R&D in advanced materials and emerging battery technologies.
- To support the reduction of carbon footprint by substituting coal-based energy with renewable energy. This will complement the net zero emission goals and enable a sustainable manufacturing ecosystem.

At Deployment Level:

- Policy and regulatory support: Government support in designing policies and regulations (contribution in energy, capacity, ancillary service, etc.) is needed to implement BESS effectively. Globally, countries like the US, Japan, Australia, Germany, and South Korea have introduced several policy initiatives to encourage deploying renewable energy and storage integration. These policies provide incentives to help reduce the cost of BESS and make it competitive with other storage technologies. The MoP introduced a viability gap funding to support 4000 MWh BESS projects in the country. Further, the government can help with a reduction in taxation rates for batteries to bring down the upfront cost of BESS installations.
- Issuance of tenders by central and state government agencies related to renewable energy in integration with energy storage will boost the deployment of energy storage in the country subject to its timely implementation and commissioning.
- To improve the efficiency of batteries and reduce degradation, the developer needs to follow the specifications recommended by the manufacturers. Optimizing the charging and discharging is essential to increase the lifetime of batteries.
- With the great push for Electric Mobility and BES deployment, it is important to analyze the role of EV batteries for grid ancillary support.
- A proper set of guidelines/standards needs to be developed for implementing BESS, and there should be a particular focus on safety while handling, transporting, installing, operating, dismantling, etc. BESS.
- The mandatory conditions for selecting the BESS site must be considered during the feasibility analysis.
- Proper waste management procedures should be followed to reduce the environmental impact of batteries post-life. End-of-life treatment and recycling of these batteries will help create a green and circular economy. Further, developing environmentally benign battery technologies will help reduce the Co_2 emissions and other environmental impact.

About Customized Energy Solutions (CES)

Customized Energy Solutions is one of the fastest growing energy consulting & services companies, operating in North America for the past 18 years. Customized is working with over 400 clients across the value chain of electricity industry globally. We started our India operations as Customized Energy Solutions India Pvt. Ltd in 2010. We work with commercial and industrial customers to help reduce their energy costs through better utilization of the energy markets and emerging technologies. We have helped bring innovative energy services such as demand response to India. We are pioneering in exploring integration of latest technologies such as energy storage, microgrids as well as smart grid maturity model to Indian consumers. Unlike most consulting companies; we help clients from the feasibility study through implementing solutions as well as offer services to optimize operations. We work with our clients to improve communication and metering, integration of renewable generation as well as other emerging technologies, and active management of resources through utilization of our 24*7 operations center.

About India Energy Storage Alliance (IESA)

India Energy Storage Alliance (IESA) is a leading industry alliance focused on the development of advanced energy storage, green hydrogen, and e-mobility technologies in India. Founded in 2012, by Customized Energy Solutions (CES), IESA's vision is to make India a global hub for R&D, manufacturing, and adoption of advanced energy storage, e-mobility, and green hydrogen technologies. The alliance has been at the forefront of efforts seminal in shaping an enabling policy framework for the adoption of energy storage, electric mobility, green hydrogen, and emerging clean technologies in India. With close to a decade of experience, IESA provides its member network a holistic eco-system to network and grow their business in India and world-over by providing in-depth analysis of the market, facilitating dialogue between industry and government stakeholders, and providing the latest skill-development training. Over the years, IESA has launched several initiatives that support its member companies to stay ahead of the curve. IESA is a proud network of 170+ member companies, encompassing industry verticals from energy storage, EV manufacturing, EV charging infrastructure, green hydrogen, microgrids, power electronics, renewable energy, research institutes and universities, and cleantech startups.

Authors	
	
Bhushan Khade Manager – Stationary Energy Storage IESA, Customized Energy Solutions	**Bhupesh Verma** Manager – Market Research IESA, Customized Energy Solutions

Contributors			
			
Dr. Rahul Walawalkar President, India Energy Storage Alliance MD, Customized Energy Solutions, India	**Debi Prasad Dash** Executive Director- IESA, Customized Energy Solutions	**Bindu Madhavi** Director – Policy & Regulatory IESA, Customized Energy Solutions	**Sameer Khirpurikar** Manager – Policy & Regulatory IESA, Customized Energy Solutions