eTECH nxt

ENERGY STORAGE-ENABLING FIRM AND DISPATCHABLE RENEWABLE ENERGY

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16th Edition
ELECRAMA 2025
Powering the Future of Energy
22 - 26 February 2025 | India Expo Mart Greater Noida, Delhi NCR

eTECHnxt

Clean Energy (R)Evolution-
Carbon Markets, Storage &
Generation

24-25 February 2025
India Expo Mart, Greater Noida
Delhi NCR

AN OVERVIEW

The energy landscape is undergoing a profound transformation, driven by the urgent need to reduce greenhouse gas emissions and transition to a more sustainable future. New energy technologies are emerging at a rapid pace, offering innovative solutions to meet the energy demands while minimizing environmental impact.

The Union Budget 2024-25 underscores India's commitment to a sustainable energy future. Commercializing indigenous Advanced Ultra Super Critical (AUSC) thermal power plant technology, promoting energy storage solutions for seamless integration of renewable energy, exploring geothermal energy potential, advancing green hydrogen production, and developing a robust carbon market are key steps towards enhancing energy efficiency, ensuring grid reliability, reducing carbon emissions, and fostering a sustainable energy landscape.

eTECHnxt platform is created to serve as a catalyst for innovation, discussing and showcasing the technologies and trends that will shape the future of electrical and allied electronics industry.

Previous editions of eTECHnxt have successfully illuminated pathways in new and cutting-edge areas like EV's, Green Hydrogen, Energy Storage, IOT and Artificial Intelligence. The conference consistently emphasizes the need for industry to seize these opportunities proactively rather than passively waiting.

KEY TRACKS

The 4th edition of eTECHnxt will delve in details on the below tracks:

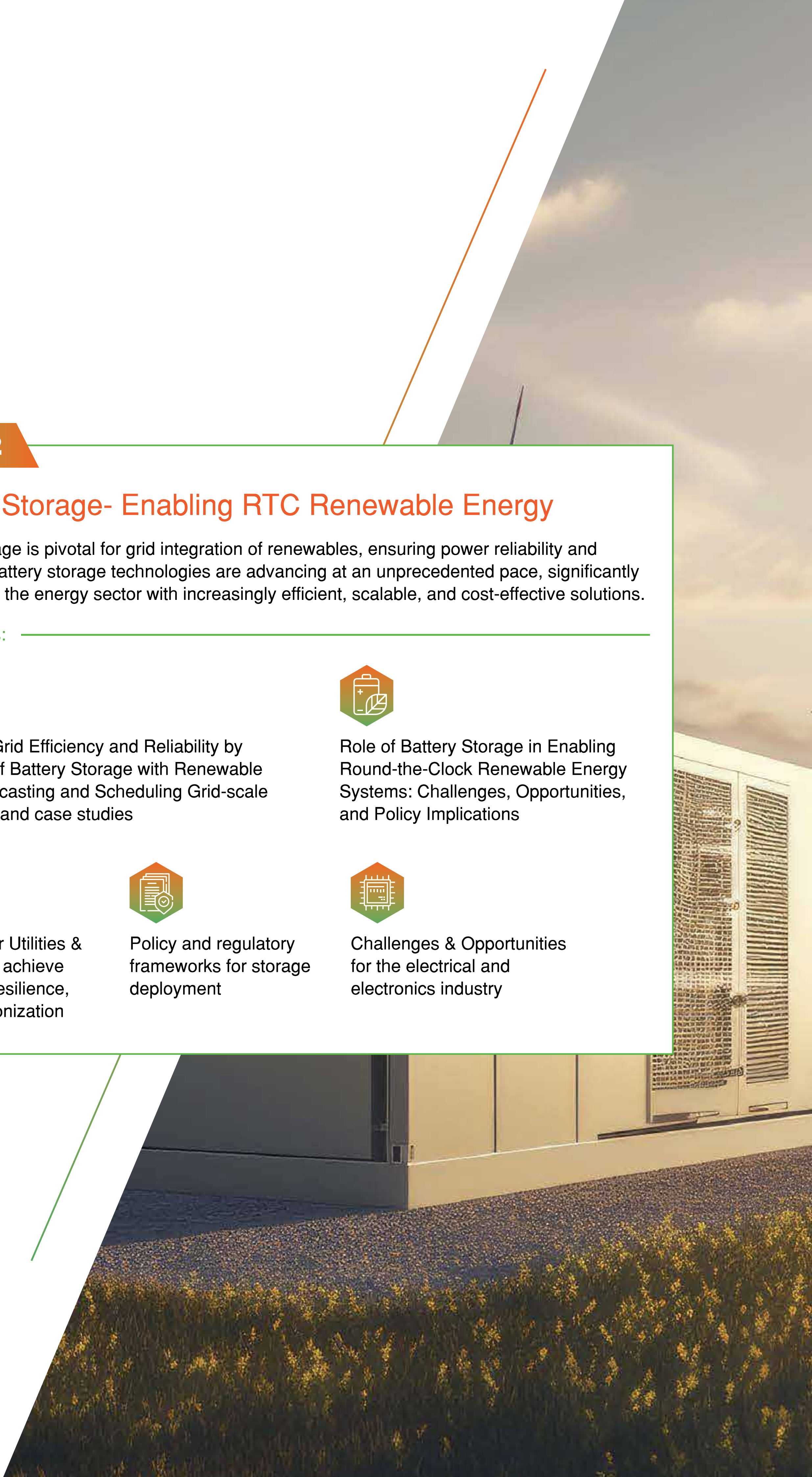
Track 1

Carbon Eco System & Markets

Decarbonization is a global imperative and carbon compliance & markets are emerging as a critical tool. India is poised to play a significant role.

Focus Areas:

- Understanding carbon eco system & markets (compliance and voluntary)
- Challenges & Opportunities for the electrical and allied electronics manufacturing industry
- Carbon credit generation and trading
- Policy landscape and future outlook



Track 2

Energy Storage- Enabling RTC Renewable Energy

Energy storage is pivotal for grid integration of renewables, ensuring power reliability and resilience. Battery storage technologies are advancing at an unprecedented pace, significantly transforming the energy sector with increasingly efficient, scalable, and cost-effective solutions.

Focus Areas:

- Enhancing Grid Efficiency and Reliability by Integration of Battery Storage with Renewable Energy Forecasting and Scheduling Grid-scale applications and case studies
- Role of Battery Storage in Enabling Round-the-Clock Renewable Energy Systems: Challenges, Opportunities, and Policy Implications
- Roadmap for Utilities & Industries to achieve Flexibility, Resilience, and Decarbonization
- Policy and regulatory frameworks for storage deployment
- Challenges & Opportunities for the electrical and electronics industry

Track 3

Power Generation NxT- New Frontiers

While renewables are at the forefront, conventional generation continues to play a role. New advancements and approaches are needed to blend diverse power sources and enhance their efficiency and sustainability.

Focus Areas:

- Clean & efficient coal technologies
- Small modular reactors (SMRs) for distributed generation
- Hybrid models combining renewables with conventional sources
- The evolving role of thermal and nuclear within India's energy mix till 2032

MESSAGE FROM THE DESK OF CHAIRMAN

Mustafa Wajid
Chairman, eTECHnxt 2025 & Chairman,
MEHER Group

Welcome to the 4th edition of eTECHnxt. This year's theme, "The Green Energy (R)Evolution" will focus on key technologies and business opportunities that will drive significant value creation in the green energy sector.

This edition of eTECHnxt @ ELECRAMA 2025 features three key tracks

- The emerging "Carbon Eco System & Markets"
- The rapidly evolving area of "Energy Storage - Enabling Round the Clock Renewable Energy", across the Electricity value chain
- Power Generation NxT - New Frontiers

By focusing on these key tracks, eTECHnxt aims to drive innovation, foster collaboration, and accelerate the transition to a sustainable energy future.

Join us at eTECHnxt 2025 to know more about the changing technology and policy landscape and imagine business opportunities that you can pursue.

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Abbreviation

2FA	Two Factor Authentication
AI	Artificial Intelligence
ARENA	Australian Renewable Energy Agency
AS	Ancillary Service
AUD	Australian Dollar
BaaS	Battery-as-a-Service
BESS	Battery Energy Storage System
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
BTM	Behind the Meter
BU	Billion Units
CAES	Compressed Air Energy Storage
CAGR	Compound Annual Growth Rate
CCGT	Close Cycle Gas Turbine
CEA	Central Electricity Authority
CHP	Combined Heat and Power
C&I	Commercial and Industrial
CLM	Customized Leasing Model
CO2	Carbon Dioxide
CPPA	Corporate Power Purchase Agreement
DFI	Development Finance Institution
DC	Direct Current
DG	Diesel Generator
DISCOM	Distribution Company
DOE	Department of Energy
DR	Demand Response
DSM	Deviation Settlement Mechanism
EMS	Energy Management System
EPC	Engineering, Procurement and Construction
ESG	Environmental, Social, and Governance
ESO	Energy Storage Obligation
ESS	Energy Storage System
EV	Electric Vehicle
EVCI	Electric Vehicle Charging Infrastructure
EU	European Union
EY	Ernst & Young
FDRE	Firm and Dispatchable Renewable Energy
FERC	Federal Energy Regulatory Commission

Abbreviation

FIP	Feed-in Premium
FIT	Feed-in Tariffs
FTM	Front of the Meter
FY	Financial Year
GW	Gigawatt
GWh	Gigawatt-hour
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IEEMA	Indian Electrical and Electronics Manufacturers Association
INR	Indian Rupee
IRA	Inflation Reduction Act
ISTS	Inter-State Transmission System
ITC	Investment Tax Credit
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life Cycle Analysis
LCOE	Levelized Cost of Energy
LDES	Long Duration Energy Storage
LFP	Lithium Iron Phosphate
LOLP	Loss of Load Probability
MDB	Multilateral Development Bank
METI	Ministry of Economy, Trade and Industry
MFA	Multi Factor Authentication
MTPA	Million Tonnes Per Annum
MV	Medium Voltage
MW	Megawatt
MWh	Megawatt-hour
NESM	National Energy Storage Mission
NIEV	NI Intelligent Electric Vehicle
NITI	National Institution for Transforming India
NMC	Nickel-Manganese-Cobalt
OCGT	Open Cycle Gas Turbine
OCV	Open Circuit Voltage
PCG	Partial Credit Guarantee
PLI	Production Linked Scheme
PPA	Power Purchase Agreement
PPP	Public-Private Partnership
PSB	Polysulphide-Bromide Battery

Abbreviation

PSH	Pumped Storage Hydroelectricity
PSO	Particle Swarm Optimization
PSP	Pumped Storage Project
PV	Photovoltaic
R&D	Research and Development
RD&D	Research, Development and Demonstration
RE	Renewable Energy
RES	Renewable Energy Source
RPO	Renewable Purchase Obligation
RTC	Round the Clock
SCADA	Supervisory Control and Data Acquisition
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SSB	Solid State Battery
SSO	Single Sign On
STEPS	Stated Energy Policies Scenario
T&D	Transmission and Distribution
TW	Terawatt
TWh	Terawatt-hour
UHV	Ultra-High Voltage
UK	United Kingdom
UPS	Uninterruptable Power Supply
US	United States
USD	United States Dollar
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant
VRFB	Vanadium Redox Flow Battery
VT	Voltage Transformer
ZBFB	Zinc-Bromine Flow Battery

1

Introduction

The global energy transition is underway, driven by the urgent need to reduce carbon emissions and mitigate the impacts of climate change. Renewable energy (RE) sources, particularly solar and wind, are at the forefront of this shift, providing cleaner alternatives to fossil fuels. However, while renewable energy generation offers significant environmental benefits, its inherent intermittency presents challenges for integrating these sources into the power grid. Solar power is only generated during daylight hours, and wind power depends on favorable weather conditions. To realize the full potential of renewables and ensure a stable, reliable energy supply, it is crucial to address the need for uninterrupted 24X7 power supply.

Energy storage technologies have emerged as a key solution to this challenge. Energy storage application provide solutions/options to store surplus energy generated during high renewable generation and discharging it during no/low renewable generation. Energy storage solutions enable firm and dispatchable renewable energy (FDRE) —allowing the grid to run on clean, renewable power round the clock.

1.1 Context

As the world continues to pivot towards a low-carbon energy future, the demand for RE is rapidly increasing. However, the variability of renewable sources, such as solar and wind, presents a unique challenge to grid operators. These energy sources do not produce power consistently or predictably, which can lead to power shortages or surpluses, complicating the grid management.

Round-the-clock RE, or the ability to ensure continuous renewable power availability regardless of intermittency, is a critical goal for achieving a fully decarbonized energy system. To achieve this, it is essential to have energy storage systems capable of bridging the gap between renewable generation and consumption. Energy storage not only addresses intermittency but also plays a vital role in enhancing grid stability, reducing dependence on fossil-fuel-based plants and enabling efficient energy use.

In this context, a variety of energy storage technologies, such as batteries, pumped hydro storage, thermal storage, and emerging solutions like hydrogen storage, are rapidly evolving to address the grid integration issues. These technologies can store excess renewable energy generated and release it during times of no/low renewable energy generation ensuring a reliable and flexible power supply.

Moreover, as renewable energy technologies become more widespread, there is a growing need for supportive policy frameworks, regulatory measures, and market structures that facilitate renewable integration into the grid. Governments, utilities, and industry stakeholders must work together to create a conducive environment for renewable integration backed by deployment of energy storage systems at scale.

This white paper delves into the role of battery energy storage in enabling firm and dispatchable renewable energy, exploring the technical advancements in storage systems, the economic and environmental benefits, and the policy and regulatory frameworks that will help drive their adoption. It aims to provide a comprehensive overview of the key factors that will enable the realization of a clean, reliable, and sustainable energy future powered by renewable sources.

1.2 Sustainable Power Supply Solution – Firm and Dispatchable RE Power

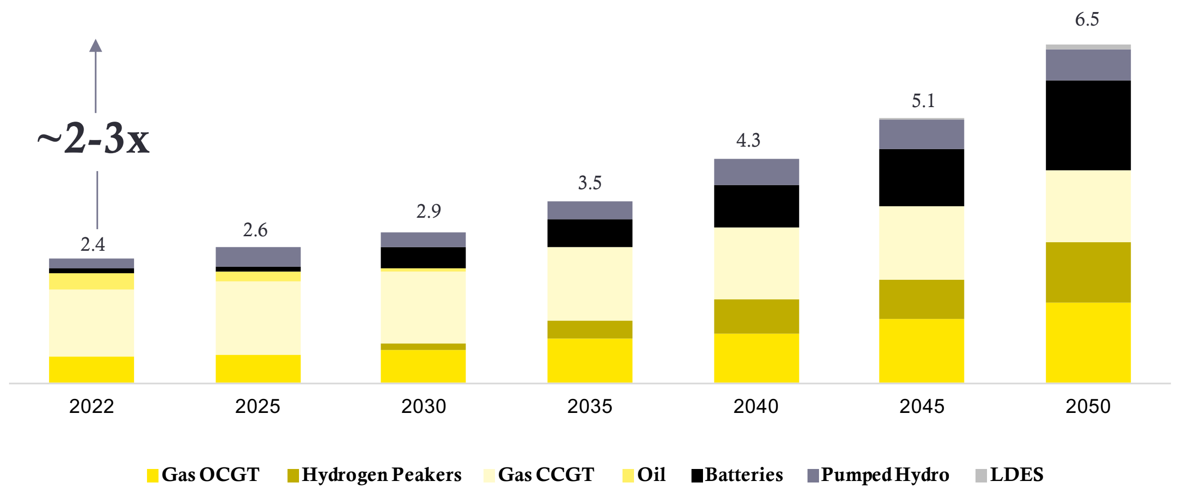
Global electricity demand is expected to more than double from 25,000 terawatt-hours (TWh) in 2022 to between 52,000 - 71,000 TWh by 2050, due to the growth in emerging markets' energy needs and electrification across the global economy1.

The RE sources contributed 32% of total global power generation and it is expected to grow at a rapid pace over the next couple of decades. RE sources are expected to contribute 45% to 50% of generation by 2030 and 65% to 85% by 20501.

With the projected growth in power demand, the retirement of older & non-flexible dispatchable capacity and the growing share of intermittent renewables, there will certainly be a greater need for flexible assets on both the supply and demand side to ensure security of supply.

In the long term, the flexible energy solutions will play a major role in ensuring grid stability and RE integration. The flexible energy solutions include options across thermal side and storage side. The thermal side options comprise of gas OCGT (Open Cycle Gas Turbine), gas CCGT (Close Cycle Gas Turbine), hydrogen and oil. The storage side options comprise of batteries, pumped hydro and LDES (Long Duration Energy Storage). The total capacity of flexible energy was 2.4 thousand GW in 2022 and is expected to reach 6.5 thousand GW by 2050, which represents 2 to 3 times growth. Among all flexible energy solutions, battery capacity appears to be most promising and expected to grow exponentially. Figure 1 indicates the global flexible capacity and current trajectory scenario1.

Fig 1: Global Flexible Capacity, Current Trajectory Scenario, Thousand GW



1.3 Role of Storage Applications in Firm and Dispatchable RE Power

FDRE is a power source that provides a continuous supply of electricity from green sources to consumers as when required in a reliable way. FDRE is achieved by integrating variable RE with Energy Storage Systems (ESSs).

FDRE is essential to steer the energy transition in the emerging era of energy resilience and sustainability. It is vital for enhancing grid stability and unleashing the complete potentials of renewable sources. The high penetration of variable and intermittent renewable energy poses challenges such as grid balancing and underutilisation of the transmission system. These challenges can be solved through FDRE power, which is obtained by transforming the variable RE into FDRE through integration with energy storage systems.

ESSs play a vital role in FDRE by storing excess energy and releasing it when needed. This helps integrate renewable energy into the grid and makes it more reliable. Battery storage is expected to grow significantly in ESSs, as seen in Figure 1 of section 1.2 and can enable FDRE availability. The benefits of battery storage will be discussed in the subsequent section.

1.4 Strategic Fit of Battery Storage

Battery Energy Storage Systems (BESS) are a strategic fit for the world's energy needs because they can provide major benefits:

01 Peak Load Management

BESS helps manage peak load by storing excess energy during off-peak times and releasing it during high demand, reducing reliance on costly peaking power plants.

02 Demand Shifting

With country having Time-of-Day tariff structure, BESS can be utilized such that consumer uptake energy from BESS during peak tariff hours.

03 Improved Power Quality

BESS supports grid by managing fluctuations in voltage and frequency, thereby enhancing power quality.

04 Better RE Utilization

BESS provides a means to store excess RE, leading to reduced curtailment, thus enhancing overall utilization of RE generation.

05 Diesel Abatement

BESS can be used to supply backup power and replace expensive and environmental unfriendly DG power and it is also an economically viable solution.

06 Energy Resiliency

BESS can help keep the electricity on during adverse conditions, such as major storms or other types of utility outages.

2

Battery Energy Storage Technologies

BESS are rapidly emerging as a cornerstone of modern energy grids, offering the ability to store excess energy generated from renewable sources and discharge it when needed. These systems are essential for enabling Round-the-Clock (RTC) RE by addressing the intermittency and variability of renewable generation. There are several types of BESS solutions and applications, which are described in the subsequent sub sections.

2.1 Solutions

BESS offer versatile solutions across various applications, from peak management and grid stability to behind-the-meter storage and long-duration energy storage. BESS enables more efficient use of renewable energy, reduces costs, and enhances energy security. These solutions are key to advancing a sustainable, resilient, and low-carbon energy future.

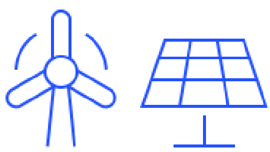
1. Peak Management / Grid Management Storage
2. Behind the Meter (BTM) Storage
3. Long Duration Energy Storage

2.1.1 Peak Management / Grid Management Storage

The primary customers for Front-of-the-Meter (FTM) installations include utilities, grid operators, and renewable developers seeking to manage the intermittency of renewables, provide grid stability services, or postpone expensive grid infrastructure investments.

Front of the Meter (FTM)

Electricity Generation and Distribution



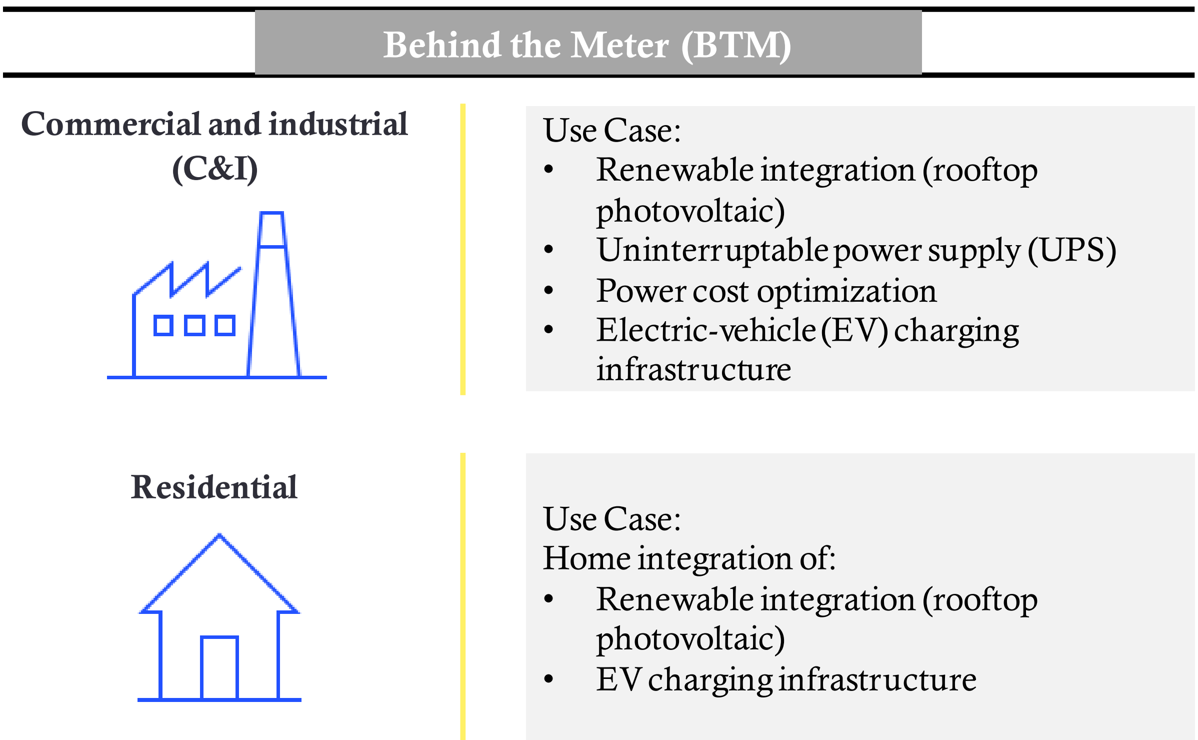
Use Case:
- Price arbitrage
- Long-term capacity payments
- Ancillary service markets
- Derisking renewable generation
- Investment deferral

BESS providers in this segment are typically vertically integrated battery manufacturers or large system integrators, who differentiate themselves through cost, scale, reliability, project management experience, and their ability to develop energy management systems and software solutions for grid optimization and energy trading.

Revenue models for utility-scale FTM BESS are highly dependent on regional market dynamics. Most players in this space adopt a revenue stacking strategy, drawing income from multiple sources, such as ancillary services, arbitrage, and capacity auctions. For example, in the UK, many BESS installations focus on ancillary services like frequency control, while in Italy, BESS providers have succeeded by securing wins in renewables-focused capacity auctions. In Germany, the focus is more on reducing the need for expensive grid upgrades.

2.1.2 Behind the Meter (BTM) Storage

BTM storage is comprised of two segments as shown in below pictogram: commercial & industrial segment and residential segment.



The C&I segment further consists of four subsegments. The first is electric vehicle charging infrastructure (EVCI). According to the McKinsey Center for Future Mobility, EVs are expected to grow significantly in global vehicle sales over the next 2 to 3 decades. This rapid growth will require the expansion of regular charging stations and superchargers, which will strain the existing grid infrastructure and require costly, time-consuming upgrades. To avoid this, charging station companies and owners will have to put a BESS or battery swapping solutions to facilitate the rapid growth of EVs.

The next subsegment of C&I is critical infrastructure, including telecommunication towers, data centers, and hospitals. In this subsegment, batteries typically provide temporary backup through an uninterruptible power supply during outages, until power is restored or diesel generators are activated. In addition to replacing lead-acid batteries, lithium-ion BESS products can also reduce reliance on less environmentally friendly diesel generators and can be integrated with renewable sources, such as rooftop solar. In some cases, excess energy stored in a battery may allow organizations to generate revenue through grid services.

The third subsegment includes public infrastructure, commercial buildings, and factories. In this subsegment, energy storage systems will primarily be used for peak shaving, integrating on-site renewables, optimizing self-consumption, providing backup power, and offering grid services. BESS has the potential to reduce energy costs in these areas by as much as 80%2. The case for The argument for BESS is especially strong in places such as Germany, North America, and the United Kingdom, where demand charges are often applied.

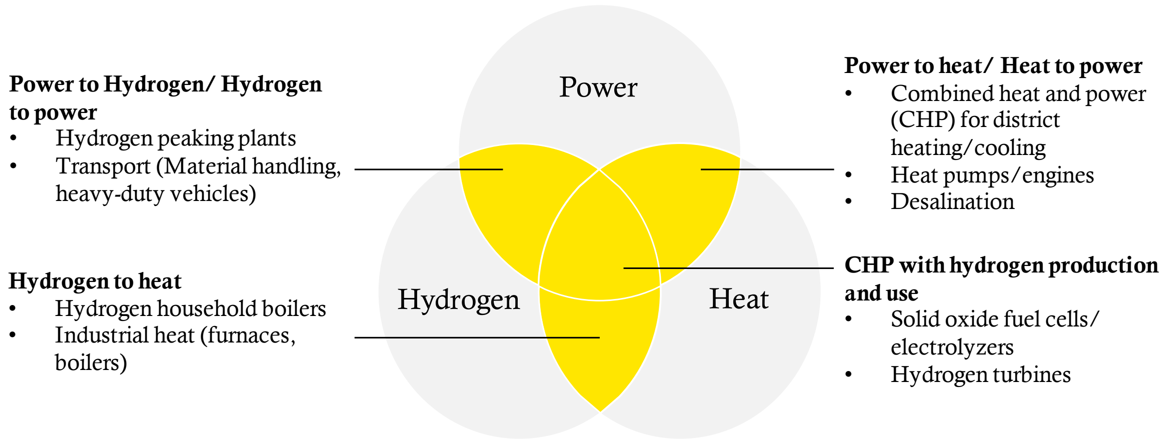
The last C&I subsegment include hard to abate sectors environments such as mining, construction, oil and gas exploration. Growth in this segment will be driven by customers transitioning from diesel or gas generators to low-emission solutions like BESS and hybrid generators. Many companies making the switch will begin by adopting hybrid genset solutions before fully transitioning to BESS.

The battery installation across residential segment are projected to reach 20 GWh by 20302, making it the smallest segment of BESS. The residential segment is highly attractive due to opportunities for innovation and differentiation, spanning from traditional home storage to the development of microgrids in remote communities. From a sales standpoint, BESS can be bundled with photovoltaic panels or integrated into smart homes and home EV charging systems. Customized products will enable residential customers to achieve objectives such as self-sufficiency, optimized self-consumption, and reduced peak power demand, potentially leading to higher profit margins in this sector.

2.1.3 Long Duration Energy Storage (LDES)

LDES includes a range of both conventional and innovative technologies, such as mechanical, thermal, electrochemical, and chemical storage, that can be deployed competitively to store energy for extended periods and scaled economically to support electricity supply for days or even weeks. LDES enhances system flexibility by absorbing and managing fluctuations in demand and supply, storing excess energy during surplus periods and releasing it when required. It provides a means of integrating and offering flexibility across the entire energy system, including power, heat, hydrogen, and other energy forms.

LDES plays a central role in allowing for energy system flexibility. The use cases for combined hydrogen and power energy sources include hydrogen peaking plants and transport applications. For combined hydrogen and heat, key use cases are hydrogen-powered household boilers and industrial heating. Combined power and heat applications involve systems such as combined heat and power (CHP) for district cooling, heat pumps, and desalination. Lastly, the integration of power, heat, and hydrogen energy sources is exemplified by solid oxide fuel cells/electrolysers and hydrogen turbines. The pictogram below shows how LDES use cases can connect energy sources3.



By 2040, LDES has the potential to deploy between 1.5 to 2.5 terawatts (TW) of power capacity, representing 8 to 15 times the total energy-storage capacity currently deployed worldwide. Similarly, it could provide 85 to 140 TWh of energy capacity, storing up to 10% of global electricity consumption. By 2040, the deployment of LDES could help avoid 1.5 to 2.3 gigatons of CO2 equivalent annually, accounting for approximately 10 to 15% of current power sector emissions3.

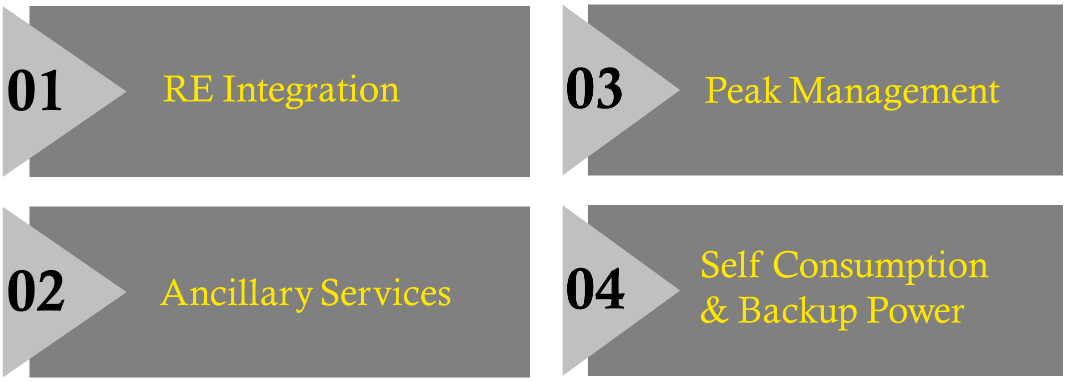
Some of the key benefits of LDES are described below:

- It entails low marginal costs for storing electricity
- It enables the decoupling of the quantity of electricity stored and the speed at which it is charged (taken in) or discharged (released).
- It is widely deployable and scalable
- It has relatively low lead times when compared to the upgrading of Transmission & Distribution (T&D) grids.

These benefits make it competitive with other energy storage technologies, such as lithium-ion batteries, dispatchable hydrogen assets, and pumped-storage hydropower, while being more economically favorable than costly and time-consuming grid upgrades. In fact, evidence suggests that for many applications, it is likely to be the most cost-effective energy storage solution for durations longer than six to eight hours.

2.2 Applications

BESS have a wide range of applications that support the integration and optimization of renewable energy. These applications include RE Integration, where storage helps manage the intermittent nature of renewables, and Ancillary Services, which ensure grid stability by providing services like frequency regulation. BESS also plays a crucial role in Peak Management, reducing stress on the grid during high demand periods, and in Self-consumption & Backup Power, enabling consumers to store energy for later use, improving energy independence & reliability. Details of each application will be discussed in the subsequent subsections.

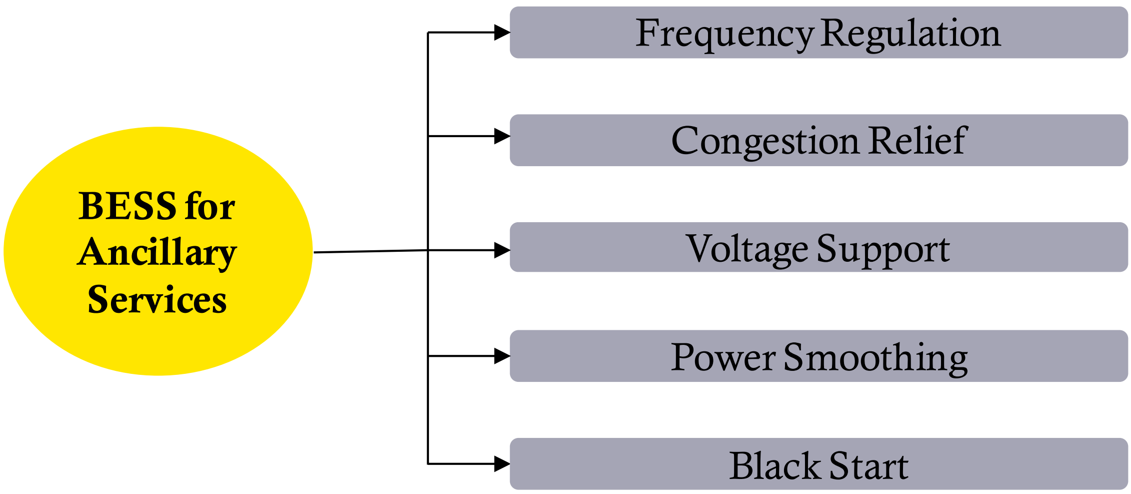


2.2.1 RE Integration

BESS plays a crucial role in integrating RE sources into the power grid by addressing their variability and intermittency. As RE generation increases, battery storage helps match generation with demand, offering a flexible and efficient solution compared to fossil-based generation. Batteries can smooth the output of wind and solar, making them more reliable and similar to conventional generation. Technologies like lithium-ion and flow batteries provide fast response times, enhancing grid stability. Storage can be co-located with RE systems or placed closer to consumers to reduce transmission congestion.

2.2.2 Ancillary Services

BESS is significant in providing ancillary services to the grid. Ancillary services encompass all the services necessary for the grid operations to maintain the system's integrity, stability, and power quality. Grid operators ensure a reliable power supply, frequency, voltage, and power load within certain limits. The schematic diagram of different ancillary services in BESSs is shown in below pictogram4.



The application of various BESS ancillary services is described in the table below.

Ancillary Services	Description
Frequency regulation	BESS effectively provides frequency regulation by quickly adjusting power to maintain grid stability. Optimal sizing and control strategies, such as Particle Swarm Optimization (PSO), enhance performance by managing fluctuations in renewable energy and battery state of charge (SOC). BESS can switch between frequency regulation and recharging, with centralized and distributed control methods optimizing grid and microgrid operations across primary, secondary, and tertiary control levels.
Congestion relief	BESS provides an efficient solution for congestion relief, surpassing traditional methods. It aids in voltage regulation and black start for distribution grids. Adaptive control algorithms and real-time frameworks optimize its use for congestion management, reducing the need for costly infrastructure upgrades.
Voltage support	BESS helps stabilize voltage in power systems, particularly when integrating large amounts of PV generation, by mitigating voltage fluctuations. However, frequent charging and discharging cycles can impact the system's cost and BESS lifespan. Strategies like real-time coordination and dynamic adjustment of charging/discharging help optimize voltage regulation while preserving the BESS's longevity and performance.
Power Smoothing (flow control between Renewable Energy Sources (RES) and the grid)	BESS offers fast response times, modularity, and scalability, making it ideal for managing fluctuations in supply and demand in power systems. It improves grid stability, mitigates voltage unbalance, and reduces network losses when integrated with PV systems. Additionally, BESS aids in frequency control and power flow management in microgrids, helping to smooth out power fluctuations caused by renewable energy intermittency.
Black start	Black start involves restoring power after a blackout using energy storage or DG sets. Microgrids with solar PV and BESS provide fast-response support for system restoration, addressing issues like reactive power balance and voltage regulation, unlike slower conventional units.

2.2.3 Peak Management

Peak load shaving is a demand response (DR) technique that reduces power demand during peak hours by cutting a portion of users' loads. BESS are commonly used in this process to discharge stored energy during high-demand periods, alleviating strain on the grid and potentially avoiding expensive infrastructure upgrades. Studies have shown that combining BESS with RES like solar and wind can reduce demand fluctuations and improve energy balance in microgrids. For example, a study on a residential microgrid demonstrated a 19%4 reduction in peak load fluctuation using a mix of BESS and renewables. Additionally, optimization frameworks and economic analyses highlight the viability and benefits of using BESS for peak shaving in grid and enterprise-level applications.

2.2.4 Self Consumption and Backup Power

BESS can be used for self-consumption and backup power in several ways, as shown in the pictogram below:

Self-consumption	BESS allows homeowners to use solar energy generated during the day to power their appliances at night. This can help homeowners optimize the use of their solar panels and increase the return on their investment.
Backup Power	BESS can provide a reliable source of power during power outages, ensuring the safety and continuity of critical household functions
Energy Independence	BESS can enable households to completely detach from the electrical or energy utility grid, providing energy independence and substantial cost savings on electricity bills
Peak shaving	BESS can be used to store energy when it is cheaper or more abundant and use it during peak demand periods. This can help reduce energy costs.

Additionally, battery energy storage systems are enabling transformative emerging applications in e-mobility, microgrids, and industrial sectors by enhancing energy efficiency, supporting off-grid solutions, and optimizing power usage. In e-mobility, they facilitate vehicle-to-grid integration, while in microgrids and industrial settings, BESS provide reliable backup power and help reduce energy costs.

Microgrids[40]	• Microgrids are small-scale power networks that can operate independently or in conjunction with the larger utility grid. Traditionally used in industry for power quality and cogeneration, microgrids with renewable energy sources are now increasingly powering remote communities. However, inverter-based renewables in these microgrids lack inertial response, which is crucial for frequency stability during system disruptions. Despite this, community microgrids are key to enhancing energy security and sustainability. Battery Energy storage has many benefits for microgrids: ➢ Providing ancillary services such as frequency regulation and voltage control, which are essential for microgrid operation ➢ Enhancing the integration of distributed and renewable energy sources ➢ Storing energy for use during peak demand hours ➢ Enabling grid modernization ➢ Integrating multiple smart-grid technologies ➢ Meeting end-user needs by ensuring energy supply for critical loads, controlling power quality and reliability at the local level ➢ Promoting customer participation through demand-side management
E-mobility[41]	• Vehicle-to-Grid (V2G) is an emerging technology that allows electric vehicles (EVs) to inject electricity back into the grid, transforming them into "batteries on wheels" that can help stabilize the grid and reduce the need for costly grid expansion. While many EV fleets are not yet equipped with bi-directional charging, the trend is shifting toward more V2G-compatible vehicles, with manufacturers like GM planning to include V2G as a standard feature in their EVs by 2026. Some models, such as the Kia EV9, already feature bi-directional charging capabilities.

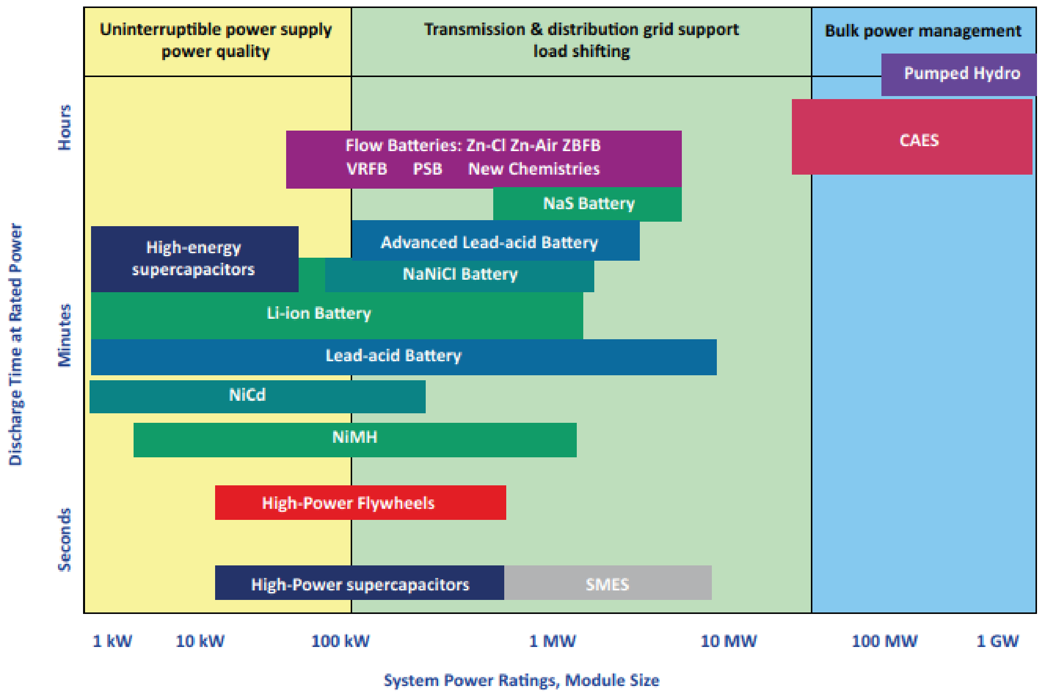
E-mobility	• Unidirectional charging, where EVs only draw power from the grid, can create strain during peak charging hours, leading to grid congestion. Smart charging offers a solution by allowing EV owners to manage charging times, typically during low-demand periods or when electricity prices are lower. In some cases, grid operators or third parties may optimize charging patterns to further alleviate grid pressures. An example of this is the NI Intelligent Electric Vehicle (NIEV) project in Northern Ireland, which explores intelligent charging to balance grid demands. • V2G goes beyond smart charging by enabling EVs to provide grid services, not just consume power. When aggregated, EV batteries can offer grid-supporting functions similar to stationary batteries, including load balancing and frequency regulation. One advantage of using EV batteries is that they eliminate the need for significant infrastructure investments, as millions of EVs are already in circulation, making the infrastructure readily available. Furthermore, the mobility of EVs allows them to address local grid challenges and congestion, a feature that stationary batteries typically cannot provide due to their fixed locations. This flexibility makes V2G a promising solution for enhancing grid resilience and optimizing energy use.

3

Technology and Market Landscapes

BESS market is rapidly evolving, fuelled by advances in battery technologies and the growing need for renewable energy integration. Key trends include the rise of lithium-ion and alternative storage technologies, driving new investment opportunities and shaping market dynamics globally. The Ragone plot13 shown in below pictogram helps in carrying out a comparative analysis of various energy storage technologies.

Fig 2: Ragone Plot



As it can be seen from the Ragone plot, chemical energy storage (batteries) covers a wide range of areas under the plot which signifies that battery storage is suitable for most of the applications.

3.1 Overview of Battery Storage Technologies

BESS stores electrical energy as chemical energy through electrochemical processes, with commonly used chemistries including lead, sodium, nickel, and lithium. BESS is increasingly favored for grid-level applications due to its quick response, energy-balancing capabilities, and falling costs. Unlike capacitors or flywheels, BESS can handle both power and energy applications. However, selecting the appropriate chemistry is crucial, as each offers different characteristics like charge/discharge rate, energy-power ratio, efficiency, and lifespan. The key parameters that can be defined and given weightage for selecting technology are described as below.

- Round trip efficiency - Round-trip efficiency is the percentage of electricity put into storage that is later retrieved. The higher the round-trip efficiency, the less energy is lost in the storage process.

- No. of life cycles - The cycle life of batteries is the number of charge and discharge cycles that a battery can complete before losing performance.

- Self-discharge - The battery loses the energy stored in it by itself due to its internal behaviour even when the connected application is not demanding any energy. Since the State of Charge (SoC) is directly linked with Battery Open Circuit Voltage (OCV), self-discharge leads to a reduction of SoC, which leads to reduction of OCV of the battery.

- Energy density - Battery energy density is the amount of energy a battery contains compared to its weight or size.

- Power density - Power density is the measure of how quickly the energy can be delivered

- Depth of discharge - The depth of discharge is the amount of a battery's storage capacity that is utilized.

The aforementioned parameters define the functional expectations from a battery storage application. The additional parameters which can be considered include Thermal Safety, Reaction time, Operating temperatures etc.

There are multiple energy storage technologies that are evolving and at various stages of deployment, as shown in the Ragone plot. Battery storage technology is rapidly advancing. Some of the battery storage technologies include lead acid, Li-ion, NaS, flow batteries, flywheel, NiCd, NiMH, and NaNiCl. The following table presents a few key battery storage technologies and their current state of maturity.

Parameter	Attributes	Lead Acid	Li-Ion	NaS	Flow Batteries	Flywheel	Na-ion
Efficiency parameters	Round Trip Energy Efficiency (DC-DC)	70-85%	85-95%	70-80%	60-75%	60-80%	90-95%
	Range of Discharge Duration (Hr)	2-6	0.25-4	6-8	4-12	0.25-4	4 – 8
	C Rate	C/6 to C/2	C/6 to 4C	C/8 to C/6	C/12 to C/4	C/4 to 4C	C/5 to 2C
	Cycle life: No. of discharges of stored energy	500-2000	2000-10000+	3000-5000	5000-8000+	100000	3000 - 5000

Cost and project parameters	Cost range per energy available in each full discharge ($/kWh)	100-300	250-800	400-600	400-1000	1000-4000	80-90
	Developer & Construction Period	6 months to 1 Year	6 months to 1 Year	6 months to 1.5 Years	6 months to 1.5 Years	1-2 Year	1-2 Year
	Operating Cost	High	Low	Moderate	Moderate	Low	-
	Estimated Space Required	Large	Small	Moderate	Moderate	Small	Large
State of Maturity	Maturity of Technology	Mature	Commercial	Commercial	Early to moderate	Early to moderate	Early traction

The flywheel battery storage technology has the highest life however the same is under very early states of maturity. Further, battery technologies with Zn-MnO2, Zn-Br2, Na-S, Na-Ion, Fe-FeCl2 are also at a good Technology Readiness level and having a great potential in terms of material availability. These technologies may be evaluated considering the Global Battery Storage requirements. The key advantages and disadvantages of each of these technologies are summarised in the following table42.

Battery Technology	Advantage	Disadvantage
Lithium-Ion	• Relatively high energy and power density • Lower maintenance costs • Rapid charge capability • Many chemistries offer design flexibility • Established technology with strong potential for project bankability	• High upfront cost ($/kWh) relative to lead acid (potentially offset by longer lifetimes) • Poor high-temperature performance • Safety considerations, which can increase costs to mitigate • Currently complex to recycle • Reliance on scarce materials
Flow (Vanadium Redox)	• Long cycle life • High intrinsic safety • Capable of deep discharges	Relatively low energy and power density.

Lead-Acid	• Low cost • Many different available sizes and designs • High recyclability	• Limited energy density • Relatively short cycle life • Cannot be kept in a discharged state for long without permanent impact on performance • Deep cycling can impact cycle life • Poor performance in high temperature environments • Toxicity of components
Sodium-Sulfur	• Relatively high energy density • Relatively long cycle life • Low self-discharge	• High operating temperature necessary • High costs
Sodium ion	• Abundantly available of sodium • Highly adaptable • Energy efficient • Fire safe • Low cost alternative • Less toxic • Stable at wider temperature	• Low energy density • Large size • Short cycle life

Battery storage technology in India is becoming increasingly important as the country accelerates its transition to renewable energy. The Indian government aims to achieve 500 GW of renewable energy by 203043, which will require efficient energy storage solutions to balance intermittent power generation from sources like solar and wind. Among the most widely used technologies in India are Li-ion batteries, Flow batteries, and Lead-acid batteries.

Li-ion batteries are currently the dominant energy storage solution due to their high efficiency, long lifespan, and compact design. These batteries are used across residential, commercial, and utility-scale applications, particularly for integrating renewable energy into the grid. With declining costs and a growing EV market in India, Li-ion batteries are set to play a major role in energy storage. Additionally, Flow batteries, such as Vanadium Redox Flow Batteries (VRFB), are gaining popularity for long-duration energy storage applications. Their scalability, durability, and ability to provide stable power for extended periods make them well-suited for large-scale grid applications and off-grid solutions in rural areas.

Lead-acid batteries continue to be used, especially for backup power and uninterruptible power supply (UPS) systems, though they are less efficient and have a shorter lifespan than Li-ion batteries. Despite this, they remain an affordable option for specific applications. As India's energy storage needs grow, these technologies will play a crucial role in supporting renewable energy integration, improving grid stability, and reducing carbon emissions.

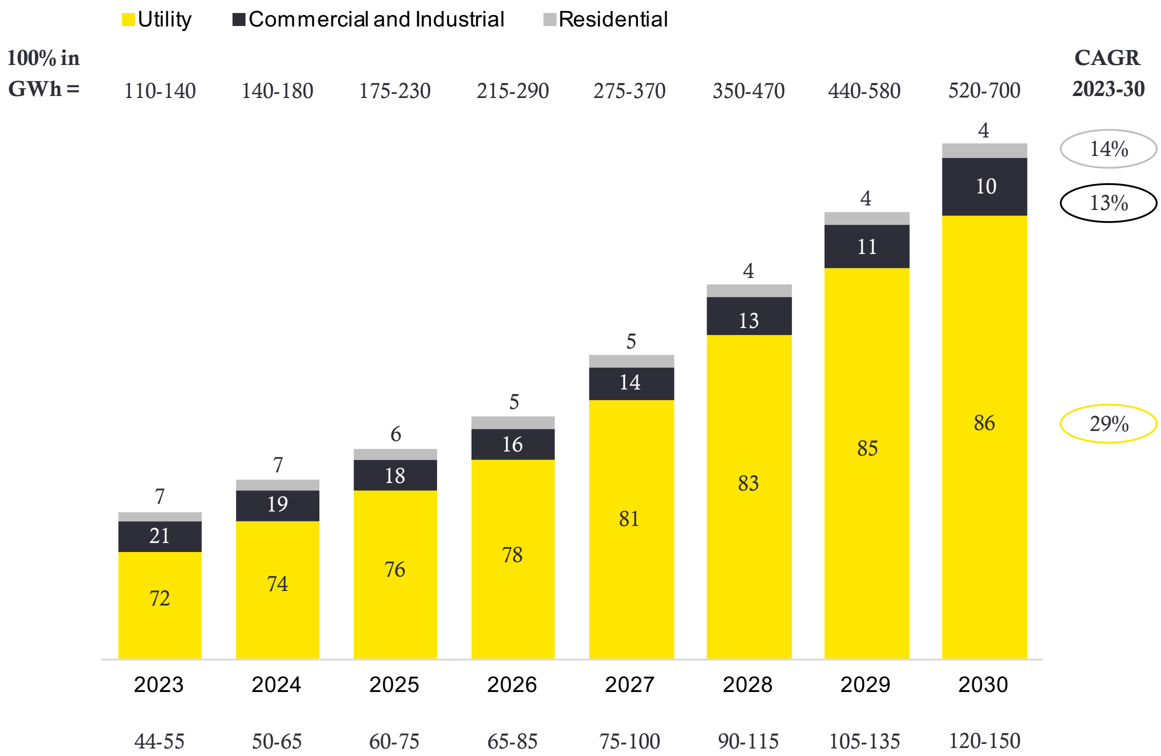
3.2 Market Size, Growth Trends, and Regional Dynamics

In 2023, BESS market was valued at USD 44-55 Billion and is expected to reach USD 120-150 Million by 2030 at the CAGR of 15% during 2023-2030 as shown in figure 36.

Utility-scale BESS, which currently represents the majority of new annual capacity, is expected to grow at a rate of approximately 29% per year for the remainder of this decade, making it the fastest-growing segment. By 2030, annual utility-scale installations are projected to range between 450 and 620 gigawatt-hours (GWh), potentially capturing up to 90% of the total market share in that year as shown in figure 36.

C&I is the second-largest segment and is expected to grow at a 13% CAGR and reach between 52 and 70 GWh in annual additions by 2030. The residential segment is expected to grow at a 14% CAGR and reach between 10 and 18 GWh in annual additions by 2030, as shown in Figure 3

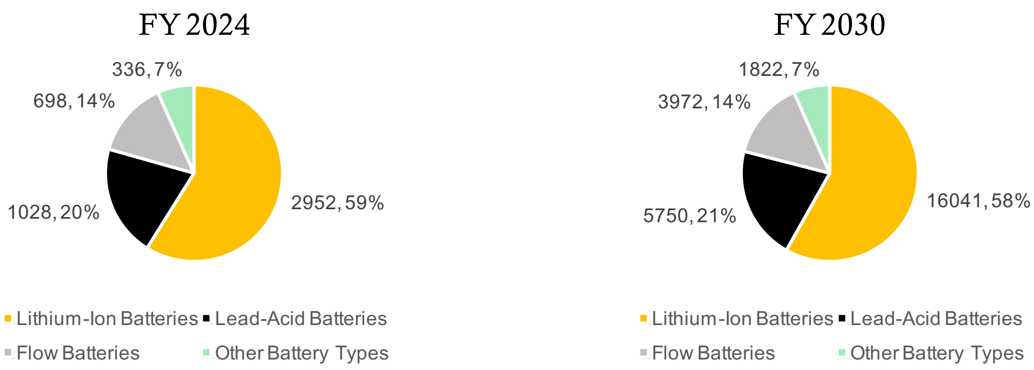
Fig 3: Annual added battery energy storage system (BESS) capacity, %



The growth of the BESS sector is closely tied to significant advancements in the automotive industry, particularly the rising demand for lithium-ion batteries driven by the electric vehicle (EV) boom. This segment, a key player in the battery energy storage market, was valued at USD 5.0 billion in 2024 and is projected to surge to USD 27.5 billion by 2030, reflecting a CAGR of 32.87% as shown in Figure 47. This upward trend highlights the increasing connection between EV adoption and lithium battery innovation, signalling a promising future for energy storage solutions

In addition to lithium, the dominant technology in the battery energy storage system (BESS) market, other battery technologies are also emerging with strong growth potential. Lead-acid batteries, known for their reliability, cost-effectiveness, and lower upfront costs compared to other battery types, are expected to grow from USD 1,028 million in 2024 to USD 5,750 million by 2030, achieving a CAGR of 33.24%[7]. Their affordability makes them a popular choice for automotive, UPS, and backup power systems.

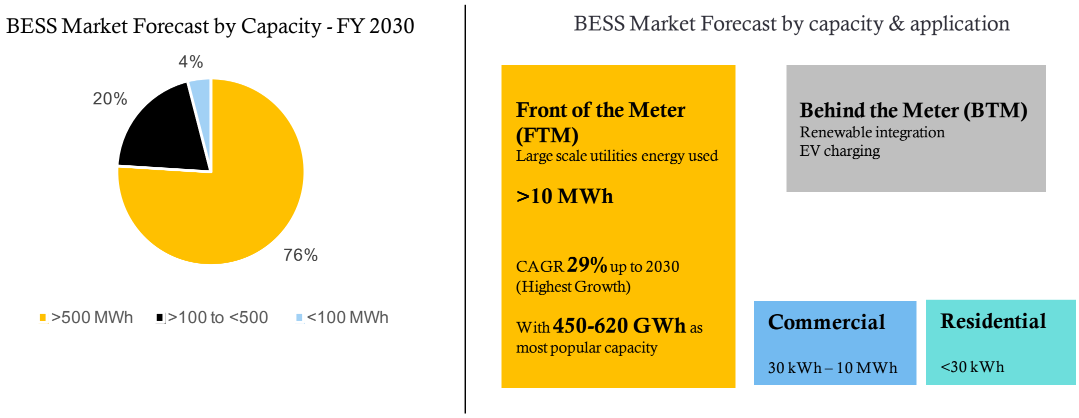
Fig 4: Global Battery Energy Storage System value (Million USD & %), by Battery



Meanwhile, flow batteries are gaining momentum due to their distinct advantages in long-duration energy storage. They are projected to grow from USD 698 million in 2024 to USD 3,972 million by 2030, achieving the highest growth rate of 33.62% among battery types, as shown in Figure 4. Flow batteries are becoming a key technology for stationary storage, offering scalability and long-term performance stability. This is exemplified by the commissioning of the world's largest vanadium redox flow battery in China, with a capacity of 100 MW and 400 MWh[7].

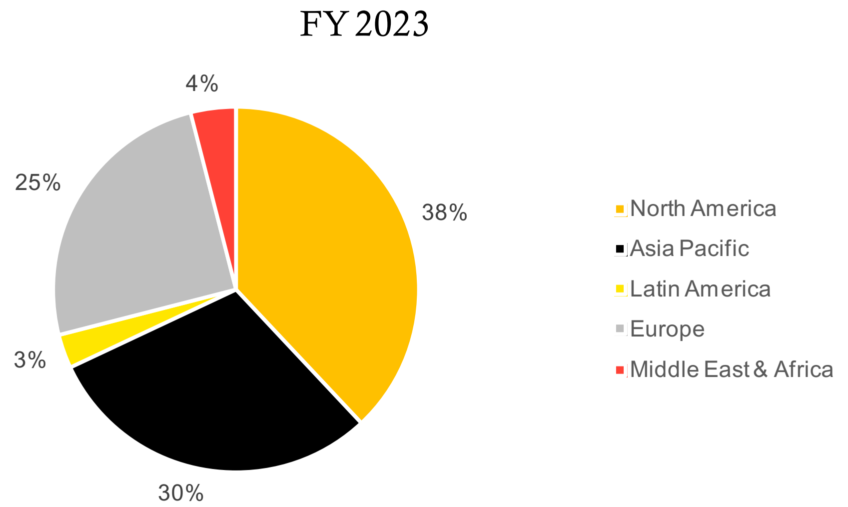
Integrating advancements in battery technology into BESS market projections, Apollo Research Reports highlights growth across various segments. The >500 MWh category is expected to increase to 76% by 2030, while the >100 to <500 MWh segment is forecast to grow to 20%. Similarly, capacities <100 MWh are projected to expand to 4% by 2030, as shown in Figure 5[7].

Fig 5: Global Battery Energy Storage System Market Forecast by Capacity Segmentation



On the basis of regions, the market is divided into regions: North America, Europe, Asia Pacific, the Middle East & Africa, and Latin America. The global battery energy storage systems market is highly fragmented, with various regions taking the lead in innovation, deployment, and policy support. The regional market share of BESS is shown in the figure below (Figure 6)[8].

Fig 6: Region Wise Market Share of BESS



North America dominates the global battery energy storage systems market due to significant investments, favorable regulations, strong governmental support, and a well-developed renewable energy infrastructure. European countries like Germany and the UK have implemented aggressive renewable energy strategies that heavily rely on energy storage systems for grid stability and energy security, boosting the battery energy storage systems market.

Asia-Pacific is witnessing the highest growth in the BESS market. After the U.S., China is the second-largest market for BESS, being a global leader in battery manufacturing and automotive production, alongside significant investments in grid-scale storage systems. Meanwhile, India is advancing rapidly with its ambitious renewable energy roadmap and electric mobility plans, as shown in Figure 6.

BESS market in India is growing rapidly, driven by the increasing integration of renewable energy and the need for grid stability. With India's target of achieving 500 GW of renewable energy by 2030, BESS will play a crucial role in managing intermittency and balancing supply and demand. Government policies like the Production-Linked Incentive (PLI) scheme and the National Mission on Transformative Mobility and Battery Storage are encouraging investment in battery manufacturing and battery energy storage projects. As per the National Electricity Plan projections of India, the estimated Installed Capacity addition of BESS during 2022-27 is 8,680 MW/34,720 MWh and is estimated to be 47,244 MW/236,220 MWh during 2027-32. According to the generation planning studies, the required energy storage capacity by the year 2026-27 is 16.13 GW/82.37 GWh, which includes 8.68 GW/34.72 GWh from BESS-based storage. By the year 2031-32, the storage capacity requirement is expected to increase to 73.93 GW (comprising 26.69 GW from PSP and 47.24 GW from BESS), with a total storage of 411.4 GWh (175.18 GWh from PSP and 236.22 GWh from BESS)9.

The below table shows the annual targets for storing the renewable energy between 2024-25 to 2029-3010. Ministry of Power's Energy Storage Obligations 2029-30 are used for estimating the utility-scale storage requirements. 19th Electric Power Survey (CEA 2022) to get India's peak energy demand (GWh) during the period is used to estimate the obligated stored energy (GWh) and corresponding batter requirement.

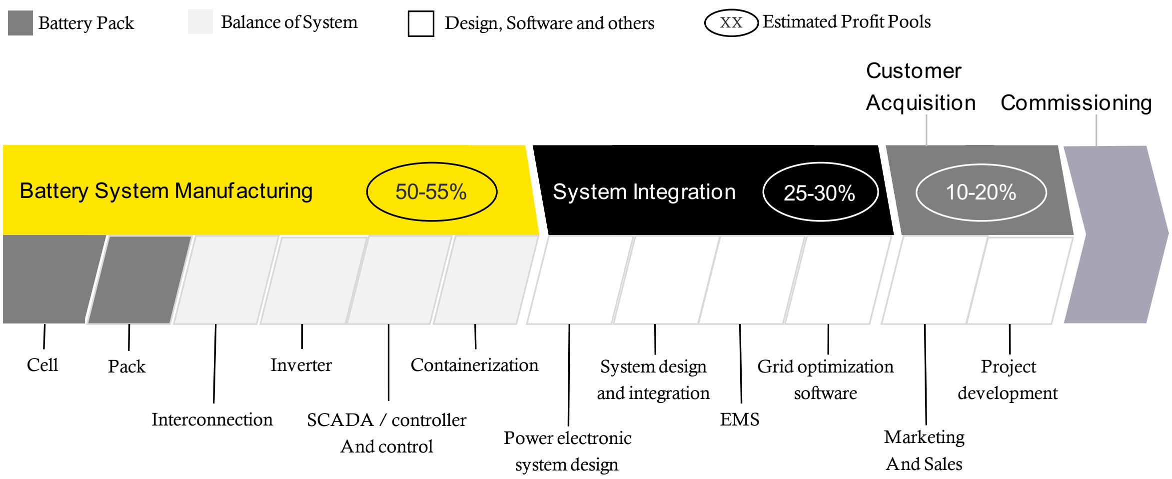
Year	India's projected peak demand (BU)	Energy Storage Obligation (%)	Energy from storage (GWh)	Battery Requirement (GWh)
2024-25	1,695	1.5%	25,420	91
2025-26	1,796	2.0%	35,933	129
2026-27	1,908	2.5%	47,696	171
2027-28	2,021	3.0%	60,632	217
2028-29	2,139	3.5%	74,869	268
2029-30	2,280	4.0%	91,187	327

The cumulative energy storage demand from grid applications comes about 327 GWh by 2030. India can capture significant value within local economy with the help of successful local battery manufacturing industry and supportive local supply chain. NITI Aayog estimates the market size for stationery and mobile batteries could surpass INR 491.4 billion by 2026 and INR 1,228 billion by 2030. An investment of INR 3,493 billion will be required between FY24-32 to achieve the above battery storage requirement10.

3.3 Supply Chain Conduciveness Across Regions

BESS value chain includes manufacturing, system integration, and customer acquisition as shown in figure 72.

Fig 7: Value chain breakdown of battery energy storage systems



BESS value chain begins with the manufacturers of storage components, including battery cells and packs, as well as inverters, housings, and other essential components in the balance of the system. This segment of the chain is expected to capture roughly half of the BESS market profit pool. Next, system integration activities, which involve the overall design and development of energy management systems and other software to enhance the flexibility and utility of BESS, will account for an additional 25 to 30% of the available profit pool. Finally, between 10 and 20% of the profit pool is associated with sales entities, project development organizations, customer acquisition activities, and commissioning2.

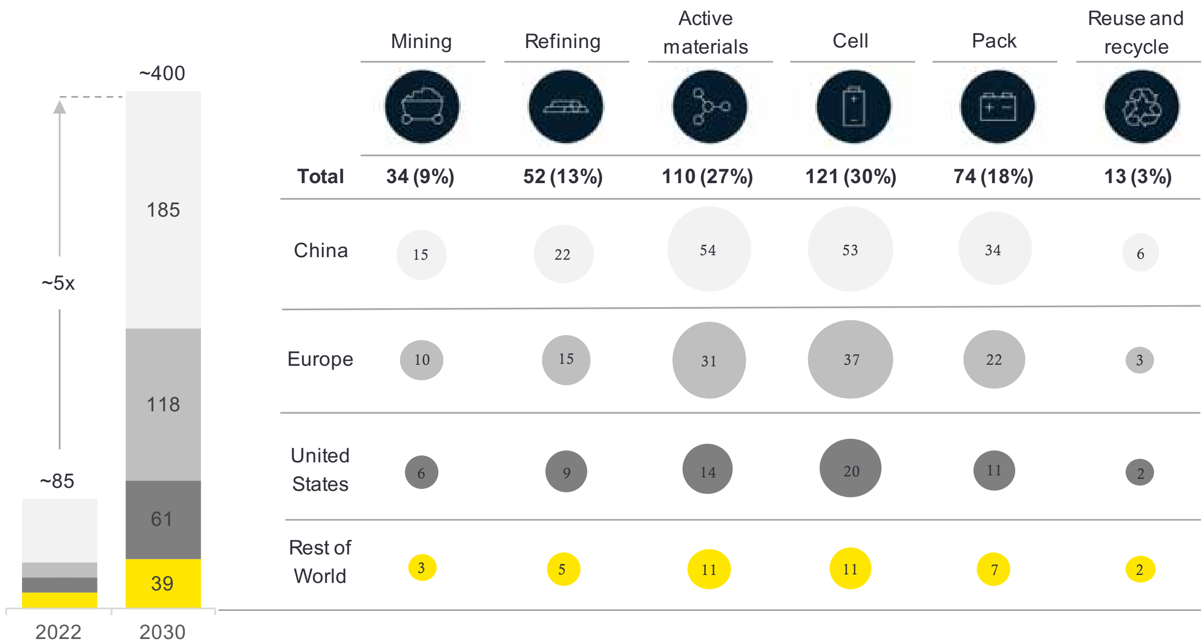
Many critical BESS components (ranging from battery cells to semiconductors in inverters and control systems) rely on complex supply chains, which are susceptible to supply shocks from a multitude of sources, including raw material shortages and regulation changes. Strategic partnerships, multi-sourcing, and local sourcing are all levers to consider when defining a supply chain strategy, while not forgetting to plan for potential technology shifts.

In addition to BESS components, another bottleneck for those in the market is engineering, procurement, and construction (EPC) capability and capacity, particularly for front-of-the-meter applications. Strategic partnerships with large EPC players ready for large-scale BESS installations are crucial to ensure successful execution of BESS projects.

The most suitable minerals for battery manufacturing include lithium (for energy density), cobalt (for stability), nickel (for higher capacity), manganese (for performance), graphite (for the anode), and aluminium (for construction). These minerals are essential in lithium-ion batteries, powering electric vehicles and energy storage systems. The Li-ion battery value chain across various geographies is shown in the figure below (Figure 8)11.

Li-ion battery value chain will provide revenue opportunities of over $400 billion by 2030 across various geographies

Fig 8: Revenues (Li-ion Battery) – 2030, $ billion



China is expected to account for 45% of total Li-ion demand in 2025 and 40% in 2030, as most battery-chain segments are already well-established in the country. However, the highest growth is anticipated to occur in the EU and the United States, driven by recent regulatory changes and the broader trend toward localizing supply chains. Globally, at least 120 to 150 new battery factories will need to be constructed by 203011.

As the demand for Li-ion batteries continues to surge across industries, revenues along the entire value chain are expected to increase 5-fold, rising from approximately $85 billion in 2022 to over $400 billion by 2030 (Figure 8)11. Active materials (27%) and cell manufacturing (30%) are likely to have the largest revenue pools. While mining remains a key source for battery materials, recycling offers an alternative. Although the recycling segment is projected to be relatively small in 2030, it is expected to grow more than threefold in the following decade as more batteries reach the end of their life cycle.

Companies in the EU and the US are among those that have revealed plans to launch new mining, refining, and cell production projects to meet growing demand, including the establishment or expansion of battery factories. Additionally, many European and US companies are exploring innovative business models within the recycling sector. Collectively, these efforts could play a significant role in localizing battery supply chains.

The battery demand in India is expected to rise to about 230 GWh by 203012 as per Niti Aayog's estimates. Despite such large demand, cell manufacturing is still at a nascent stage in India. Numerous players are looking to venture into Li-ion battery manufacturing in India. Most of companies in India are currently focusing on battery-pack manufacturing and are importing cells from China and Korea.

There is a critical need to localise the cell supply chain. The cell materials constitute round 40% of its cost, and India has minimal availability of cell raw materials. If India targets to achieve 60% of the value addition (As mandated by the PLI), it needs to localise the manufacturing of anode, cathode, and electrolyte. India currently imports most of the crucial metals required for lithium-ion cathode production, yet it has great potential for anode production. The availability of raw materials in India is shown in the table below12

Category	Material	Description
Cathode	Lithium	• India currently imports all its lithium. • The Atomic Minerals Directorate have estimated lithium reserves of 14,100 tonnes in a small patch of land in Southern Karnataka.
	Cobalt	• India currently imports all its cobalt. According to the Bureau of Mines, there is no cobalt production yet. • India is reported to have ore resources of 44.9 million tonnes, the potential is yet to be tapped.
	Manganese	• According to Geological Survey of India, total manganese reserves are estimated at 167 million tonnes. • About one-fifth of the world's manganese ores are found in India.
	Nickel	• As per National Mineral Inventory (NMI) database, resources of nickel are estimated at 189 million tonnes. • Odisha has the largest share of nickel ore in the country at 175 million tonnes (93%) followed by Jharkhand & Nagaland.
	Iron	• India is abundant in iron ores. The prominent ores of iron found in India are Hematite and Magnetite. According to NMI, the reserve of the ores are: • Hematite: Approximately 18,000 million tonnes, Magnetite: Approximately 10,500 million tonnes
Cathode	Phosphate	• India is deficient in Apatite & Rock Phosphate availability and is majority dependent on imports. • As per NMI, the total reserves of apatite re 24 million tonnes and of rock phosphate are 46 million tonnes.
Anode	Graphite	• India has graphite reserves of 11 million tonnes and resources of 158 million tonnes. • There are 3 graphite mine belts, mainly distributed in Andhra Pradesh and Orissa.
Electrolyte	Fluorspar	• As per NMI database, total reserves/resources of fluorite re 17.89 million tonnes. • Gujarat accounts for 66% of the total reserves, followed by Rajasthan 29%.

India is currently heavily dependent on imports for lithium-ion batteries, which account for a significant portion of the cost of energy storage systems. The production of lithium-ion cells in India is still in its early stage, but it is expected to grow rapidly in the coming years due to the government's initiatives to promote domestic manufacturing and the increasing demand for energy storage systems.

4

Policy and Regulatory Frameworks

Robust Policy and regulatory frameworks play a crucial role in accelerating the speedy adoption of BESS. Policies can provide the necessary incentives, streamline deployment processes, and ensure a supportive regulatory environment, while addressing barriers such as grid access, market participation, and safety standards. These frameworks are essential for enabling the integration of storage solutions into energy systems and supporting long-term sustainability goals. A quick snapshot of global policies landscapes are discussed in subsequent sub sections.

4.1 Policies Driving Battery Storage Adoption

Globally, policies have played a pivotal role in driving the adoption of BESS, which are crucial for enabling the transition to renewable energy by addressing intermittency and enhancing grid stability. As countries strive to reduce greenhouse gas emissions, energy storage has become essential to support the integration of renewable energy and ensure a reliable power supply. Battery storage, in particular, has emerged as the fastest-growing energy storage technology due to its efficiency, flexibility, and rapidly declining costs. Policies promoting energy storage are predominantly found in regions with advanced economies that possess the technical expertise and infrastructure to support innovation in the sector. Countries such as the United States, the United Kingdom, Germany, South Korea, Japan, China, and Australia have implemented mature ESS policies, fostering research, development, and demonstration (RD&D) projects that advance battery storage technologies. These policies typically include financial incentives, soft loans, and regulatory frameworks that create a level playing field for market participation. However, the adoption of ESS policies (including BESS) remain limited to a small number of countries. It is anticipated that emerging economies will draw lessons from these leaders and adopt similar policies to support local innovation and accelerate the transition to sustainable energy solutions. Some of the policies/ initiatives driving ESS in some of the major economies in the world are illustrated below:

Country	Policy/ Scheme/ Agency for Energy Storage
Australia	• Commonwealth Scientific and Industrial Research Organisation (CSIRO) is an Australian government agency who takes care of scientific research in the field of energy storage. • Australia Capital Territory - AUD 25 million Next Generation Battery Storage scheme aims at providing subsidized battery storage for 5,000 Canberra homes and businesses by 2020. • Queensland - No interest loans and rebates to be provided in 2018 to drive uptake of batteries. 100 MW reverse auction for energy storage, which forms part of 400 MW renewables auction. $50 incentive for owners who register their storage system with a new State database. • South Australia - Proposed a $100 million grant program to facilitate batteries in 40,000 homes.

Canada	• Power Advisory and Energy Storage Canada together are working on number of reports related to energy storage. • The Ontario Independent Power System Operator (IESO) will review and modify its Market Rules, where possible, to clarify the division of storage resources in markets managed by this operator. • The Ontario Energy Board (OEB) should review its grid codes to consider participation in energy storage and its regulatory framework. • The Government of Ontario should consider the role of energy storage as part of new legislation and regulations, as well as amendments to existing legislation and regulations, including Ontario Regulations 124/02 and 442/01 relating to the charging of gross income and tariff protection plan surcharge for rural and remote areas. • The OEB will consider the application of charges and the setting of tariffs as initiatives foreseen in its Business Plans, in order to identify the necessary regulatory interventions to facilitate the integration of DERs, including storage.
China	• Accelerating the Development of New Energy Storage and Participation in the Electricity Market and Power Conditioning: enabled energy storage to participate in ancillary services independently, rather than serving solely as solar-plus-storage. • National Development and Reform Commission (NDRC) - The 14th Five-Year plan specified development goals for new energy storage in China, by 2025, new energy storage technologies will step into a large-scale development period and meet the conditions for large-scale commercial applications.
France	• Article 85 of the Climate and Resilience Act dated 22 August 2021 created Article L. 352-1-1 of the French Energy Code, which provides direction for the calls for tenders to develop electricity storage capacities.16 • Storage facilities are defined in the Ministerial Order of 7 July 2016 as “a set of stationary electricity storage equipment allowing the storage of electric power in one form and its reconversion, while being connected to the public power grids.17
Germany	• Federal Requirements Plan (BBPlG), Energy Industry Act (EnWG) and Grid Expansion Acceleration Act (NABEG) now define energy storage as an asset.44 • The German Federal Ministry for Economic Affairs and Climate Action published a strategy for electricity storage aimed at supporting the ramp-up of electricity storage and achieving the “optimal integration” of storage into the electricity system18.
India19	• Energy Storage Obligations (ESO) Target set to 4% of energy requirement by 2030, 10 states includes the same in state RE policies. • National Framework for Energy Storage in India recommends mandatory 5% ESS participation in all Renewable tenders. • ISTS waivers, transmission charge waiver along with grant of connectivity approval for ESS formulated. • Viability Gap Funding (VGF) of INR 3,760 Crores to support 12 GWh of Standalone BESS projects approved, 8 states included. • Guidelines shared for competitive bidding for standalone BESS, Pumped Hydro and RE+ ESS projects. • BESS allowed to participate in Secondary and Tertiary Ancillary Markets along with participation in HP-DAM segment. • Energy Storage identified as Champion Sector and included in Harmonized Group of Infrastructures. • Separate Policy to promote Pumped Hydro announced in Union Budget 2024-25, draft shared by MoP in August 2024. • INR 18,100 crores approved for production linked incentive scheme for building 50 GWh of ACC Battery Gigafactories in India by ’25. • 30 Critical Raw Minerals identified by Government, auctions in progress.

India	• Government reaches out to critical mineral producers in US, Australia, UK, South Korea and Japan for processing tech. • PLI scheme for critical raw mineral mining being planned. • State Governments giving incentives and subsidies to battery manufacturers to set up facilities in States. • Exemption of customs duty for critical minerals and Critical Minerals Mission announced. • India set KABIL initiative to investigate securing long term supply of raw minerals through collaborations and partnerships. • Ministry in plan to design a PLI scheme for battery recycling to boost circularity.
Japan	• Storage Battery Strategy, 2012 by the Ministry of Economy, Trade and Industry (METI) mandating Commerce and Information Policy Bureau as responsible for battery industry and information policies.45 • Electricity Business Act by METI - Required approval for large electricity storage system more than 80,000 kWh.13 • Government support of energy storage projects to demonstrate the ability to time-shift demand by 10% in conjunction with expanded use of renewable generation resources. METI funding up to 75% of storage system cost to drive down the total cost.13 • METI has set aside JPY81 billion to resolve grid-related issues and to increase renewable energy. Additionally, the Ministry provides incentives for energy storage systems, which can be implemented onto solar power stations or substations.13
United States of America	• USAID Energy Storage Decision Guide for policy makers in 202146. • Storage act of 2011, US Congress - A bill to amend the Internal Revenue Code of 1986 to provide for an energy investment credit for energy storage property connected to the grid, and for other purposes.20 • Energy Storage Technology Advancement Partnership, Department of Energy - it is a federal-state funding and information sharing project that aims to accelerate the deployment of electrical energy storage technologies in the U.S., through the creation of technical assistance and co-funding partnerships between states, Sandia National Laboratories, and the U.S. Department of Energy.13 • Storage OIR Proceeding, California Public Utilities Commission - it is a process to refine policies and programs for energy storage. The OIR was opened in response to Assembly Bill 2514, which established the Energy Storage Procurement Framework and Program.13 • HB 2193 - Relating to Energy Storage, Oregon Public Utility Commission - In 2015 the Oregon legislature passed HB 2193, which required Portland General Electric (PGE) and PacifiCorp to procure by 2020 one or more energy storage systems.13

4.2 Analysis of Incentives, Standards, and Regulatory Barriers

The deployment of BESS is increasingly recognized as a crucial component in enhancing grid stability and supporting the integration of RES. Financial incentives and mechanisms play a pivotal role in accelerating the adoption of BESS by addressing economic barriers and ensuring that these systems can compete effectively in energy markets. Various financial incentives, government subsidies, market-based mechanisms, and risk-sharing arrangements that contribute to the successful deployment of BESS are described below.

Financial Incentives	• Financial incentives are crucial in encouraging the adoption of BESS. Feed-in tariffs (FiTs) and capacity payments are key examples. • Feed-in tariffs provide guaranteed payments for energy generated by BESS and injected into the grid, offering a stable revenue stream for developers. This helps offset initial investment costs and ensures financial predictability. • Capacity payments compensate BESS operators for providing grid services like peak load management and reserve, further incentivizing investment and enhancing grid reliability.
Subsidies & Grant	• Government subsidies and grants are critical in supporting BESS projects. These financial supports help reduce capital costs, making it more feasible for a broader range of stakeholders to invest in and implement these systems. • Various jurisdictions have established grant programs and subsidies to lower BESS installation and operation costs. For example, U.S. federal and state governments offer investment tax credits (ITCs) and grants to support BESS projects, reducing overall expenditure. Such subsidies improve the economic viability of BESS projects by reducing upfront costs and enhancing return on investment.
Market Based Mechanism	• Market-based mechanisms, such as energy arbitrage and frequency regulation markets, offer financial opportunities for BESS operators. • Energy arbitrage involves purchasing electricity during low demand when prices are lower and selling it during peak demand when prices are higher, allowing BESS operators to capitalize on price fluctuations. • Frequency regulation markets compensate BESS that help maintain grid frequency by responding to deviations. • These mechanisms offer financial incentives and highlight the role of BESS in providing essential grid services that contribute to grid stability and reliability.
Risk-Sharing Mechanism	• Evaluating risk-sharing mechanisms between public and private sectors is crucial for advancing BESS deployment. • Public-private partnerships (PPPs) help distribute financial risks and encourage private investment. • Risk-sharing mechanisms may include government-backed loan guarantees, insurance programs, or co-financing arrangements, which mitigate uncertainties and make BESS projects more attractive. • For example, some governments offer loan guarantees to reduce risk for private lenders and facilitate access to capital. Insurance programs cover potential operational risks, further alleviating concerns for investors and developers. By sharing financial risks, these mechanisms align the interests of both public and private stakeholders and promote BESS deployment.

There are various incentives, subsidies, and grants provided by countries around the world. Some of the key incentives provided by major economies are shown in the table below.

Country	Incentives
United States	• 30% tax credit for standalone BESS under IRA21 • Billions allocated for energy storage R&D and projects, including $500M for demonstration projects and $2.8B for battery materials and manufacturing21 • Loan support for innovative energy storage projects under the DOE21
Japan	• ¥13 billion allocated for standalone BESS, covering up to one-third of costs22 • Feed-in Premium (FIP) Scheme: Replaces FIT, offering a premium on market electricity prices. BESS integration is incentivized to manage supply fluctuations22 • Standalone BESS classified as Electricity Generation Businesses since April 2023, enabling grid connection and market participation23
European Union	• Horizon Europe funding for research and innovation24 • Netherlands: €100 million subsidy allocated for 2025 to support BESS in solar PV projects, as part of a €416 million, 10-year plan. Additional €200 million reserved for 2026. Scheme includes rooftop and grid-scale BESS of all sizes25 • Germany: Plans to expand battery storage capacity from 1.8 GW to 5.5 GW by 2027, aligning with renewable energy growth. Estimated €2.5 million savings in natural gas imports with an additional 2 GW of storage26
India	• Up to 40% of the capital cost is proposed for initial BESS projects to lower levelized costs and support adoption. Projects must be commissioned within 18-24 months27 • Complete waiver of ISTS charges for BESS projects commissioned up to June 30, 2025. Transmission charges gradually increase starting July 1, 202527 • Avoidance of double taxation principles, exempting Electricity Duty and Cross-Subsidy Surcharge for input power used in charging BESS27 • Access to concessional green finance and sovereign green bonds to fund BESS infrastructure27
China	• Investments in 5G, EV charging, data centres, and UHV grids drive demand for BESS28 • Hybrid solutions combining renewables and BESS reduce energy curtailment and enhance grid stability28 • Repurposing EV batteries for stationary storage supports cost-effective deployment28 • The growing EV market lowers battery costs, making BESS more accessible28 • While direct financial subsidies (like feed-in tariffs) are limited, China's focus on strategic infrastructure development, hybrid solutions, and cost reduction through scale is expected to drive the growth of its BESS market significantly28
Australia	• New South Wales: Discounts of AUD 770–2,400 for battery installations and AUD 250–400 for VPP connections under Peak Demand Reduction Scheme29 • Victoria: Interest-free loans up to AUD 8,000 for battery systems under Solar battery loan program29 • Northern Territory: Grants of AUD 400/kWh, capped at AUD 5,000 under Home and Business Battery Scheme30

This paper discusses the various incentives provided by countries to support the development and deployment of BESS. Subsequently, it transitions to the topic of standards in BESS, which are crucial for ensuring the safety, efficiency, and interoperability of these systems across different applications and markets.

The standardization of grid interconnection protocols is vital for BESS integration. Clear and consistent standards are necessary to ensure efficient and reliable connection to the grid. These standards address technical requirements, safety protocols, and operational procedures, helping to mitigate compatibility issues between BESS technologies and existing grid infrastructure. For example, adopting common communication protocols facilitates seamless integration with grid management systems and reduces interconnection complexity. Regulatory bodies in several regions are working to develop standardized protocols, enhancing the reliability and efficiency of BESS integration and minimizing integration barriers.

Performance metrics and standards for grid services provided by BESS are essential for ensuring system effectiveness. Clear metrics help assess BESS capability in delivering critical services like frequency regulation, voltage support, and peak shaving. Metrics such as response time, efficiency, and reliability measure performance and contribution to grid stability. Performance standards ensure BESS meet minimum operational requirements and deliver reliable services. Regulatory frameworks often include specific criteria and testing protocols to ensure compliance before deployment. By setting and enforcing these metrics, regulators ensure BESS technologies effectively support grid stability and renewable energy integration.

Clear and unified standards are crucial to ensure safety, facilitate grid integration, and provide fair market access, enabling faster adoption and investment in BESS technologies. Without these standards, BESS deployment faces uncertainty, increasing costs and slowing progress toward a sustainable energy future. Inconsistent or outdated standards can complicate the permitting process, delay installations, and limit interoperability with existing infrastructure. Regulatory barriers related to standards play a significant role in hindering the deployment and integration of BESS.

Regulatory barriers significantly impede the growth of BESS, posing challenges in permitting, outdated safety standards, and unclear integration guidelines. Furthermore, the lack of recognition for BESS's critical role in grid stability and renewable energy integration limits investment opportunities. Addressing these barriers is crucial to realizing BESS's potential for a sustainable energy future. The integration of RES and BESS into the electrical grid introduces regulatory challenges that must be overcome to maintain grid stability and efficiency. These challenges include financial, technical, issues surrounding grid interconnection standards, ensuring fair market access for BESS operators, and the impact of existing energy market structures on the deployment of BESS, all of which are described below.

Financial Challenges	• A primary barrier to widespread BESS adoption is the high capital cost, which makes it challenging for smaller entities or individual consumers to participate. • Despite decreasing battery costs, the financial burden remains significant, with long payback periods deterring potential adopters. While financial incentives and subsidies help mitigate costs, they are not always sufficient or available, limiting BESS adoption in some regions
Technical Challenges	• Technical challenges hinder BESS adoption, including the need for advanced control systems and integration technologies to ensure effective interaction with existing grid infrastructure. • Variability in technical standards across regions complicates integration, leading to compatibility issues. • Additionally, factors like battery degradation impact performance and reliability. Overcoming these challenges requires coordinated efforts to develop standardized protocols and improve technology resilience.
Grid Interconnection Standards and Protocols Challenges	• Outdated or inadequate grid interconnection standards hinder BESS and RES integration. • Many standards, designed for traditional energy sources, may not accommodate BESS characteristics, causing delays, higher costs, and reliability issues. To ensure effective operation, regulatory bodies must update and harmonize these standards for smoother integration.
Fair Market Access for BESS Operators Challenges	• Ensuring fair market access for BESS operators is a significant regulatory challenge. • In many energy markets, BESS operators face difficulties competing on equal terms with traditional energy providers due to regulatory frameworks that fail to account for the diverse services BESS can offer, such as frequency regulation, peak shaving, and energy arbitrage. • Barriers like minimum size requirements and bid structures that favor larger, conventional generators often limit smaller BESS operators. These obstacles not only restrict competition but also reduce grid flexibility and efficiency, hindering renewable energy integration and preventing BESS from reaching its full potential.
Impact of Energy Market Structures on BESS Deployment Challenges	• Existing energy market structures present challenges for BESS deployment. • Traditional markets, designed for centralized generation, often fail to accommodate the decentralized nature of renewable energy sources (RES) and BESS. These markets prioritize base-load generation and lack mechanisms to value BESS services like frequency regulation and peak shaving. • As a result, BESS operators may not receive adequate compensation, limiting investment and slowing adoption. • Reforming market structures to better incentivize BESS is crucial for optimizing RES integration and unlocking the full potential of energy storage technologies.

5

Economic and Financial Aspects

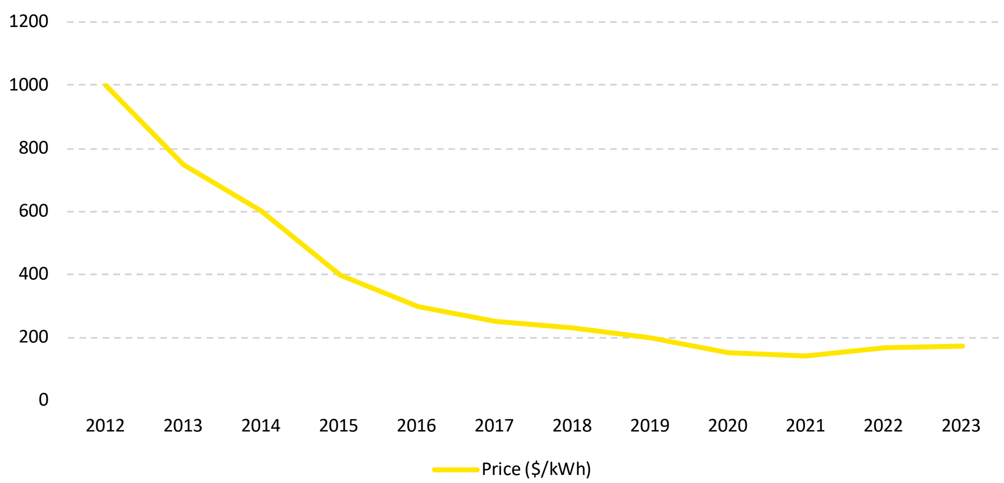
Energy balance of modern power systems becomes increasingly challenging when a high penetration of RE is required to fulfil the ambitious goal of carbon neutrality. Cost effective energy storage such as battery storage is urgently needed to provide flexibility resources to accommodate the intermittent RE. Cost trends, investment opportunities and funding models are described in the subsequent sub sections.

5.1 Cost Trends and Economic Viability of Battery Storage Solutions

The global shift towards renewable energy sources has spotlighted the critical role of battery storage systems. These systems are essential for managing the intermittency of renewable sources like solar and wind. Understanding the cost and economics of battery storage is vital for investors, policymakers, and consumers alike. The high cost of energy storage technologies, specifically battery storage is seen as the major impediment in the adoption of large-scale storage systems. There has always been ambiguity around the prices of battery storage systems, unlike pumped hydro energy storage systems which is an established technology. This mainly attributed to different costs associated with different applications, mainly due to different power and energy requirements for the particular operational use case, the ticket size of the project, domestic manufacturing efficiencies and competitiveness, the different components, and region-specific ease of availability of integration equipment such as Energy Management System (EMS), Battery Management System (BMS), etc. For example, the cost of installing large-scale BESS can differ between countries like China and India for the same application.

Battery storage systems also offer a wide range of applications, including integration with solar PV, wind turbines, and smart inverters, making cost standardization challenging. The historical cost trend of the Li-ion battery, which is the main component of the BESS, is shown in the figure below (Figure 9)31.

Fig 9: Li-ion Battery Cost ($/kWh)



The Li-ion battery prices have dropped by 82% from USD 1000/kWh in 2012 to USD 172/kWh in 202331. It is projected that the average battery price will drop to USD 59/kWh by 203032. The cost of battery storage systems (mainly batteries) has been declining significantly over the past decade. This reduction is attributed to advancements in technology, economies of scale in production, and increased market competition. However, the total cost of installation for a battery storage system includes not just the battery itself, but also the cost of power electronics, integration, and installation, which can vary depending on the scale and location of the project.

BESS have gained significant attention in India due to their potential to support the country's renewable energy goals and grid stability. Understanding the cost trends and economic viability of BESS is crucial for evaluating their role in India's energy transition.

Over the past decade, the global cost of Li-ion batteries, which dominate the BESS market, has dropped significantly. This decline has been driven by technological advancements, increased manufacturing scale, and better supply chains. As India increasingly looks to integrate large-scale renewable energy projects, the cost reduction in battery storage is pivotal to making these systems more affordable.

Global and Indian market trends suggest that by 2030, the cost of Li-ion batteries could decrease in line with global market trends. This reduction will make battery storage more viable in India, particularly for applications like grid stabilization and off-grid power solutions in remote areas. India's focus on establishing a domestic battery manufacturing ecosystem (through initiatives such as the Production-Linked Incentive (PLI) Scheme for Advanced Chemistry Cells) is expected to further reduce costs by lowering import dependencies and promoting local innovation.

The economic viability of BESS in India is improving due to the significant reduction in battery costs, government support, and the growing need for grid stability. As lithium-ion battery prices decline, BESS becomes more affordable for utilities and businesses, enabling efficient integration of renewable energy. Additionally, energy storage supports load management, reduces reliance on thermal power plants, and enhances grid resilience. Government initiatives, such as the National Energy Storage Mission and incentives for renewable energy projects, further boost the attractiveness of BESS. However, challenges such as high initial costs and the need for clearer policy frameworks remain. As India's energy storage ecosystem continues to mature, BESS will likely become a cornerstone of the nation's sustainable energy infrastructure.

5.2 Investment Opportunities and Financing Models

Presently, the adoption of BESS is still relatively low, and the growth of adoption is slower than expected. According to the IEA, global BESS capacity reached 85 GW by the end of 2023 but needs to expand to 1,200 GW by 203033 to ensure the seamless grid integration of renewable energy, supporting the global target of net-zero emissions by 2050. This gap presents significant investment opportunities in BESS on a global scale, driven by the growing demand for renewable energy integration, grid modernization, and energy security.

As the world accelerates its transition to cleaner energy, BESS becomes a critical enabler, particularly for addressing the intermittency of renewable sources like wind and solar. Investment in large-scale storage projects, including grid-scale batteries and microgrids, is growing worldwide. Battery manufacturing, particularly with advancements in alternative technologies like sodium-ion and solid-state batteries, is also a high-growth sector, driven by the increasing demand for storage solutions. Therefore, the push for higher BESS adoption is not only essential for meeting renewable energy targets but also presents substantial business opportunities across various sectors.

Moreover, as energy storage technologies mature, opportunities in battery recycling and second-life applications are becoming increasingly important. The global push for sustainability and circular economies drives the need for efficient battery management and repurposing used batteries. Emerging markets, especially in Africa, Southeast Asia, and Latin America, offer untapped potential for off-grid and mini-grid BESS solutions, providing reliable and affordable energy access in regions with limited grid infrastructure. With strong government support, public-private partnerships, and technological advancements, global investments in BESS are expected to continue growing, positioning energy storage as a key enabler of a cleaner, more resilient energy future.

Key trends and technologies providing new business opportunities in the RE sector are shown in the below figure. Among all the key trends and technologies, BESS assets are creating business opportunities in RTC and peak power supply tenders.

Fig 10: Key trends and technologies providing new business opportunities in the renewable energy sector

Value Added Offering	**Energy-as-a-service business model**	Companies adding higher margin revenue lines
Corporate Decarbonisation	**Corporate Power Purchase Agreements (CPPA)**	Co-investment in CPPA model and deep decarbonisation solutions
Value Chain Integration	**Production linked incentive scheme**	PLI Scheme and Discom privatisation
Hybrid RE Projects	**Wind solar hybrid projects**	Stake sale in operational projects by developers as they recycle capital
Battery Energy Storage (BESS)	**BESS assets**	Round the clock and peak supply tenders
Offshore Wind	**India's offshore wind potential**	Collaboration opportunities with domestic players as the sector opens up
Green Hydrogen	**Target of 5 million tonnes per annum (MTPA)**	Green hydrogen mission provides policy side tailwinds

India's increasing renewable energy demand offers strong investment opportunities in BESS, driven by supportive policies and market growth. India is expected to increase its energy storage capacity twelve-fold to 60 GW by FY 2032, a growth that significantly outpaces the expansion of RE sources. This trend is evident in the evolving renewable energy tender landscape, with the share of projects incorporating storage solutions rising from just 5% in FY 2020 to 23% in FY 2024. While pumped storage projects (PSPs) currently dominate the energy storage market, BESS are expected to capture the lion's share by FY 2030. The flexibility of BESS, coupled with technological advancements, falling tariffs, and rapid response times, will

enable them to surge 375 times, reaching 42 GW by FY 2032 from FY 2024 levels34.
India's ambitious target of 500 GW of renewable energy capacity by 203043 presents a tremendous opportunity for the growth of battery energy storage solutions. From BESS projects to cell manufacturing and components, the sector is poised for substantial growth. Government initiatives such as waivers on interstate transmission charges and the introduction of energy storage obligations (ESO) and renewable purchase obligations (RPO) are expected to accelerate this growth. These supportive policies will create a strong incentive for distribution companies (DISCOMs) to adopt storage solutions, driving further demand for BESS across the country.

This expansion of the BESS ecosystem presents a funding opportunity valued at INR 3.5 trillion by FY 203234, covering both project-level and upstream investments. A key driver of this growth will be the medium-term potential within the battery cell manufacturing sector, which is projected to attract INR 800 billion34 in investment. As India continues to scale up its energy storage capacity, both domestic and international investors stand to benefit from the rapid growth and technological advancements shaping the future of energy storage in the country.

The growing investment opportunities in the BESS sector necessitate innovative business & financing models like blended financing, outcome-based financing, and battery-as-a-service (BaaS). These models, supported by favorable government policies such as incentives and storage obligations, provide the capital needed for large-scale deployment, driving the growth and sustainability of the BESS ecosystem. Below are key business and financing models that can drive this growth.

- **Blended financing**
  Blended financing as a financial model may be considered where public capital is used as a first-loss capital or guarantee for BESS projects to crowd in private investors. This offers comfort to private financers to provide capital at a competitive rate. Independent BESS projects, only supporting renewable energy projects, can be bundled together, and issued as green bonds to potential large investors. Partial credit guarantee (PCG) can be provided by public capital providers that can improve the credit ratings of green bonds, which is necessary to attract low-risk and low-return seeking private investors.

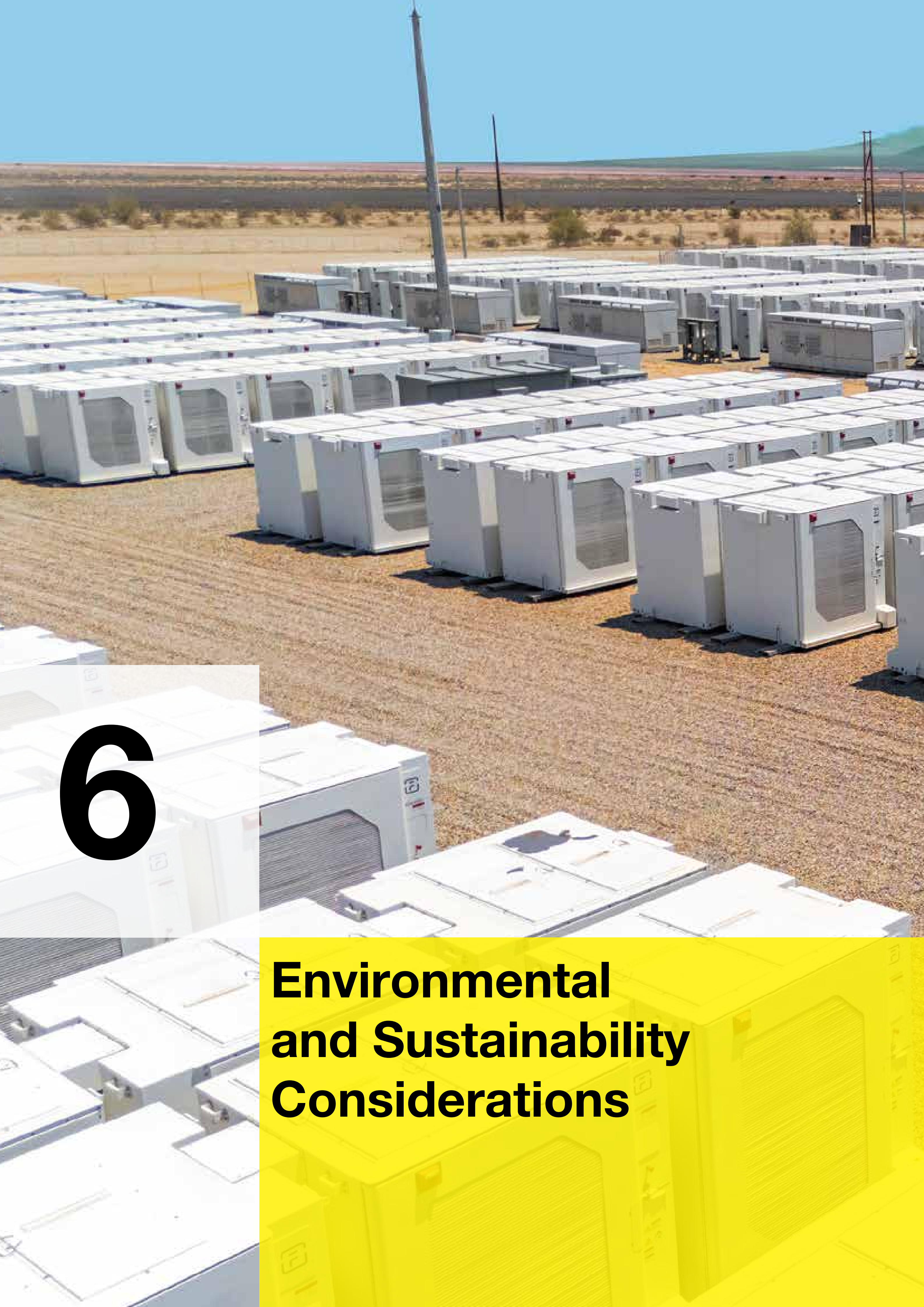
- **Outcome-based financing**
  Debt financing can be structured in such a way that BESS is optimally used. For example, the outcome can be a number of charge/discharge cycles, the ability to respond to supply/demand with very low breakdown times, the cost of supplying electricity, the ability to recycle after-life BESS systems, etc. All these incentives can entice developers to come up with smart combinations of BESS technology, business, and execution models. It also sends a signal to manufacturers to produce superior-quality and environmentally benign BESS equipment.

- **New-age business models**
  New-age business models such as BaaS allows the user to avoid high-upfront costs and technology performance risks. BaaS includes Customized Leasing Models (CLM) where the lessor bears the upfront capital. This can cater to the evolving needs (back-up power, distributed energy, and self-consumption optimization) of residential, C&I consumers while promoting behind-the-meter deployment.

Consumers can simultaneously procure electricity from distribution grids while selling surplus electricity produced from rooftop solar systems. Similar business models can also be explored for front-of-the-meter players like electricity generation and transmission companies. BaaS can spare such companies from incurring high upfront capital for BESS and optimize investments in grid upgrades. Here, governments, Multilateral Development Banks (MDBs), and Development Finance Institutions (DFIs), in conjunction with relevant private capital providers, can accelerate the adoption of this business model.

Another evolving model that can create an additional revenue stream for BESS adopters is the trading of green credits by virtue of facilitating clean energy. This is increasingly relevant as more countries are establishing structured and regulated carbon markets in their jurisdictions as per global best practices. Carbon credits earned from BESS projects can be traded in the market at a favourable price. PPPs and green bonds are also other financing models that can be considered.

BESS is considered as a “sunshine industry”. Thus, it is important for technology, business, and policy stakeholders to forge a winning partnership to help the global economy leapfrog into a net-zero future.



6

Environmental and Sustainability Considerations

BESS play a crucial role in supporting renewable energy integration and reducing carbon emissions. However, their environmental impact requires careful consideration, particularly through life-cycle analysis (LCA) to assess the ecological footprint from manufacturing to disposal. This includes exploring strategies for recycling and repurposing battery materials to minimize waste and reduce resource consumption. By focusing on sustainable practices, BESS can contribute to a cleaner energy future while mitigating environmental impacts throughout their life cycle. LCA, recycling, repurposing, and environmental footprints of BESS are described in the subsequent sub sections.

6.1 Life-Cycle Analysis of Battery Storage Solutions

Life-cycle analysis of BESS is a comprehensive assessment that evaluates the environmental impacts associated with each stage of the system's life, from raw material extraction to manufacturing, operation, and end-of-life disposal or recycling. This analysis helps identify energy consumption, carbon emissions, and resource use at each phase, allowing for a more sustainable design and operational approach. By understanding these impacts, LCA provides valuable insights for improving BESS efficiency, promoting eco-friendly materials, and optimizing the recycling and repurposing of batteries, ultimately supporting greener energy solutions and reducing the overall environmental footprint.

In this section, the paper will analyze the life cycle of three key energy storage technologies including battery storage: Lithium-Ion Batteries, Flow Batteries, and Pumped Hydro. This paper will also compare battery technology with pumped storage technology for comparison purpose. A comparative analysis of energy storage technologies, focusing specifically on Lithium-Ion Batteries, Flow Batteries, and Pumped Hydro, has produced significant findings in the areas of the environment, economy, and society. The parameters such as capacity, efficiency and life cycles of energy storage technology considered for comprehensive assessment of environmental consequences are shown in below table35:

Technology	Capacity (MWh)	Efficiency (%)	Cycle Life (cycles)
Lithium-Ion Battery	500	90	5000
Flow Battery	700	85	8000
Pumped Hydro	1000	80	12000

The environmental impact indicators considered for comprehensive assessment of environmental consequences are carbon footprints, water usage, and land use. The details of evaluation of environmental consequences are shown in below table35:

Technology	Carbon Footprints (kg CO2/kWh)	Water Usage (liters/ MWh)	Land Use (m2/MWh)
Lithium-Ion Battery	500	2000	5
Flow Battery	30	1500	3
Pumped Hydro	20	1000	2

In terms of carbon footprint, Lithium-Ion Batteries exhibit a carbon footprint of 50 kg CO2/kWh, while Flow Batteries and Pumped Hydro show relatively lower values of 30 kg CO2/kWh and 20 kg CO2/kWh, respectively. The analysis of percentage change reveals a significant 40% reduction in carbon footprint for Flow Batteries compared to Lithium-Ion Batteries, and a notable 60% reduction for Pumped Hydro. These findings underscore the environmental advantages of Flow Batteries and Pumped Hydro in terms of reduced greenhouse gas emissions.

In terms of water usage, Lithium-Ion Batteries exhibit a higher consumption rate of 2000 liters/MWh, whereas Flow Batteries and Pumped Hydro have lower values of 1500 liters/MWh and 1000 liters/MWh, respectively. The analysis of percentage change reveals a significant 25% reduction in water consumption for Flow Batteries compared to Lithium-Ion Batteries, and a notable 50% decrease for Pumped Hydro. This highlights the substantial water-saving benefits of Flow Batteries and Pumped Hydro.

In terms of land use, Lithium-Ion Batteries occupy 5 m^2/MWh, while Flow Batteries and Pumped Hydro require less land, with values of 3 m^2/MWh and 2 m^2/MWh, respectively. The percentage change analysis shows a 40% reduction in land usage for Flow Batteries compared to Lithium-Ion Batteries and an impressive 60% decrease for Pumped Hydro. This emphasizes the superior land efficiency of Flow Batteries and Pumped Hydro over Lithium-Ion Batteries.

The social impact indicators considered for comprehensive assessment of social consequences are employment generation, community acceptance and health & safety incidents. The details of evaluation of social consequences are shown in below table35:

Technology	Employment Generation (jobs/MWh)	Community Acceptance (%)	Health & Safety Incidents (per million MWh)
Lithium-Ion Battery	5	80	2
Flow Battery	7	85	1
Pumped Hydro	10	90	0.5

Lithium-Ion Batteries create 5 jobs/MWh, while Flow Batteries and Pumped Hydro generate 7 and 10 jobs/MWh, respectively. Flow Batteries see a 40% increase in job creation, and Pumped Hydro experienced a 100% rise, highlighting their stronger employment potential.

In community acceptability, Flow Batteries and Pumped Hydro have higher approval rates at 85% and 90%, compared to Lithium-Ion Batteries' 80%. Flow Batteries see a 6.25% increase, and Pumped Hydro a 12.5% gain, emphasizing their favorable social perception.

For health and safety, Lithium-Ion Batteries report 2 incidents per million MWh, while Flow Batteries and Pumped Hydro have lower rates of 1 and 0.5, respectively. Flow Batteries experienced a 50% reduction in incidents, and Pumped Hydro see a 75% decrease, indicating their superior safety performance.

Despite the environmental and operational advantages of Flow Batteries and Pumped Hydro in terms of carbon footprint, water usage, land use, job creation, community acceptability, and safety, Lithium-Ion Batteries remain a promising technology for the future. Their widespread use, continuous advancements in efficiency, and significant role in energy storage systems make them a crucial component in the transition to a sustainable energy future. As technologies evolve, it is likely that Lithium-Ion Batteries will continue to improve, further minimizing their environmental impact while maintaining their strong performance in various energy storage applications.

6.2 Recycling, Repurposing, and Minimizing Environmental Footprints

Integrating LCA with recycling, repurposing, and minimizing environmental footprints is key to enhancing BESS sustainability. LCA insights help identify opportunities for reducing environmental impacts through efficient recycling, second-life applications, and strategies that minimize waste throughout the product lifecycle.

Recycling plays a pivotal role in mitigating the environmental impact of battery manufacturing. By recovering valuable materials from spent batteries, recycling reduces the need for raw material extraction, conserves resources, and minimizes waste generation. Additionally, recycling enables the recovery of critical metals like lithium, cobalt, and nickel, which can be reused in new battery production, thus creating a closed-loop system that reduces dependence on virgin materials.

Numerous initiatives are advancing battery recycling and sustainable manufacturing, with collaboration between governments, industry, and research institutions focused on improving recycling technologies, establishing infrastructure, and implementing regulatory frameworks. Innovations like blockchain are being explored to enhance transparency and responsible sourcing.

The future of battery manufacturing relies on sustainability, resource efficiency, and environmental responsibility. By adopting recycling initiatives and circular economy principles, the battery industry can reduce its environmental impact, with governments, businesses, and consumers all playing vital roles.

The battery energy storage and electric vehicle revolution has heightened the need for sustainable battery recycling. As demand grows, recycling becomes essential to prevent environmental harm and resource shortages. The IEA forecasts a surge in battery production, yet environmental risks remain as batteries reach their end of life without proper recycling. There are three diverse approaches to address this challenge as shown in below pictogram.

Reuse	Extending battery life by repurposing them for stationary energy storage offers a sustainable solution.
Transformation	Repurposing old batteries into compact power units for electronics demonstrates environmental responsibility.
Recycling	This crucial technique involves breaking down used batteries and extracting valuable metals and compounds, which are then utilized in new batteries, reducing reliance on fresh resources.

Recycling used batteries involves methods like direct recycling, which preserves components with high purity but faces technical challenges; hydrometallurgy, a water-based method that is flexible yet costly; and pyrometallurgy, which incinerates batteries to retrieve metals but raises environmental concerns. Key challenges include technical issues, complex designs, material variety, and the need to scale research for industrial use. The economic viability of recycling hinges on recovering valuable metals and reducing costs. To foster trust and wider adoption, rigorous testing and collaboration across the supply chain are essential to ensure recycled materials match or exceed the performance of new ones.

7

Ensuring Safety, Integration and Cyber Security in BESS

BESS are becoming increasingly crucial for enhancing grid stability, integrating renewable energy, and providing backup power. Key considerations, including safety, integration, and cybersecurity, are discussed in the following subsections.

7.1 Safety

BESS require a robust framework of safety measures to ensure secure and reliable operation while addressing potential hazards such as thermal runaway, fires, explosions, and extreme environmental conditions. The following guidelines provide an overview of best practices for enhancing the safety of BESS installations:

- **Thermal Runaway, Fires, and Explosions**

Li-ion batteries are prone to thermal runaway, a chemical reaction that can escalate temperatures and pressure, potentially causing cell ruptures, release of flammable gases, and explosions. Key safety measures include:

1. Hazard Detection Systems:
    - Install smoke, heat, and gas detection systems monitored by control centers to promptly alert operators in case of emergencies.
2. Thermal Runaway Prevention
    - Use advanced technologies within battery cells to prevent overheating.
    - Employ heating, ventilation, and air conditioning (HVAC) systems with continuous monitoring of temperature, voltage, and current.
    - Design containers to protect against external heat sources, such as high ambient temperatures or nearby wildfires.
    - Incorporate failsafe mechanisms to shut down the system if other protective measures fail.
3. Fire Suppression
    - Install fire suppression systems such as sprinklers, ensuring they can effectively suppress fires within battery racks.
    - Use water cautiously for cooling and fire suppression, while minimizing the risk of electrical short circuits or toxic runoff.
    - Gaseous suppression agents can help control incipient fires but are not sufficient to stop thermal runaway.
4. Electrical Components
    - Ensure safe electrical installations with adequate clearances, weatherproof enclosures, and protection against overvoltage or short circuits.
5. Ground Fault Protection:
    - Design systems to automatically disconnect during electrical faults to prevent fires or overheating. Ensure proper grounding to manage potential over-voltages.

6. Electrolyte Spill Containment:
   - Design systems to safely contain and manage spills from batteries using liquid electrolytes, such as lead-acid or nickel-cadmium batteries.
7. Ventilation:
   - Implement adequate ventilation systems to manage gases released during normal operations or abnormal conditions like thermal runaway. Use safeguards such as fire suppression and explosion prevention systems to mitigate risks.
8. Explosion Prevention:
   - Design enclosures to reduce the risk and impact of explosions by including ventilation systems and panels that can release pressure safely.

- **Extreme Weather, Geological, and Environmental Hazards**

BESS installations should be resilient to extreme weather and environmental conditions, ensuring the safety of personnel, equipment, and the surrounding environment:

1. Monitoring and Response Plans:
   - Develop emergency response plans that outline communication protocols, assign responsibilities, and establish shutdown procedures for severe weather or natural disasters.
2. Resilient Design:
   - Design systems to withstand local environmental conditions, such as strong winds, heavy snowfall, flooding, and earthquakes.
   - Protect systems against lightning, excessive humidity, salinity, dust, and intrusion by animals or vegetation.

- **Additional Design Considerations**

1. Site Access:
   - Ensure maintenance personnel have uninterrupted access to the site for regular operations or emergencies.
2. Lighting:
   - Provide adequate emergency lighting in indoor installations to facilitate emergency response or maintenance activities.
3. Signage:
   - Display clear and reflective signs at the installation site. Include details about system technology, potential hazards, protective equipment requirements, emergency contacts, shutdown procedures, evacuation routes, and assembly points.

By implementing these safety measures, BESS installations can reduce risks, protect workers and equipment, and ensure safe and efficient operation in diverse environmental and operational conditions.

7.2 Integration

When designing and integrating Battery Energy Storage Systems (BESS) into electrical networks, various technical aspects must be addressed to ensure seamless operation and grid compatibility. Key considerations include:

- **Grid Connection**

The point of connection for the BESS must be determined early in the design process. Depending on system requirements, the BESS can be divided into multiple independent units to support redundancy and enable flexible operation across different sections of the grid.

BESS systems typically operate at DC link voltages ranging from 900 to 1100 V. These voltages are carefully selected to exceed peak grid voltage requirements and ensure safe operation. For instance, a 690 V grid system requires DC link voltages to maintain a peak of approximately 950 V, while a 1000 V threshold is critical to prevent reverse conduction through the inverter switching bridge36.

- **Synchronization Control**

To enable efficient synchronization of the BESS with the grid:

1. Conventional pulse-based synchronizing relays may be utilized to match voltage and frequency.
2. Alternatively, voltage transformers (VT) can provide direct voltage feedback from the transformer primary and medium voltage (MV) bus, allowing the BESS controller to manage synchronization independently.

- **Transformer Winding Ratios**

To maintain stable operation and connection to the grid across all expected MV bus voltage levels:

1. Transformer voltage regulation must be analyzed during full-load charging and discharging cycles of the BESS.
2. Optimized transformer winding ratios should be selected to reduce DC link operating voltages, promoting efficiency compared to a direct connection setup.

- **Transformer and MV Network Interface**

When interfacing the BESS with an MV network, installing a transformer is essential for compatibility. The design must account for whether the BESS will energize the transformer before connection. This determines the synchronization strategy—either conventional methods for live/live connections or a black start capability for independent startup.

BESS operates by integrating various software solutions developed by multiple vendors, creating inherent complexity. This challenge is managed through a robust energy management system that serves as the software backbone, ensuring seamless connection and control of all components. Inadequate software architecture that fails to address these integration challenges could render the entire BESS solution ineffective. As the size of the BESS increases, integration risks multiply, making it crucial to address these issues comprehensively through well-designed software solutions.

7.3 Cybersecurity

The exponential growth in the development and deployment of BESS has significantly transformed the power industry. However, the integration of connected devices and IoT-based networks into these systems has also exposed them to heightened cybersecurity risks.

This makes the implementation of robust cybersecurity measures essential to ensure the safety, reliability, and long-term security of BESS and the broader power sector.

- **The Importance of Cybersecurity in BESS**

As the power industry increasingly relies on battery technology, innovative solutions such as lithium-ion-based BESS are playing a pivotal role in modern energy storage systems. A report by GlobalData highlights that over 30 companies, including major players like Enersys, LG, Mitsubishi Electric, Schneider Electric, Siemens, ABB, Shell, and Eaton, are actively involved in the development of BESS, collectively filing more than 3,500 patents in this space37.

However, the rapid advancement of these technologies has also made them a prime target for cybercriminals. Cyberattacks can disrupt operations, compromise connected devices, and result in significant financial and reputational damage. Consequently, implementing proactive cybersecurity measures is no longer optional—it is a critical requirement for safeguarding the power industry.

Preventative measures are more cost-effective than reactive approaches, as they can mitigate the risks of physical damage, data theft, operational downtime, and revenue losses. Furthermore, prioritizing cybersecurity fosters customer trust and strengthens the resilience of BESS against evolving threats.

- **Key Cybersecurity Measures for BESS**

To establish a sustainable cybersecurity posture for BESS, the following technical measures are essential:

1. Authentication Mechanisms: Implementing Single-Sign-On (SSO), Two-Factor Authentication (2FA), or Multi-Factor Authentication (MFA) ensures that only authorized personnel can access and control BESS. These mechanisms require multiple layers of identity verification, such as passwords, tokens, or biometric data, reducing the risk of unauthorized access.
2. Encryption and Firewalls: Encryption of data transmission within BESS is vital to prevent unauthorized interception and data breaches. Secure communication channels at the transport layer, coupled with robust firewalls, protect sensitive information and block malicious activities.
3. Physical Security: Physical vulnerabilities, such as tampering or theft, must be addressed through measures like perimeter security, surveillance cameras, biometric access controls, and alarm systems. These safeguards ensure that the physical components of BESS remain secure.

4. User Education and Awareness: Empowering users through regular cybersecurity awareness training is critical to mitigating insider threats and human error. Informed users are better equipped to identify potential risks and respond to cyber threats effectively.

5. Continuous Assessment and Gap Analysis: Routine assessment of cybersecurity measures and identification of vulnerabilities help organizations stay ahead of emerging threats. Conducting regular gap analyses ensures that security protocols are aligned with the latest industry standards.

6. Collaboration with Experts: Engaging experienced cybersecurity firms and industry mentors, such as Battery Ventures, can provide valuable guidance in developing comprehensive defensive strategies tailored to BESS.

- **Building a Resilient Cybersecurity Posture**

To address the unique challenges posed by BESS, organizations must adopt a holistic approach to cybersecurity. This involves not only implementing technical solutions but also fostering a culture of cybersecurity awareness across all levels of the organization. By investing in advanced security measures and innovative technologies, businesses can enhance system reliability, protect sensitive data, and prevent potential financial losses caused by cyberattacks.

The reliance on software in BESS exposes it to potential cyber threats, which could have serious national security implications, particularly when integrated with the grid. Given the growing geopolitical tensions, it is essential for India to proactively address these risks to safeguard critical infrastructure and ensure energy security.

8

Future Trends

The future of BESS is shaped by technological advancements, evolving global supply chains, and growing adoption in emerging markets. These trends are driving innovation in energy storage applications, from renewable integration to electric mobility and off-grid solutions. Upcoming breakthroughs, procurement trends, emerging market and use cases are described in the subsequent sub sections.

8.1 Upcoming Breakthroughs in Technology and Materials

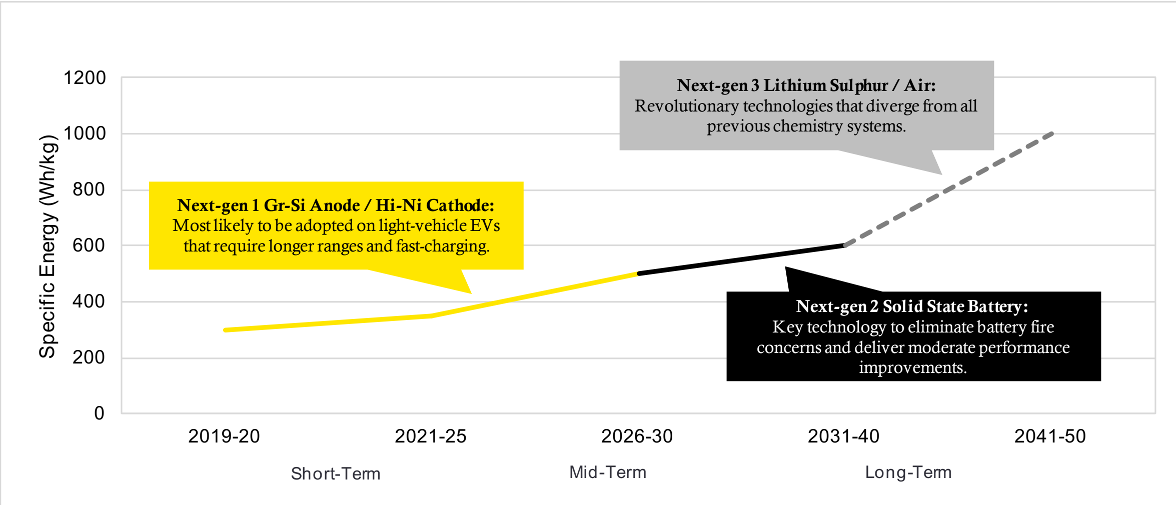
The future of lithium-ion battery technology is based on three specific technological advancements. Advancements in new battery technology can be realized through a wide range of methods, targeting different components to enhance specific performance characteristics. While battery technology evolution could follow multiple paths, researchers have identified three alternative options to lithium-ion batteries, as shown in the table below38.

Overview of Next-Generation Battery Technology			
Current Conventional Li-ion	Next-generation 1: Gr-Si Anode / Hi-Ni Cathode	Next-generation 2: Solid State Battery (SSB)	Next-generation 3 : Lithium Sulphur / Air
Most favorable technologies for today's EV and stationary energy storage applications • Cathode material: NMC 532, NMC 622, NCA, or LFP • Anode material: artificial graphite or natural graphite • Electrolyte: carbonate-based liquid organic solvents • Separator: Polymer thin films • Current collector: Cu and Al foils	Most likely to be adopted on light vehicle EVs that require longer ranges and fast charging. • Cathode material: NMC 811 or NCA 90 • Anode material: natural/artificial graphite with SiOx or pure Si • Electrolyte: carbonate-based liquid organic solvents • Separator: Polymer thin films • Current collector: Cu and Al foils	Key technology to eliminate battery fire concerns and deliver moderate performance improvements. • Cathode material: NMC 811, NCA 90, LNMO (high-voltage) • Anode material: graphite with large amount of pure Si or Li-metal • Electrolyte: ceramic, polymer or sulphur-based solid electrolyte • Separator: as part of solid-state electrolyte • Current collector: Cu and Al foils	Revolutionary technologies that diverge from all previous chemistry systems. • Cathode material: Li-metal • Anode material: Sulphur or Oxygen/Air • Electrolyte: solid-state • Separator: as part of solid-state electrolyte • Current collector: Porous carbonaceous material, noble metal catalysts, and Cu foil

The evolution of battery technologies, from conventional Li-ion to next-generation systems such as Gr-Si Anode/Hi-Ni Cathode, Solid-State Batteries (SSB), and Lithium Sulphur/Air, showcases significant advancements in energy storage solutions. Each technology offers unique advantages in terms of performance, safety, and application, paving the way for more efficient and sustainable energy storage in EVs and stationary applications. As these innovations continue to mature, they hold the potential to revolutionize energy storage, addressing critical challenges like energy density, charging speed, and safety.

Lithium-ion batteries currently dominate the rechargeable battery market, driven by their high energy density, fast charging, and long lifespan, making them ideal for grid energy storage, electric vehicles, and electronics. Despite this, innovations in battery technology, such as solid-state and flow batteries, are emerging, offering potential advantages in cost, efficiency, and sustainability. The latest generation of grid-scale Li-ion batteries delivers higher capacity and longer lifespans, enhancing their suitability for large-scale energy storage. The Li-ion battery roadmap from 2019 to 205038 in figure 11 shows expected improvements in energy density, cost reduction, and recyclability. While new technologies may complement Li-ion in the future, Li-ion batteries will likely remain a key player in the energy storage sector due to their continued advancements and widespread adoption.

Fig 11: Li-ion battery technology roadmap from 2019 to 2050



Recent advancements in new battery technology offer a variety of enhancements over conventional battery technologies, including:

- Improved specific energy and energy density (more energy stored per volume/weight)
- Longer lifetime
- Better safety / less flammable
- Require less time to be fully charged
- Reduced levelized cost of energy (LCOE)

The upcoming breakthroughs in technology and materials are closely linked to global procurement trends, as advancements in battery chemistry and design drive the demand for new and improved materials. These technological innovations influence sourcing strategies, supply chain dynamics, and the global competition for critical resources, shaping the future of energy storage.

8.2 Drivers for BESS Procurement

Drivers for BESS Procurement reflect the increasing focus on renewable energy integration, grid stability, and energy independence. Key factors shaping procurement trends in the BESS market include:

• **Increased Demand for Renewable Energy Integration:** With the global shift towards cleaner energy, the demand for BESS has surged. Energy storage helps address the intermittent nature of renewable sources like solar and wind, enabling their reliable integration into the grid. As a result, countries and companies are increasingly investing in large-scale BESS projects to support renewable energy generation.

• **Cost Reduction and Efficiency:** As battery technology evolves, costs for BESS have significantly decreased. Procurement trends show a growing focus on cost-effective solutions that provide high efficiency and longevity. The development of lithium-ion batteries, solid-state batteries, and other emerging technologies is driving down prices, making energy storage solutions more accessible.

• **Focus on Sustainability and ESG Goals:** Organizations are placing a strong emphasis on sustainability and environmental, social, and governance (ESG) criteria in their procurement processes. BESS allows companies to reduce their carbon footprint by supporting the use of clean energy and enhancing energy efficiency.

• **Government Incentives and Policy Support:** Many governments worldwide offer financial incentives, tax credits, and subsidies to encourage the adoption of BESS. These incentives have become a critical factor in the procurement process, driving demand for energy storage projects.

• **Advanced Procurement Models:** Long-term procurement agreements, power purchase agreements (PPAs), and energy storage-as-a-service models are gaining traction. These innovative procurement strategies help manage risks and optimize financial outcomes, especially for large-scale deployments.

• **Energy Security and Grid Stability:** With increasing concerns about energy security, BESS is being seen as an essential solution to enhance grid stability. Governments and private entities are investing in energy storage to ensure a reliable and resilient energy supply, particularly in regions with fluctuating demand or unreliable grid infrastructure.

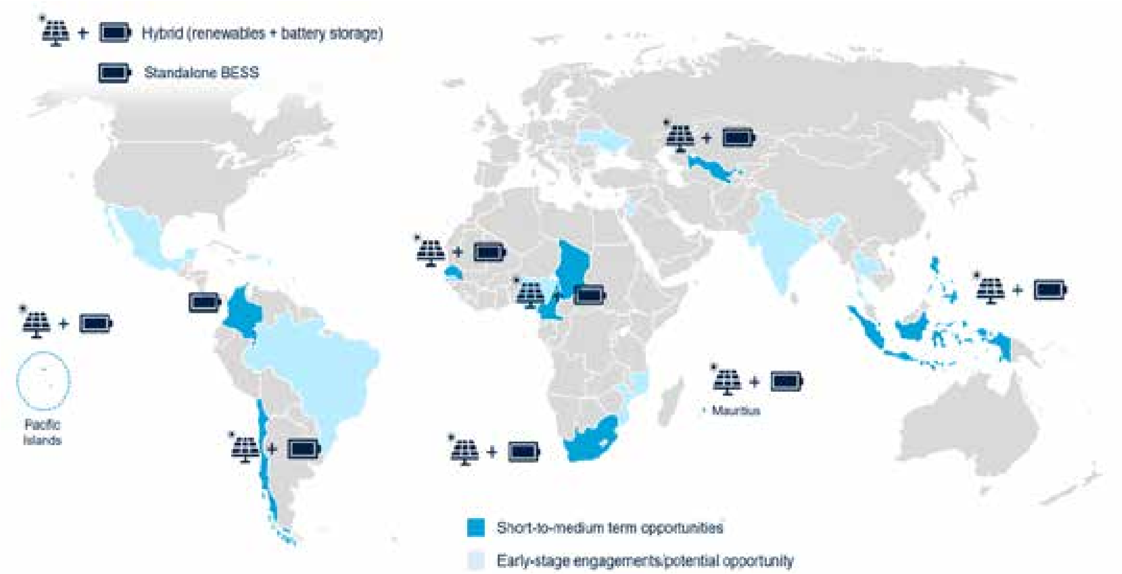
• **Local Sourcing and Supply Chain Considerations:** To mitigate supply chain risks and reduce dependency on specific regions (e.g., Asia), there is a growing trend toward sourcing BESS components locally. Companies are looking to diversify their supply chains and secure more reliable access to critical raw materials like lithium, cobalt, and nickel.

• **Decentralized Energy Systems:** Increasingly, decentralized energy systems (microgrids and community storage solutions) are being procured to serve remote areas, industrial applications, and critical infrastructure. This trend is driven by the need for localized energy solutions and grid independence.

8.3 Emerging Markets and Use Cases

Emerging markets for BESS are expanding rapidly as the demand for clean energy solutions and grid reliability grows globally. These markets are driven by the need for renewable energy integration, energy security, and economic development. Key emerging markets for BESS is shown in the pictogram below.

Fig 12: Emerging Markets with on-going and potential BESS activity



Asia Pacific region holds the largest share of the battery energy storage system market. The Asia Pacific market is segmented into China, Japan, India, Australia, and rest of the region. The region is the largest market for battery energy storage and is home to some of the fastest growing economies in the world. Investments in energy storage are projected to rise significantly in the region, driven by favourable government policies that aim to enhance the quality and reliability of power distribution for residential, commercial, and industrial customers. Several countries in Asia Pacific are planning for electrification in remote areas that are mainly off-grid. These factors contribute to the BESS market growth in the Asia Pacific countries.

BESS installations offer use cases throughout the entire power system value chain, be it in generation, transmission, distribution or to end-consumers. The critical use cases that are likely to make energy storage adoption commercially viable for distribution utilities and C&I consumers, along with suitable contracting arrangements for BESS adoption, are shown in the tables below:

BESS USE CASES FOR DISTRIBUTION UTILITIES[39]						
	Peak load management	Alignment with electricity drawal and injection schedule	Avoiding power outages	Network upgrade deferral	Participation in ancillary service market	Enabling RE dispatchability
Use Case	To meet peak load, DISCOMs often enter into contracts with peaking/ costlier sources of power	Utilities are subject to stringent penalties for non-adherence to committed schedules	Ensuring grid reliability & adequacy by reducing outages and loss of load	Distribution utilities have to upgrade their network due to congestion even if the same occurs for a very short time	Ancillary services is procured through regulatory mechanism	To make renewable power available when needed by the grid
Application	BESS can be discharged during time of high demand and charged when there is surplus generation in the system and prices are low	BESS can ramp up almost instantaneously to meet the ramping requirement following a change in solar/ wind generation: and help utilities to comply with committed Schedules	BESS can offer localized power supply to a group of consumers during outage/ congestion	BESS can be used as non-wire alternative for transmission and distribution network planning and avoid investments in additional transformers and lines.	BESS can effectively participate in both energy market and AS market	BESS can be hybridized with infirm renewable power to provide round--the-clock RE supply to DISCOMs
Value Stream	Reduction in peak power procurement cost	Reduction in DSM penalties	Additional revenue and meeting LOLP (loss of load probability) targets	Savings in infrastructure upgrade costs	Additional revenue from energy & AS markets	Reduction in power procurement cost

The above table highlights the diverse use cases of BESS for distribution utilities, focusing on peak load management, grid reliability, and renewable energy integration. It emphasizes BESS applications in optimizing grid operations, reducing costs, and ensuring power availability. The value streams illustrate the potential savings, increased revenue opportunities, and enhanced grid performance, showcasing BESS as a critical enabler for modern energy systems.

The below table outlines the key use cases of BESS for C&I companies, emphasizing their role in reducing demand charges, enhancing power quality, and enabling uninterrupted power supply. BESS also facilitates energy cost optimization through renewable integration and energy arbitrage, while providing reactive power support to maintain grid stability. These applications collectively highlight the cost savings, operational reliability, and sustainability benefits BESS offers to C&I sectors.

BESS USE CASES FOR C&I COMPANIES[39]						
	Demand charge reduction	Enhanced power quality	Diesel abatement	Enhanced renewable power procurement	Energy arbitrage	Reactive power support
Use Case	Reduce contracted demand from distribution utilities	Frequent power supply fluctuations can lead to revenue loss	Diesel abatement for providing uninterrupted power supply	Increase utilization of existing and planned renewable power plants	Energy arbitrage by BESS provides an additional revenue stream	There is a need for local reactive power support in tail-end of distribution network to maintain adequate voltage profile
Application	BESS provides a part of peak demand and eases reduction of contracted demand from distribution utility to that extent	BESS can provide reliable power supply to consumers who are located in areas which are prone to supply quality issues	BESS can help in providing uninterrupted power supply to C&I consumers who have tight supply tolerances	BESS saves surplus renewable power for later use by consumer	BESS can be charged at negligible cost during surplus hours and can provide energy services during peak times	BESS inverter/converter has the ability to locally compensate the reactive power, hence, influence the supply voltage
Value Stream	Reduction in demand charges in electricity bills	Savings in revenue loss due to improved power quality	Replacement of costlier sources of alternate supply	Reduction in power procurement cost	Time-of-use rate/market-based arbitrage	Reduction in costs of reactive power compensators

9

Recommendations and Roadmap

The following recommendations and roadmap outline key actions for various stakeholders to accelerate the adoption and development of BESS. These strategic directions provide policymakers, investors, industry leaders, and researchers with clear guidance to drive innovation, investment, and sustainable growth in the energy storage sector.

9.1 For Policymakers: Actionable Policy Directions

To enhance grid stability through the integration of RES and BESS, policymakers must adopt adaptive, forward-looking regulatory policies that address current challenges and future needs. Developing flexible frameworks that anticipate technological advancements and market changes is essential for fostering a resilient energy system. Key strategies include incentivizing BESS grid services, standardizing grid interconnection protocols, setting performance metrics, and supporting R&D to drive innovation in storage technologies.

Balancing grid reliability with renewable energy growth requires integrated planning that optimizes storage use and mitigates variability in renewable generation. Modernizing the grid with smart technologies will enhance real-time responses to energy input fluctuations. Long-term policy goals, clear targets for renewable energy and storage, and promoting public-private partnerships will drive investment and accelerate deployment. Removing regulatory barriers and streamlining permitting will further support a smooth energy transition

9.2 For Investors: Strategic Investment Opportunities

Investors looking to capitalize on the growing battery energy storage market should focus on key strategic opportunities that align with the rapid expansion of renewable energy and the evolving regulatory landscape.

- Diversification in Storage Technologies: Investors should consider diversifying their portfolios by investing in different types of energy storage technologies (e.g., lithium-ion, flow batteries, and solid-state). This approach mitigates risks related to technological obsolescence and capitalizes on innovation in the energy storage sector.

- Long-Term Contracts and PPAs: Investment opportunities tied to long-term PPAs and grid service contracts can offer stable revenue streams. This includes investments in BESS systems that provide ancillary services such as frequency regulation, peak shaving, and voltage control, which are becoming increasingly valuable as grid reliability and flexibility are prioritized.

- Collaboration with Energy Providers and Utilities: Partnering with utility companies or energy providers to integrate BESS into existing infrastructure can help scale storage capacity, while ensuring regulatory compliance. Such collaborations can improve profitability through shared risk and access to established markets.

- Emerging Markets: Focus on emerging markets where energy storage demand is growing, particularly in regions with high renewable energy potential, such as Asia, Africa, and Latin America. These markets offer opportunities to invest in grid modernization, off-grid solutions, and large-scale storage projects.

- Public-Private Partnerships (PPPs): Strategic investment in public-private partnerships can de-risk large-scale storage projects. Governments in many countries are offering incentives, subsidies, and favorable regulations for energy storage systems, making them an attractive investment opportunity.

- Sustainability and Green Bonds: Investors interested in sustainability should consider financing BESS projects through green bonds, which have become a popular tool for raising capital for environmentally friendly projects. These bonds offer a way to align financial returns with positive environmental impact, as energy storage plays a critical role in decarbonizing the energy sector.

9.3 For Industry Leaders: Technology and Market Entry Strategies

Industry leaders should focus on advancing BESS technologies, such as solid-state and flow batteries, to improve efficiency, lifespan, and cost-effectiveness. Developing modular, scalable solutions for various applications, from residential to utility-scale, will enhance market appeal. Strategic partnerships with utilities, technology providers, and regulators can help accelerate market entry and ensure seamless integration with renewable energy. Additionally, offering value-added services like system integration and predictive maintenance can provide a competitive edge. Expanding into high-growth emerging markets and securing a sustainable supply chain for critical materials will support long-term growth. Lastly, engaging in policy advocacy can help secure favourable regulatory environments and investment incentives. These strategies will position industry leaders for success in the rapidly growing BESS market.

9.4 For Researchers: Priority Areas for Innovation

Researchers should focus on enhancing the energy density, efficiency, and lifespan of BESS technologies to improve their overall performance and cost-effectiveness. Innovations in solid-state batteries, lithium-sulfur, and flow batteries are promising for increasing storage capacity and reducing degradation. Developing advanced materials for better conductivity, higher stability, and lower environmental impact is crucial for sustainable energy storage. Additionally, research into smart grid integration, optimization algorithms, and AI for predictive maintenance can enhance BESS operation in dynamic grid environments. Exploring recycling techniques and second-life battery applications will also help address sustainability concerns. Collaborating with industry and policy experts to align research efforts with real-world needs will ensure that innovations are scalable and impactful for the energy transition.

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For details, please contact:

Kumar Rahul
kumar.rahul@ieema.org | +91 87890 98209

Ginni Banga
ginni.banga@ieema.org | +91 99581 98875

Pratik Shah
pratik.shah@ieema.org | +91 75060 75756

Indian Electrical & Electronics Manufacturers' Association
85A, First Floor, Rishyamook Building, Panchkuian Road, New Delhi-110001, INDIA
T: +91-11-23363013 | F: +91-11-23363015

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