GOVERNMENT OF INDIA
MINISTRY OF NEW AND RENEWABLE ENERGY

UK Government

Assessment of the Global Landscape for Sodium-Ion Batteries and Their Potential in India

ASPIRE Programme

Accelerating Smart Power and Renewable Energy in India

Disclaimer

सत्यमेव जयते

अजय यादव, भा.प्र.से.
AJAY YADAV, IAS

ITUWTSA
NEW DELHI 2024

संयुक्त सचिव
भारत सरकार
नवीन और नवीकरणीय ऊर्जा मंत्रालय
JOINT SECRETARY
GOVERNMENT OF INDIA
MINISTRY OF NEW AND RENEWABLE ENERGY

Foreword

India's energy landscape is undergoing a significant transformation, driven by the growing demand for electricity, the increasing share of renewable energy and need for greater energy security. Government of India has set a target to reach 500 GW of installed electricity capacity from non-fossil fuel sources by 2030. Most of this capacity will be catered by Renewable Energy (RE) sources like solar and wind, which are intermittent in nature. Energy storage has emerged as a key enabler of this transformation, offering a range of benefits including improved grid stability, enhanced renewable energy integration, and increased energy access.

Various types of energy storage, including battery storage, pumped storage, thermal energy storage, hydrogen storage among others are expected to play a role during this transition. While each type has its unique advantages, battery energy storage is particularly significant due to its quick commissioning time and falling costs.

Currently India has already installed around 211 GW of non-fossil installed electric capacity, however, the installed capacity of grid scale Battery Energy Storage System (BESS) in the country is around 220 MWh only. In addition, tenders for over 16 GWh of grid scale BESS are currently active or awarded. To meet the emerging demand of round the clock, Firm and Dispatchable RE a significant increase in grid scale BESS is expected. According to the Central Electricity Authority (CEA), anticipated requirement of energy storage through BESS will increase to 35 GWh by the year 2026-27 and 208 GWh by the year 2029-30.

The Government of India has launched various schemes and guidelines to promote the development of BESS in the country. These include setting targets for energy storage called Energy Storage Obligations(ESOs), waiving interstate transmission system (ISTS) charges for BESS projects, offering incentives for manufacturing advanced batteries under ACC-PLI scheme, and providing financial support under viability gap funding scheme for BESS projects.

Considering the BESS targets of the country, in addition to established technologies such as lithium-ion batteries, there is a space for other emerging technologies like sodium-ion batteries, flow batteries etc. There is also a need to promote research & development, testing & certification and skill development for these new technologies besides securing the supply chains. There is also a focus on developing a coherent regulatory framework to incentivize stakeholders to participate in the battery recycling process.

This report on 'Assessment of the Global Landscape for Sodium-Ion Batteries and Their Potential in India,' aims to provides an overview of sodium-ion batteries as an innovative technology with significant potential in India. The report contains the analysis of the sodium-ion battery technology, including its current global landscape, potential market & applications in India, supply-side considerations, and the existing policy ecosystem. The report also identifies areas to address for the deployment and promotion of Sodium-ion batteries in India and provides recommendations for the same.

I am confident that developing a strong ecosystem for adopting emerging battery technologies, such as sodium-ion batteries, will enable the smooth integration of renewable energy into the grid. This will help meet the ambitious targets set for 2030 and contribute to achieving the goal of net zero emissions by 2070.

(Ajay Yadav)

Atal Akshay Urja Bhawan, Opp. CGO Complex, Lodhi Road, New Delhi-110003
Tel.: 91-11-20849098, 20849063 • E-mail : yad.ajay@ias.gov.in • Website : www.mnre.gov.in

Acknowledgement

This report was developed under the guidance of the Energy Storage Department of the Ministry of New and Renewable Energy (MNRE), Government of India, with inputs and support provided by Dr. Kuldeep Rana (Scientist E), Mr. Chalapathi Rao (Scientist D), and Mr. Saransh Gupta (Young Professional).

This report was developed as part of the Accelerating Smart Power and Renewable Energy in India (ASPIRE) Programme of the Foreign, Commonwealth & Development Office (FCDO), Government of the United Kingdom. Guidance and inputs were provided by the technical assistance team at FCDO, including Ms. Archana Chauhan (Head- Energy Sector Reforms), Mr. Nishant Singh (Senior Advisor, Energy Security and Lead for Renewable Energy), and Mr. Yash Khandelwal (Policy Advisor-Low Carbon Growth).

We would like to thank KPMG in India for providing support and detailed analysis for the preparation of this report.

TABLE OF CONTENTS

List of Figures

List of Tables

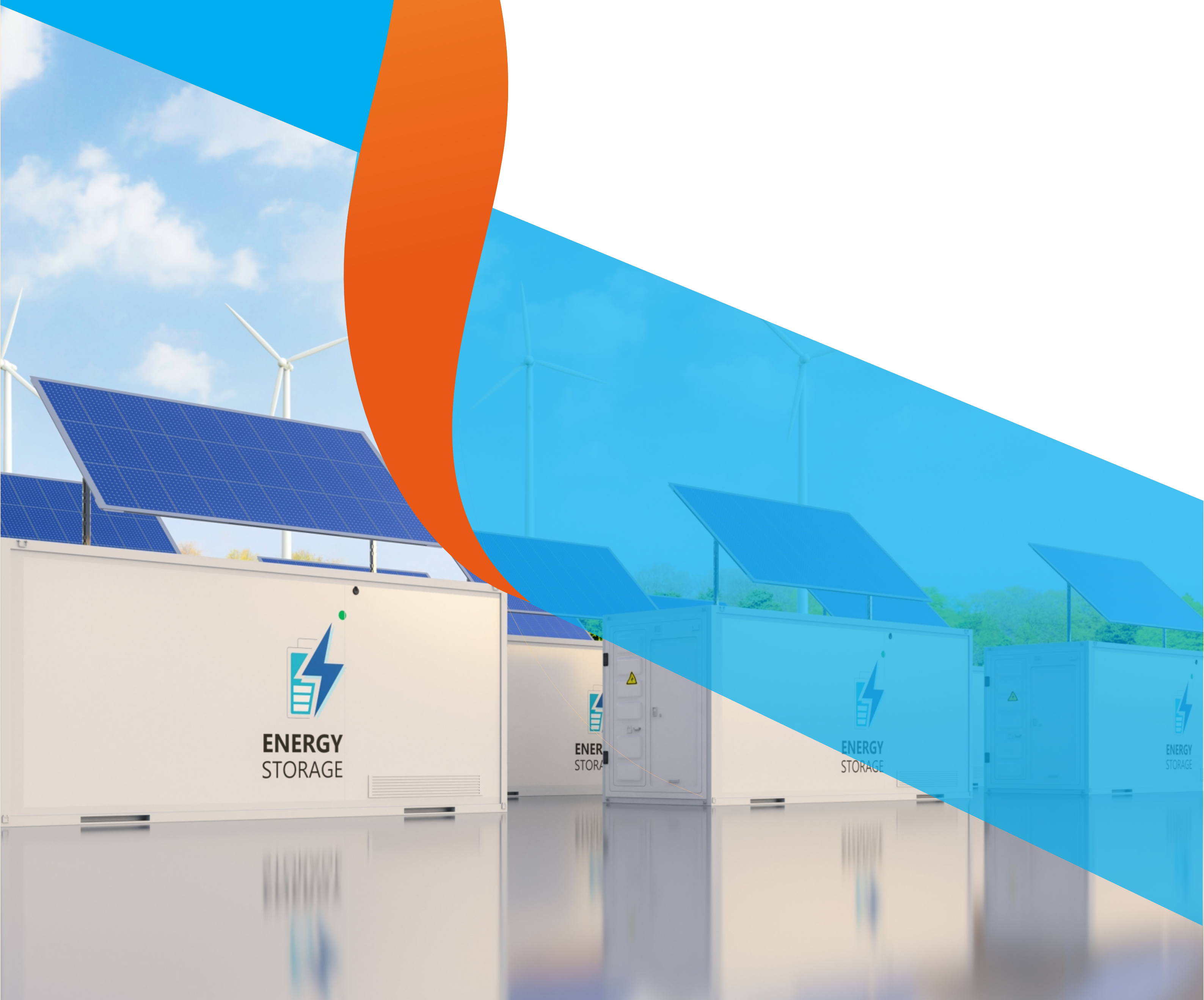
Abbreviations

ACC	Advanced Chemistry Cells
AIT	Austrian Institute of Technology
AMBIC	Advanced Materials Battery Industrialisation Centre
APC	Advanced Propulsion Centre
ASPIRE	Accelerating Smart Power and Renewable Energy
ATF	Automotive Transformation Fund
BBB	British Business Bank
BESS	Battery Energy Storage System
BIS	Bureau of Industrial Standards
BMS	Battery Management System
BOS	Balance-of-System
BT	Billion Tonne
CATL	Contemporary Amperex Technology Company Limited
CEA	Central Electricity Authority
CEIF	Clean Energy Innovation Facility
CEEW	Council on Energy, Environment and Water
DERC	Delhi Electricity Regulatory Commission
DESNZ	Department for Energy Security and Net Zero
DHI	Department of Heavy Industry
DoD	Depth of Discharge
DPIIT	Department for Promotion of Industry and Internal Trade
DRC	Democratic Republic of Congo
DSM	Demand Side Management
DST	Department of Science and Technology
EoDB	Ease of Doing Business
EOL	End of Life
EPC	Engineering Procurement Construction
ESO	Energy Storage Obligation
ESS	Energy Storage System
EV	Electric Vehicle
e-2W	Electric Two Wheelers
FAME	Faster Adoption and Manufacturing of Electric and Hybrid Vehicles
FBC	Faraday Battery Challenge
FCDO	Foreign Commonwealth and Development Office
FDRE	Firm and Dispatchable Renewable Energy
FY	Financial Year

GESI	Gender Equality and Social Inclusion
GHG	Green House Gas
GoI	Government of India
GW	Giga Watt
GWh	Giga Watt Hour
HVM	High-Value Manufacturing
IEA	International Energy Agency
IIT	Indian Institute of Technology
IISER	Indian Institute of Science Education and Research
IoT	Internet of Things
JPY	Japanese Yen
kg	Kilo gram
kT	Thousand Tonne
kW	Kilo Watt
kWh	Kilo Watt Hour
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Battery
LCoS	Levelised Cost of Service
LODES	Longer Duration Energy Storage Demonstration
MNRE	Ministry of New and Renewable Energy
MoP	Ministry of Power
MOU	Memorandum of Understanding
MT	Million Tonne
MWh	Mega Watt Hour
MW	Mega Watt Hour
NCA	Nickel Cobalt Aluminium
NEDO	New Energy and Industrial Technology Development Organisation
NESFF	National Electrification Skills Framework and Forum
NMC	Nickel Manganese Cobalt
NSDC	National Skill Development Corporation
PBA	Prussian Blue Analogues
PCS	Power Conversion System
PHS	Pumped Hydro Storage
PLI	Production Linked Incentive
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energy
RPO	Renewable Purchase Obligation
RTC	Round-The-Clock
SIB	Sodium-Ion Battery

TCA	Trade and Cooperation Agreement
TEA	Transforming Energy Access
TWh	Terra Watt Hour
UK	United Kingdom
UKBIC	United Kingdom Battery Industrialisation Centre
UKIB	United Kingdom Infrastructure Bank
UKRI	United Kingdom Research and Innovation
UPS	Uninterrupted Power Supply
US	United States
UT	Union Territories
VGF	Viability Gap Funding
VRE	Variable Renewable Energy
Wh	Watt Hour
WMG	Warwick Manufacturing Group

Executive Summary

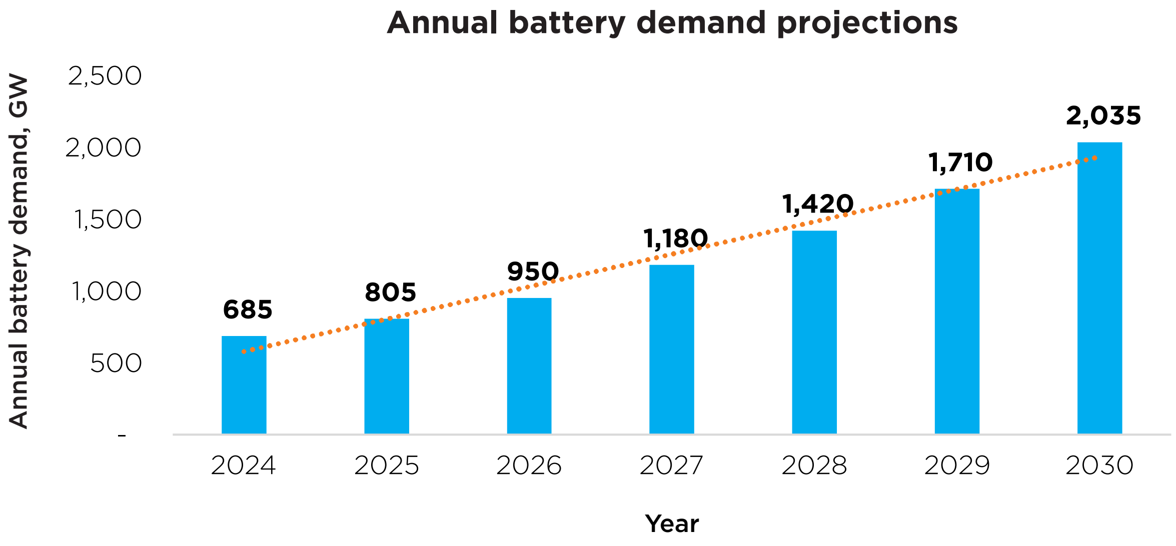


The global drive for net zero has ignited a massive surge in the demand for batteries and energy storage solutions worldwide. This surge stems from the imperative to combat climate change and transition towards sustainable energy systems. As nations commit to ambitious decarbonisation goals, renewable energy (RE) sources like wind and solar power are being rapidly adopted. However, their intermittent nature poses challenges to grid stability.

These challenges are already being observed in countries like India. With a strong mandate to achieve 500 GW of non-fossil fuel electricity capacity and 50% share of non-fossil fuel energy in the energy mix by 2030, India has set ambitious targets for its pathway to achieving net zero by 2070. As part of these targets, the country is rapidly scaling up its RE generation capacity but is facing grid integration challenges due to the intermittency in such sources.

Energy storage systems (ESSs) offer a solution for this intermittency by storing surplus energy during peak production and releasing it when demand increases. Energy storage technologies, especially Battery Energy Storage System (BESS) have shown remarkable technological improvements over the last decade resulting in a sharp decrease in costs. Therefore, BESS is now an integral part of the energy planning framework. As a consequence of this, coupled with the growth of electric vehicles (EVs), demand for batteries is projected to grow over three-fold by 2030.

Executive summary figure 1: Projected annual battery demand by 2030



Source: Statista

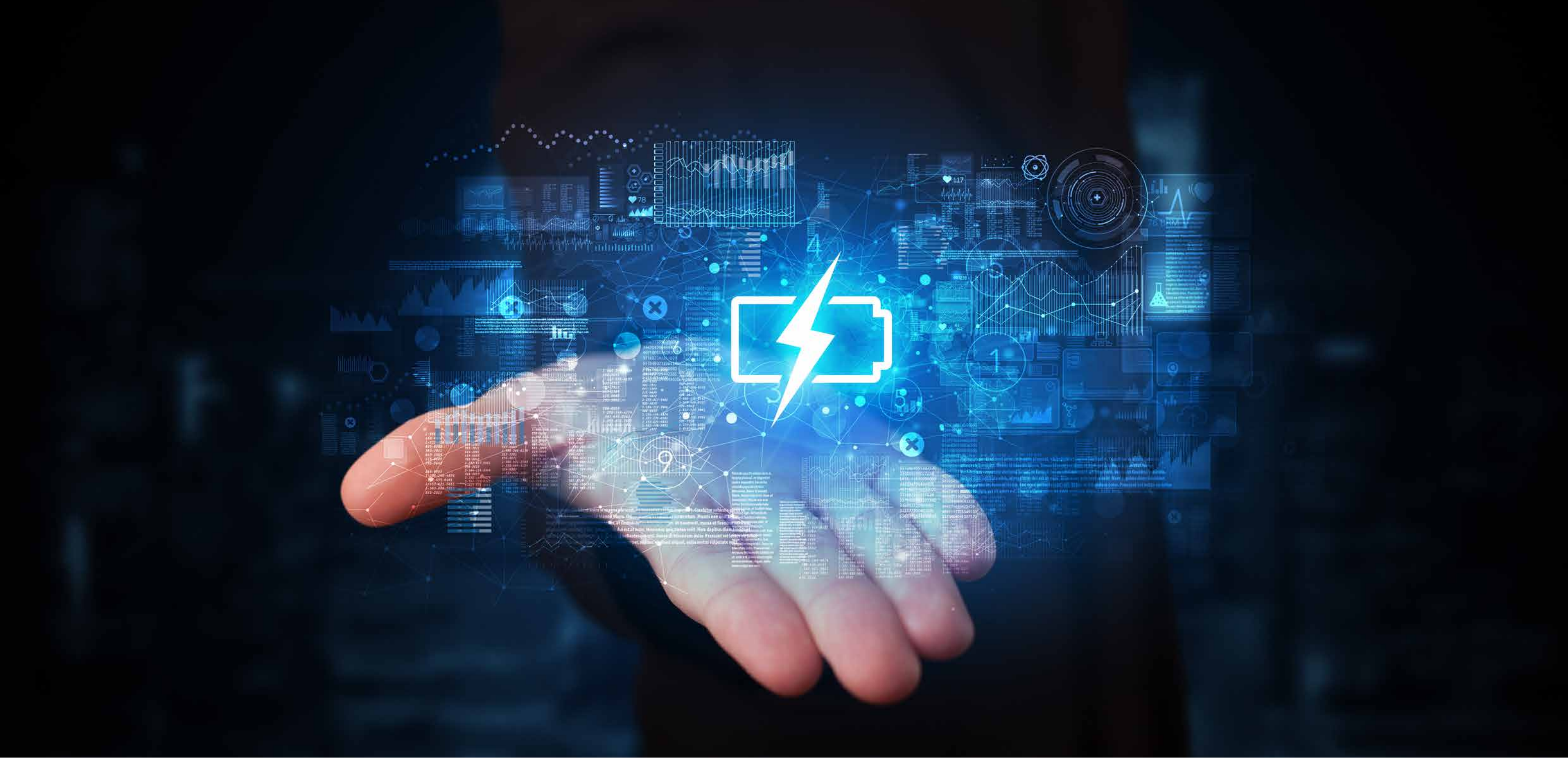
Within BESS, many different technologies and chemistries exist, but the lithium-ion battery (LIB) is one of the most mature technologies. LIB demand has risen exponentially due to growing demand for EVs and grid-scale applications, and its costs have fallen sharply in the last decade. While the initial demand for BESS has been predominantly fulfilled by LIBs thanks to their technological and cost related benefits, there are several risks associated with them. Concerns surrounding the LIB supply chain, environmental impact, and safety, coupled with the growing demand for BESS amid the global energy transition, have led to the need for identifying and developing alternative BESS technologies.

Sodium-ion battery (SIB) technology can potentially address the concerns surrounding LIBs and emerge as an alternative BESS technology. SIBs benefit from limited reliance on critical minerals and improved safety parameters, among other traits, and are particularly suited to meet BESS demand for grid-scale energy storage. Although the technology is at a nascent stage worldwide, both industry players and academic institutions are working to drive commercialisation and deployment. Thus, SIBs are well placed to meet global BESS demands for key applications as the energy transition progresses.

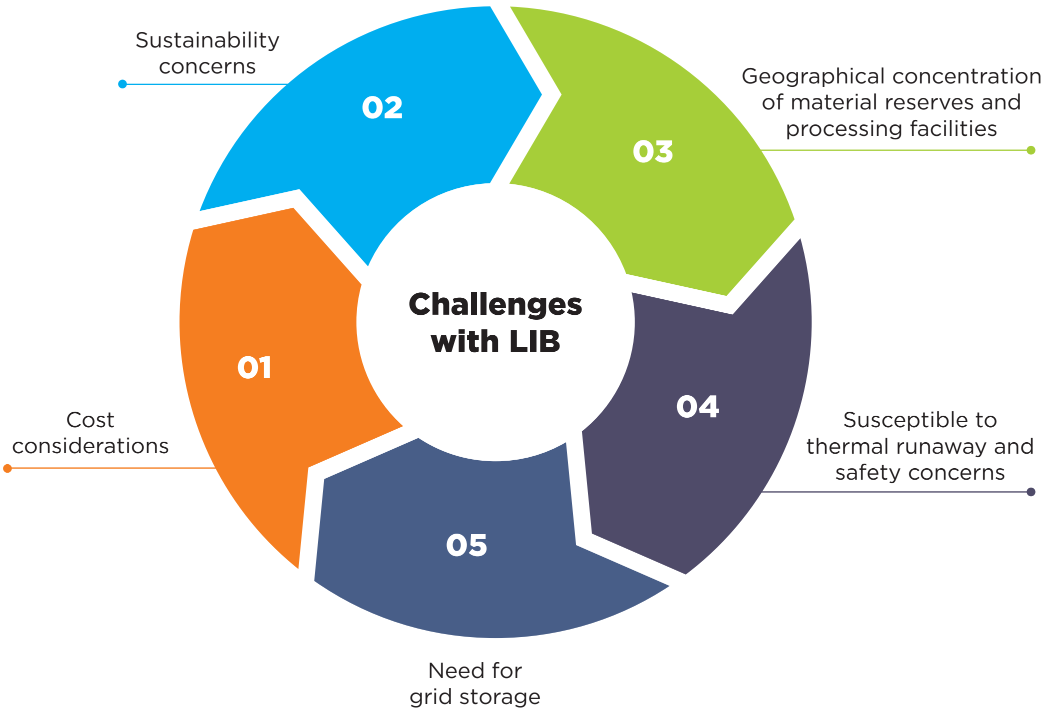
SIBs can also play a key role in India's energy transition. India needs to explore new battery materials beyond lithium due to the scarcity of key materials required for LIB development. The country lacks essential LIB resources like cobalt and lithium. The demand for LIBs is projected to increase significantly by 2030, with India currently relying on imports from resource-rich countries for its lithium supply. As the global automotive industry shifts towards electrification, and the power industry shifts towards RE integration, the need for critical minerals like cobalt, nickel, lithium, and manganese is escalating, posing a challenge for India's energy sector. Moreover, the dominance of specific countries in battery manufacturing and the uneven distribution of these resources globally necessitate India to diversify its battery material sources to ensure energy security and self-sufficiency. By exploring alternative battery technologies like SIB, India can reduce its dependence on lithium and enhance the competitiveness and sustainability of its battery industry.

In this context, this report has been developed as part of Accelerating Smart Power and Renewable Energy (ASPIRE), a bilateral programme implemented by the Foreign Commonwealth and Development Office (FCDO), Government of the United Kingdom (UK), in association with the Ministry of Power (MoP) and Ministry of New and Renewable Energy (MNRE), Government of India (GoI). The report intends to provide a comprehensive overview of SIBs in both the global and Indian context, showcasing its technological parameters, the existing market landscape of SIB technologies with a focus on both demand side and supply side developments, existing regulatory and policy landscape, and Gender Equality and Social Inclusion (GESI) considerations. The report also identifies areas to address and outlines recommendations to support SIB deployment in India. The key findings of the report are as shown below:

- **Growing LIB demand raises multiple social, environmental, technical, and economic concerns:** There are several concerns associated with LIB, including sustainability of mining of critical minerals used in LIBs, unpredictability in lithium costs, geopolitical concentration of supply chains, limited raw material availability and concentration of processing facilities, and safety risks. All these challenges have raised awareness about the importance of developing alternative energy storage technologies that can meet the ever-growing global demand. Some of the major challenges of LIB are demonstrated in figure given below:

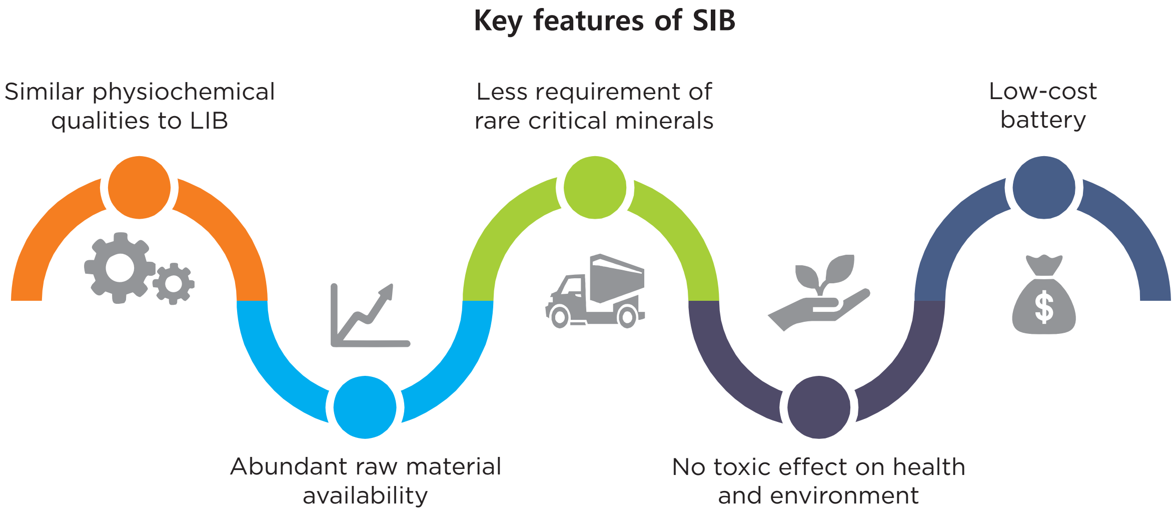


Executive summary figure 2: Key challenges of LIBs



- **SIBs are emerging as a cost effective and sustainable alternative to LIBs:** SIBs benefit from the high availability of sodium sources in the earth's crust and seawater. This availability of raw materials, coupled with the low cost of sodium in comparison with lithium, has led to SIBs gaining significant interest as a promising technology choice for BESS in the years to come. SIB battery chemistries also benefit from reduced usage of critical minerals such as cobalt (whose mining also raises sustainability and human rights concerns), and improved safety. Some of the key features of SIBs are mentioned in the figure below:

Executive summary figure 3: Key features of SIBs



- **SIBs share some common component materials with LIBs, but crucially differ in cathode, anode, and electrolyte materials:** The three primary components of SIB and LIB consist of the cathode, anode, and electrolyte, along with additional components such as separator and current collector. The component wise difference in materials used in LIBs and SIBs, is described in the table below:

Executive summary table 1: Component wise materials of lithium-ion and sodium-ion batteries

Component	Lithium-ion Batteries	Sodium-ion Batteries
Anode	Graphite, Si-graphite, Lithium Titanite Oxide (LTO)	Hard carbon / expanded graphite / tin or antimony alloyed with sodium metal
Separator	Polymer	Polymer
Electrolyte	Organic carbonates: Lithium salt and sodium salt, solid electrolyte	Organic carbonates: Sodium salt
Cathode	Lithium Cobalt Oxide (LCO) Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminium (NCA), Lithium Iron Phosphate (LFP) and modified LFP as Lithium Manganese Iron Phosphate (LMFP)	Prussian Blue and analogues, Layered Transition Metal Oxides, Polyanion (Combinations of sodium, iron, manganese, phosphorus, sulfur, vanadium, nickel, and carbon)
Collector	Aluminium	Aluminium

Source: Wood Mackenzie

- **SIBs have comparable performance to LIBs, except in energy density:** Due to similarities in their operating principles, SIBs are often compared to LIBs. Their comparable lifecycle, enhanced safety, and lower cost make them one of the best-suited battery technologies for grid-scale storage applications.

Executive summary table 2: Overview of key battery parameters

Parameter	Lithium-ion batteries	Sodium-ion batteries	Significance
Energy Density (Wh/Kg)	80 - 300	100 - 170	Applications requiring batteries with compact form factors, such as long-haul EVs, may not be suited for SIBs.
Suitable Storage Duration (Hours)	0 - 6	2 - 6	SIBs are not suited for short storage duration applications such as frequency response.
Cycle Life (Number of cycles)	2,000 - 6,500	3,500 - 6,000	The comparable cycle life of SIBs make them well suited for repeated charging and discharging.
Round Trip Efficiency (%)	92 - 97	80 - 85	Lower round trip efficiency means greater energy losses during battery operations. However, improvements are expected for SIBs with further research and development (R&D).
Calendar Life (Years)	10 - 15	10 - 15	Comparable calendar life for SIBs means they can operate for around the same number of years as LIBs.
Depth of Discharge (DoD) (%)	80	100	100% DoD is a significant benefit, allowing SIBs to be transported at 0% charge, improving safety.
Self-discharge rate (%/Day)	0.1	0.1	The comparable self-discharge rate makes SIBs equally suited for long duration storage applications.

Source: Wood Mackenzie

- **SIBs can offer ~15-20% cost reduction as compared to LIBs:** LIBs currently hold a cost advantage due to their established market presence and mature technology and manufacturing process but reached a price of $128 (£101) per kWh in 2022, due to high critical mineral prices. SIB cells are currently more expensive than LIBs, but various forecasts suggest that SIB cost will steadily decline over the next decade, driven by advancements in technology, and economies of scale. By 2030, SIBs are expected to achieve costs that are 15-20% lower than those of LIBs, making them increasingly competitive for various applications.[1,2]

1 Review of Grid-Scale Energy Storage Technologies Globally and in India | Lawrence Berkeley National Laboratory | August 2023 | Link
2 Electric vehicle battery prices are expected to fall almost 50% by 2026 | Goldman Sachs | October 2024 | Link

Executive summary table 3: SIB and LIB costs

Battery Technology	Global unit cost ($/kWh), year 2022	Global unit cost ($/kWh), year 2030 projected	LCOS (INR/kWh), year 2022	LCOS (INR/kWh), year 2030
SIB	77 (£60) (Cell)	40 (£31) (Cell)	5.4 (£0.05) (India)	4.3 (£0.04) (India)
LIB	128 (£101) (Cell)	47.8 (£37.8) (Cell)	4-hr: 7.0 (£0.06) (India) 10-hr: 5.9 (£0.05) (India)–LFP	4-hr: 4.5 (£0.04) (India) 10-hr: 3.5 (£0.03) (India)–LFP

Source: Lawrence Berkeley National Laboratory, Goldman Sachs

- **SIBs are suitable for a range of grid-scale energy storage applications:** With higher discharge time at rated power and feasibility for deployment as large-scale storage systems, SIBs have more applicability towards bulk power services such as forward capacity, transmission and distribution support, RE firming, energy arbitrage. These applications will become increasingly necessary to integrate significant amounts of RE generation into the grid to meet energy transition objectives. However, SIBs are not suitable for all grid-scale energy storage applications. SIBs showcase less suitability for applications requiring rapid response time i.e., frequency regulation, black start, or voltage support. SIBs can also be suitable for short-haul EVs such as E-bikes.

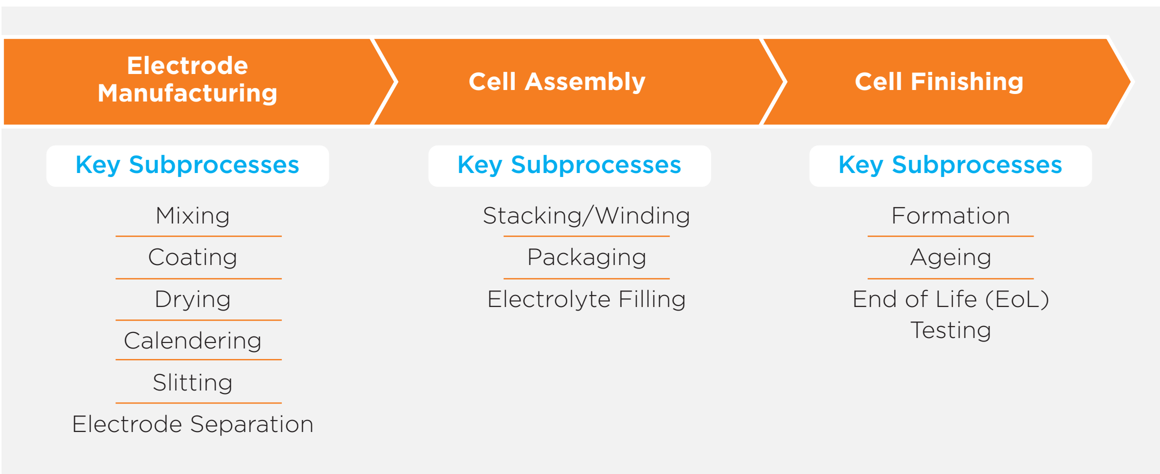
Executive summary table 4: Suitability of SIBs for battery demand driving sectors

Sector applications		Sodium-ion battery
Stationary storage (Grid-scale)	Grid balancing	Good
	Residential storage, Smart Grid	Very Good
Consumer electronics	Computer, tablets, smart phone, smart watch	Poor
EV	E-bikes	Good
	Moped	Poor
	Motorcycle	Not Suitable
	Sports car	Not Suitable
	Sedan	Average
	Sports utility vehicle	Not Suitable
	Pick-up trucks	Not Suitable
	Heavy duty trucks	Not Suitable

Source: Volta Foundation

- **SIBs can help address multiple grid-scale storage use cases in India:** Based on their technical parameters, SIBs are well suited to address various grid-scale applications in India, including forward capacity or resource adequacy, distribution upgrade deferral, transmission congestion relief, and transmission upgrade deferral. SIBs may also see deployment for daily energy arbitrage and daily and seasonal renewable firming applications.
- **SIBs have a similar manufacturing process to LIBs:** The close resemblance of SIB manufacturing processes with those of LIBs allows for LIB production lines to be modified for use in SIB manufacturing. The three key manufacturing stages, with the main subprocesses involved, are detailed in the figure below:

Executive summary figure 4: Key manufacturing stages and subprocesses of LIBs and SIBs



- **India can achieve self-sufficiency in SIB manufacturing:** Key elements employed in SIBs consist of sodium, iron, manganese, phosphorus, sulfur, and aluminium. These elements are sourced from ore or minerals and then extracted and refined in the required form. India is the third largest producer of sodium chloride (salt) worldwide. It produced 26.5 million tonnes (MT) in 2021 and contributed 10% to the global salt production. In addition to India's abundant salt reserve, the country has production capacity for the other important SIB minerals such as iron ore, manganese ore, phosphates, and sulfur. This abundance of input materials, coupled with limited need for critical minerals for SIB manufacturing, make SIBs a viable choice for India to reduce its reliance on imports to meet its storage needs.

- **Market players from US, UK, Europe, and India are endeavouring to penetrate the SIB market:** China is currently a key player in the global SIB battery market, leveraging its robust manufacturing capabilities and strategic initiatives in RE technologies. However, countries like UK, United States (US), Japan, France, and India are rapidly advancing in SIB R&D and manufacturing. The UK in particular is home to some of the leading companies active in the SIB sector, including AMTE Power, and LiNa Energy Limited. Additionally, a number of Indian companies are also active in the SIB sector, including Indi Energy, KPIT Technologies Private Limited, Sodion Energy Private Limited, Cygni Energy, and Uneverse.

- **India's strong policy and regulatory environment for energy storage makes it conducive for SIB deployment:** India's focus on modern ESSs began in 2014, with the formation of MNRE's standing committee on energy storage. Subsequently, a number of policy and regulatory initiatives have supported the storage sector, including the development of Round the Clock (RTC) and Firm and Dispatchable Renewable Energy (FDRE) tenders, development of the Production Linked Incentive (PLI) scheme for Advanced Chemistry Cell (ACC) battery storage, inclusion of Energy Storage Obligations (ESO) within Renewable Purchase Obligations (RPO), and Viability Gap Funding (VGF) for storage projects. Incorporating SIBs within the policy framework can drive its uptake.

- **SIB specific policy interventions can drive sectoral growth in India:** Avenues for SIB related policy interventions can include support for manufacturing capacity, technology-specific VGF, developing R&D and industry partnerships,

skill development initiatives, demand side support, and development of technical and quality standards.

- **Opportunities to collaborate with the UK:** The Indian government and the UK government could collaborate in several ways to improve SIB research and manufacturing in India. Collaboration avenues could include joint research partnerships, business-to-business partnerships, combined efforts to scale up manufacturing capabilities, and sharing of policy and regulatory best practices. These collaborative efforts could significantly accelerate the development and deployment of SIBs in India.

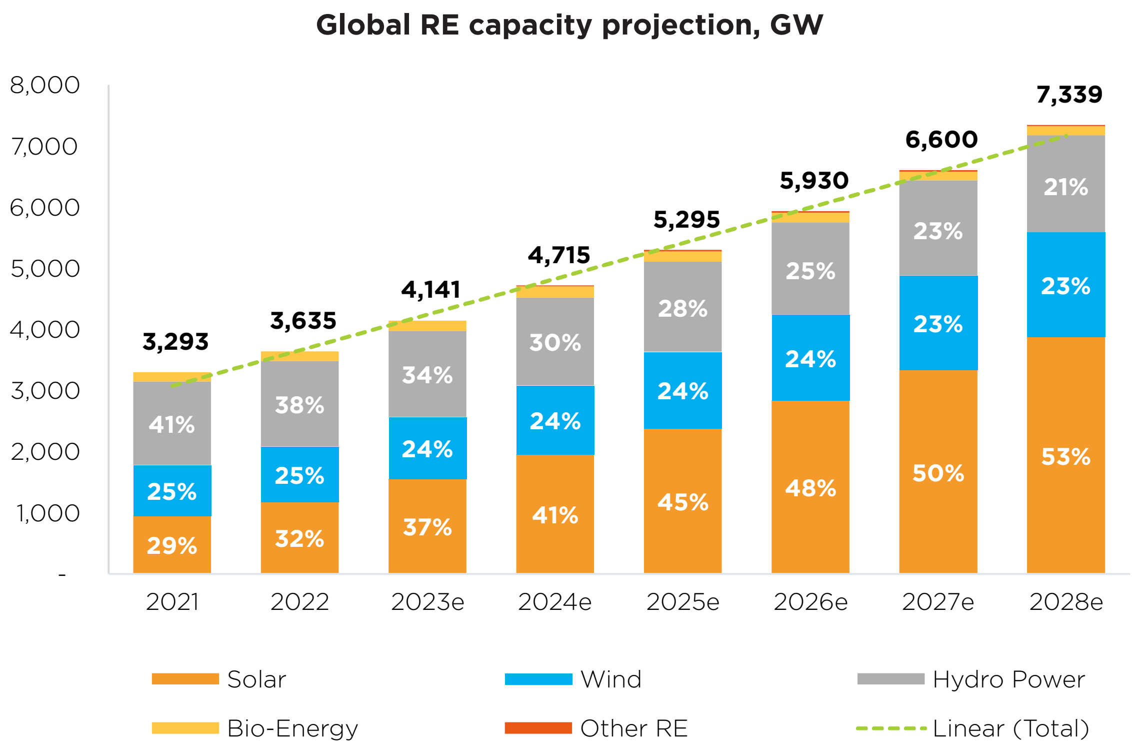
SIBs are poised to play a significant role in supporting RE integration, grid stability, and electrification efforts worldwide. With ongoing research, development and investments, SIBs are well-positioned to unlock their full potential and contribute to a cleaner, more sustainable energy future on a global scale.

01

Introduction

In the face of escalating climate change concerns, the global community has rallied around the ambitious goal of achieving net zero emissions by 2050[3] and reducing global temperature rise to 1.5°C. At the heart of this endeavour lies the imperative to transform the power sector, which is responsible for ~40% of global greenhouse gas (GHG) emission.[4] Countries are rapidly transitioning from conventional energy sources to RE sources to combat the GHG emissions in power sector. Global RE capacity was expected to reach up-to ~4,141 giga watt (GW)[5] in 2023, almost 15% higher than in 2022, the fastest growth rate in the past two decades. It has been estimated by the International Energy Agency (IEA) that the renewable power capacity additions will continue to increase in the next five years.

Figure 1: Global renewable energy capacity projection



Source: IEA

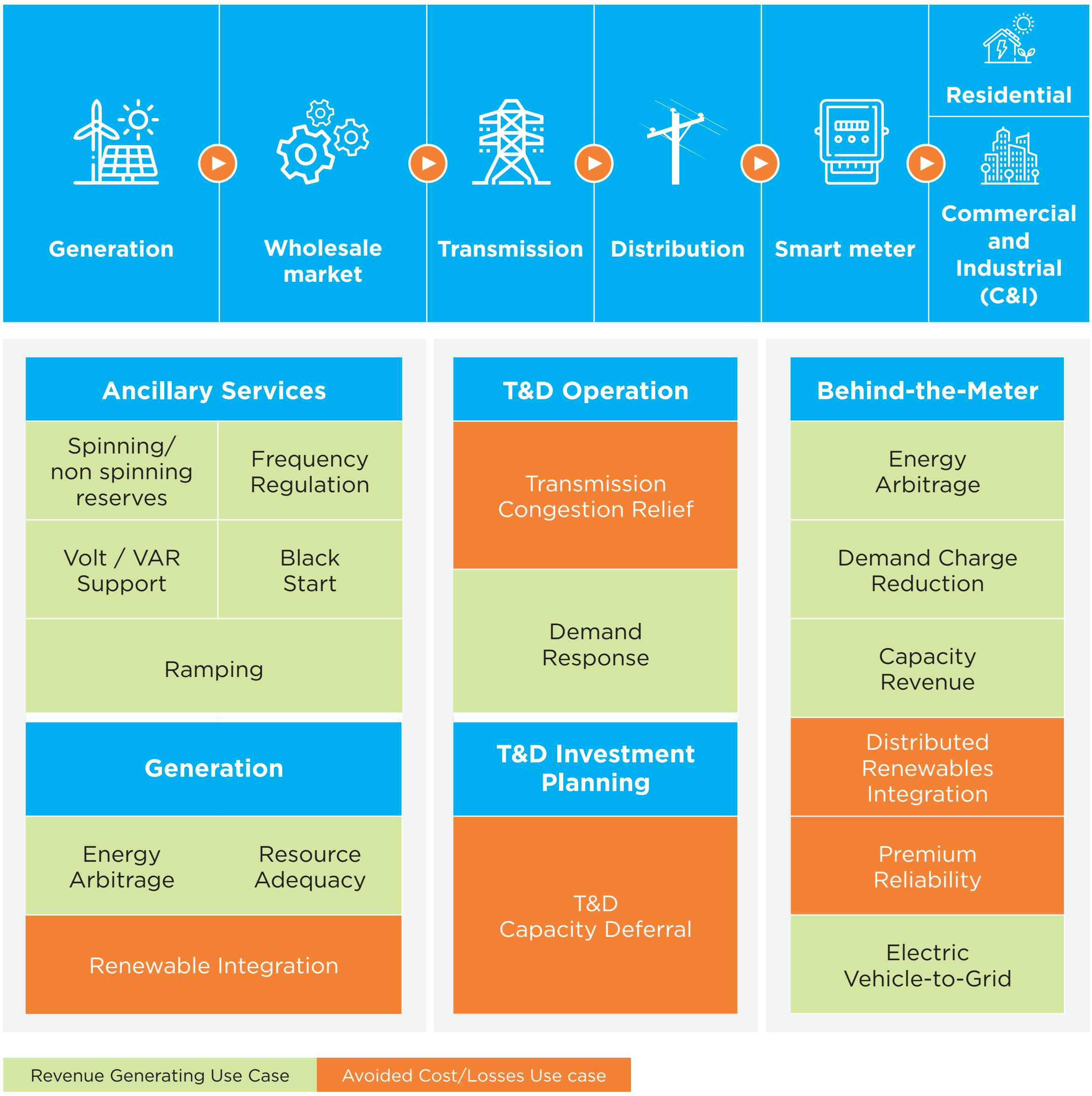
However, unlike conventional power plants fuelled by coal, oil, or natural gas, RE generation is subject to variability and intermittency depending on factors such as weather conditions, time of day and seasonality. Intermittency poses a significant challenge to the reliable and stable operation of electricity grids and requires an effective mechanism of balancing demand and supply in real-time while ensuring grid stability and reliability.

Energy storage is a key solution to manage the variability and intermittency of solar and wind generation. Energy storage technologies, especially BESS, have shown remarkable technological improvements over the last decade resulting in a sharp decrease in costs. Therefore, BESS is now an integral part of the electricity planning framework. Energy storage finds applications across the energy value chain and has a unique benefit of addressing multiple use cases through a single

3 Net Zero by 2050 A Roadmap for the Global Energy Sector | International Energy Agency (IEA) | October 2021 | Link
4 CO_2 Emissions in 2022 | International Energy Agency | March 2023 | Link
5 Cumulative renewable electricity capacity in the main and accelerated cases and Net Zero Scenario, 2021-2030 | International Energy Agency | February 2024 | Link

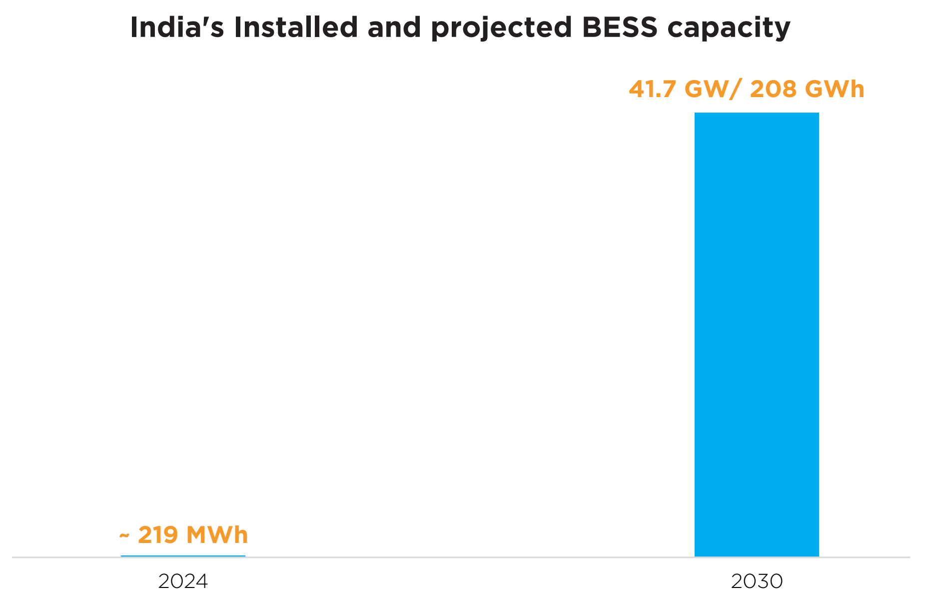
installation (known as multi stacking benefit) which makes it an attractive solution. While the majority of deployments in the front of the meter applications have been for renewable integration, frequency response and demand side management (DSM), there have also been installations in behind the meter applications such as uninterrupted power supply (UPS) for data centres, institutions, and telecom towers.

Figure 2: Energy storage solutions in power sector value chain



In line with the global net zero vision, India has also committed to reducing GHG emissions by 45% by 2030 from the 2005 level and achieving 50% of cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030. The country has already installed over 150 GW of RE capacity as of September 2024,[6] and is aiming to achieve 500 GW of RE installed capacity by 2030. BESS will play a critical role in managing this growing variable renewable energy (VRE) capacity. As per the Central Electricity Authority (CEA), India is likely to require ~41.7 GW/208 giga watt hour (GWh) of cumulative BESS capacity by 2030 to meet the 500 GW RE capacity deployment target.[7]

Figure 3: India's RE and BESS capacity and future projections



Source: CEA and KPMG Analysis

Within BESS, many different technologies and chemistries exist with varied maturity levels. These include lead acid batteries, LIBs, flow batteries, sodium batteries, high temperature batteries, and metal-air batteries, among others. LIB is one of the most mature technologies whose demand has risen exponentially driven by declining costs and growing demand for EVs.

The dominance of LIBs is primarily due to its favourable characteristics, including high energy and power density, higher coulombic efficiency, higher voltage, high cycle life, and limited self discharge rates. The technology particularly benefits from its versatility and potential to be deployed across a range of scales, from kilowatt (kW) to mega-watt (MW). As a result, it is well suited for use in both EVs and grid-scale storage.[8] Despite several benefits, there are specific challenges associated with LIBs such as concerns regarding sustainability of lithium sources and other critical minerals, limited availability of the transition metals and consequent expected price increase, concerns over mining practices, supply chain and others. All these challenges have raised awareness about the importance of developing alternative energy-storage technologies that can sustain the ever-growing energy demand.

6 All India Installed Capacity of Power Stations | CEA | September 2024 | Link
7 Report on Optimal Generation Mix 2030, Version 2.0 | CEA | April 2023 | Link
8 Why does lithium-ion dominate the battery market today? | CEEW | Link

Additionally, while the initial demand for grid-scale battery storage applications has been largely catered through LIBs, the landscape for newer battery technologies is also rapidly evolving, which will provide higher capacity, higher efficiency, low-cost extended lifespans, and augmented safety features. The need for alternative technologies has also been felt due to heavy concentration of raw materials and refineries of lithium-ion in select group of countries.

SIB is one of the most promising alternatives to LIBs. Because of the comparatively high amount of sodium sources in the earth's crust and seawater, SIB has recently gained a lot of interest as a promising commercial choice for large-scale ESSs. Furthermore, because sodium belongs to the same periodic table group as lithium and has similar physicochemical qualities, SIB's operating mechanism is almost similar to LIB's. This battery chemistry has the dual advantage of relying on lower-cost materials than LIBs, leading to cheaper batteries, and reduced dependence on critical minerals. Although they currently exhibit lower energy density and cycling stability compared to LIBs, ongoing research focuses on enhancing their performance through innovative electrode material and electrolyte solutions. As per the NITI Aayog report, lion's share of deployments in India are led by lithium-ion; however, going forward, the uptake of other technologies such as sodium-ion is expected to increase once available commercially at a large scale. The share of SIBs for energy applications including EVs and BESS is expected to rise from 0% today to 4% by 2030.[9]

Ensuring the adoption of cutting-edge storage technologies such as SIBs can play a significant role in both the global energy transition as well as India's energy transition. However, it is important to have a clear understanding of the SIB ecosystem, including technology, demand and supply considerations, cost, and policy ecosystem, to gauge the potential impact of SIB deployment around the world and in India.

9 Need for Advanced Chemistry Cell Energy Storage in India: Part II of III | Niti Aayog | April 2022 | Link


ENERGY
STORAGE

02

Sodium-ion technology overview

2.1 SIBs: Need and technology

2.1.1 Understanding batteries

Batteries typically consist of a few basic components:

- **Anode:** The anode is the negative electrode, and consists of a material that undergoes oxidation (loss of electrons) when the cell discharges.
- **Cathode:** The cathode is the positive electrode which is the source/host for lithium or sodium-ions, and consists of a material that undergoes reduction (gain of electrons) when the cell discharges.
- **Electrolyte:** The electrolyte is a medium that is typically liquid, and allows the movement of ions from one electrode to another during cell discharge.
- **Separator:** The separator is a permeable membrane that ensures the two electrodes are kept apart to prevent short circuits while still allowing the flow of ions between them.
- **Current Collector:** The current collector facilitates and connects the flow of electrons between the active material and the external terminals of the battery:

These elements are present in practically all batteries. Battery technologies thus primarily differ in terms of the material used for the anode, cathode, and electrolyte. These materials determine the key characteristics of batteries, which in turn influence the applications for which they are suited. Some of these key parameters include:

Table 1: Overview of key battery parameters

Parameter	Unit	Description
Energy Density	Wh/Kg or Wh/L	Energy density is the total energy divided by the weight (Wh/kg) or volume (Wh/L) of the battery and measures the compactness of the battery.
Power	Watts	The rate at which the battery can deliver energy, typically in watts (W). It depends on both the voltage and the current the battery can supply.
Cycle Life	Number of cycles	Cycle life is the number of cycles that can be performed before capacity decreases to 80% of initial capacity. This parameter measures the overall longevity of the battery.
Round Trip Efficiency	%	Round trip efficiency is the ratio of the total energy output of the battery to the total energy input into the battery. This is expressed as a % value, and is always less than 100% due to unavoidable inefficiencies in charging and discharging.
Self-Discharge	%/Day or Month	These are the fully recoverable 'idling losses' that occur during times of no-usage. Once the cell is recharged, the idling losses are recovered. Self-discharge is strongly dependent on the temperature.

Parameter	Unit	Description
Calendar Life	Years	The calendar life for a battery estimates the amount of time a battery can be stored or operated before it fails to meet specific performance criteria (typically capacity < 80% of initial capacity).
Charge/discharge C-Rate		C-Rate is the measure of the rate at which a battery is discharged in relation to its capacity. For example, a 1C discharge rate would mean a discharge current that would discharge the entire battery in 1 hour.
Operating Temperature	ºC	The cycle life and performance of a battery is strongly dependent on the ambient temperature, and a range of operating temperatures are typically provided.
Voltage (Nominal, cut-off and charge voltage)	V	Nominal voltage: The average voltage a battery operates at during discharge. Cut-off voltage: The minimum voltage at which the battery is considered fully discharged Charge voltage: The voltage at which the battery is charged.
DoD	%	DoD indicates the share of the battery that has been discharged relative to the overall battery capacity. Typically, this is used to express the degree to which a battery should be discharged without impacting its performance or lifespan.
State of Charge (SOC) and State of Health (SoH)	%	SoC: The current charge level of the battery expressed as a percentage of its total capacity. SoH: An indicator of the battery's overall condition compared to its ideal performance, often expressed as a percentage.
Scalability		Scalability is the capability of the battery to change itself in configuration to enable functionalities such as fault tolerance, fail-safety, hybrid connections, parallel/series interchangeable connections, and customised output terminals.
Memory effect		Memory is the ability of the battery to remember its regular use pattern and can affect the overall capacity of the battery.

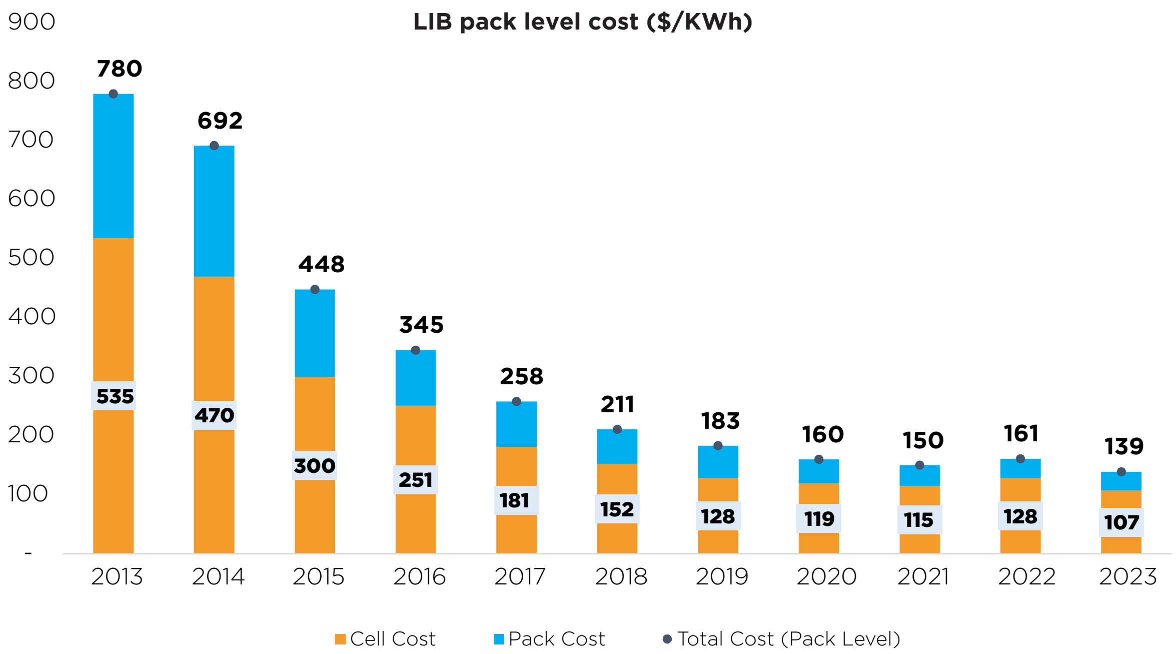
The various parameters of a battery technology vary depending on the technology selected. There are a number of battery technologies available, each with their own set of benefits and downsides, and varying materials utilised. In recent years, LIBs have emerged as the market leader for battery energy storage worldwide.

2.1.2 Lithium-ion: The current dominant technology

The dominance of LIBs is primarily due to its favourable characteristics, including high energy and power density, higher voltage, higher coulombic efficiency, high cycle life, low self-discharge rates. The technology particularly benefits from its versatility and potential to be deployed across a range of scales, from kW to MW. As a result, it is well suited for use in both EVs and grid-scale storage.[10] Due to these advantages, coupled with the growing demand for batteries for EVs, global manufacturing capacities for LIBs have grown rapidly in recent years, which in turn has driven down prices significantly.

As depicted in the figure below, lithium-ion pack costs have fallen by ~80% between 2013 and 2023, which has helped scale their deployment globally.[11]

Figure 4: LIB pack price trend (2013 – 2023)



Source: BloombergNEF[12]

LIBs have been integral to the uptake of BESS over the past decade. However, there are several concerns surrounding the technology and its supply chain:

- **Geopolitical concentration of material reserves and processing facilities:** Lithium is classified as a critical mineral for the global energy transition, and demand is expected to continue growing as the BESS market scales. However, global lithium reserves are limited and restricted to a few major countries. Australia, Chile, and China cumulatively accounted for ~90% of lithium mined worldwide as of 2023. Similarly, the processing facilities for lithium are also restricted to a few countries. China accounted for nearly 60% of global lithium processing as of 2023, with Chile accounting for nearly 30%. Additionally, processing of graphite, the typical anode material for LIBs, is concentrated in China.[13] This geopolitical concentration of reserves and processing facilities is a concern considering the need to develop secure and robust supply chains that can avoid potential supply shocks that can emerge from geopolitical tensions, natural disasters, shifts in associated costs, and other unexpected events. These concerns will also get exacerbated as lithium demand

10 Why does lithium-ion dominate the battery market today? | Council on Energy, Environment, and Water (CEEW) | June 2021 | Link
11 Lithium-ion battery pack prices hit record low of $139/kWh | BloombergNEF | November 2023 | Link
12 Lithium-ion battery pack prices hit record low of $139/kWh | BloombergNEF | November 2023 | Link
13 Geopolitics of the Energy Transition: Critical Materials | International Renewable Energy Agency | July 2023 | Link

is also expected to grow from 130 kt in 2022 to 600 – 1300 kt by 2030, a 5 to 10-fold increase in just 8 years.[14] Countries are recognising this potential risk and responding through policy initiatives. The UK government published its critical minerals strategy in July 2022. The strategy sets out the government's approach to securing the supply of critical minerals, which are essential for a wide range of industries, including the battery industry. The strategy includes several measures to increase the UK's domestic production of critical minerals, as well as to diversify the UK's sources of supply. The strategy identifies lithium, graphite, cobalt and nickel as critical minerals. The strategy also includes a number of measures to support the development of new technologies that use critical minerals more efficiently.[15]

- **Cost considerations:** LIBs have seen significant price volatility in recent years. The price of lithium carbonate nearly tripled in just a year (November 2021 – 2022) before stabilising.[16] Such price fluctuations have raised concerns regarding the global dependence on LIBs, which is only expected to grow further as demand for EVs and grid-scale battery storage increases. Price instability will hamper the scale at which energy storage and EV deployment dependent on LIBs will take place, in turn potentially risking the rate of the energy transition.

- **Sustainability concerns:** Certain LIB chemistries, such as LCO, NMC, and NCA, utilise cobalt. Cobalt, a toxic element, suffers from similar supply chain concerns and price volatility as lithium, but is also associated with significant sustainability concerns. Cobalt mining is primarily located in the Democratic Republic of Congo (DRC), which provides ~75% of global cobalt supply[17], and the industry is a major livelihood provider in the country. However, cobalt mining in the DRC is often carried out through smaller artisanal mines, which have a negative impact on the environment, and are associated with social challenges. The artisanal mining sector is linked to habitat destruction, water and air pollution, child labour, forced labour, and sexual exploitation.[18]

- **Need for grid-scale storage solutions:** LIBs are highly suited for use in EVs due to their high energy density and life cycle but are not necessarily cost effective for grid-scale storage applications. There remains a market for battery technologies that are highly suited for grid-scale deployment in order to support the integration of growing variable RE generation in the grid.

- **Safety concerns:** LIBs need to be transported with a minimum level of charge to avoid dissolution of current collectors, which creates a safety risk. Additionally, LIBs are susceptible to thermal runaway, and have a flash point that leaves them susceptible to ignition. These create significant risks considering the widespread use of LIBs for EVs.

14 Critical Minerals Market Review | International Energy Agency| July 2023 | Link
15 Resilience for the Future:The United Kingdom's Critical Minerals Strategy | 2022 | Link
16 This abundant material could unlock cheaper batteries for EVs | MIT Technology Review | May 2023 | Link
17 The dangers of Cobalt mining in the Congo | Harvard T.H. Chan School of Public Health | February 2023 | Link
18 Mining Cobalt better | International Institute for Environment and Development | September 2021 | Link

2.1.3 Sodium-ion: A promising alternative

Due to the reasons detailed above, there is a pressing need to develop alternative battery technologies that are not as reliant on critical minerals as LIBs and supply chain issues. In this context, SIBs are emerging as a key technology that can replace LIBs for certain applications, in turn reducing the reliance on a single technology, and de-risking the broader global energy storage supply chain.

SIBs operate on similar principles as LIBs but utilise sodium ions as the charge carriers as compared to lithium ions. The two metals used for these batteries, lithium and sodium, are both Alkali metals and thus share similar chemical characteristics. Other key battery components, such as the anode, electrolyte, and current collector, can also differ. The component-wise materials used in LIBs and SIBs are described in the table below:

Table 2: Component wise materials of lithium-ion and sodium-ion batteries

Component	Lithium-ion Batteries	Sodium-ion Batteries
Current Collector (Anode)	Copper	Aluminium
Anode	Graphite, Si-G, LTO	Hard carbon
Separator	Polymer	Polymer
Electrolyte	Organic carbonates: Lithium salt, solid electrolyte (under commercialisation)	Organic carbonates: Sodium salt
Cathode	LCO, NMC, NCA, LFP, LMFP	Prussian Blue and analogues, Layered Transition Metal Oxides, Polyanion (Combinations of sodium, iron, manganese, phosphorus, sulfur, vanadium, nickel, and carbon)
Current Collector (Cathode)	Aluminium	Aluminium

Source: Wood Mackenzie[19]

Due to a combination of the chemical and material characteristics of its components, SIBs benefit from a number of advantages when compared to LIBs:

- **Cost:** SIBs are cost-competitive and may become even cheaper than LIBs in the long term since sodium compounds are cheaper than lithium equivalents. Additionally, SIBs do not use copper current collectors like LIBs and instead use cheaper aluminium current collectors. SIB chemistries also do not require cobalt, which is scarce and expensive. As a result, once SIBs achieve widespread production and benefit from economies of scale, their overall costs could be 15%-20% lower than LFP LIBs.[20]

- **Supply chain decentralisation:** Sodium is abundantly available, and present in almost all countries. The processes for synthesising sodium compounds used in batteries leverage seawater and limestone and are well established. Additionally, SIBs use hard carbon instead of graphite (whose manufacturing is concentrated in China) as the anode material. Thus, a number of countries can realistically aim to develop manufacturing capabilities

19 Sodium-ion update: A make-or-break year for the battery market disruptor | Wood Mackenzie | January 2023
20 Sodium-ion Batteries: Inexpensive and Sustainable Energy Storage | The Faraday Institution | May 2021 | Link

for sodium-ion technologies. As a result, a shift towards SIBs from LIBs would help reduce the current geopolitical concentration of supply chains, making them more secure and resilient.

- **Sustainability:** SIBs do not require the use of certain critical minerals, such as cobalt and lithium, that are essential components of most lithium-ion chemistries. By avoiding the usage of cobalt and lithium, they mitigate the sustainability and social concerns associated with the mineral's supply chain.

- **Technology:** SIBs bring certain technological advantages that allow them to be suitably deployed for certain applications where LIBs may not be optimal. For example, SIBs have a better range of operational temperatures than LIBs, allowing them to be safely deployed in areas with greater temperature variation. SIBs also have a comparable cycle life to LIBs, improving their suitability for applications where repeated charging and discharging are expected.

- **Safety:** Unlike LIBs, SIBs can be transported at zero voltage i.e. in a fully discharged state. As a result, there is less fire risk for such batteries during transportation and less requirement for expensive safety measures. SIBs also benefit from not using copper as a current collector. The presence of copper in LIBs can lead to dissolution, which negatively impacts performance and poses safety hazards due to the potential for short circuits. Sodium-ion electrolytes also have a higher flash point than lithium-ion chemistries, which makes them less likely to ignite.

Although not a direct advantage with respect to LIBs, SIBs are also emerging as a promising alternative to LIBs due to the similarities in their production processes. Existing lithium-ion manufacturing facilities can be leveraged to manufacture SIBs. This provides SIBs a clear pathway to reaching large-scale manufacturing and economies of scale.

The combination of favourable material costs, improved safety considerations, potential for geographically diverse manufacturing supply chains, and mitigation of sustainability concerns means that SIBs have massive potential to revolutionise the energy storage space.

2.2 Comparing lithium-ion and sodium-ion batteries

Although SIBs are operationally similar to LIBs, they differ in key performance parameters. A summarised comparison between the two across key performance parameters is provided below:

Table 3: Comparison between LIBs and SIBs based on key performance parameters

Parameter	Lithium-ion batteries	Sodium-ion batteries	Significance
Energy Density (Wh/Kg)	80– 300	100 – 170	Applications requiring batteries with compact form factors, such as long-haul EVs, may not be suited for SIBs.
Suitable Storage Duration (Hours)	0 – 6	2 – 6	SIBs are not suited for the shortest storage duration applications such as frequency response.

Parameter	Lithium-ion batteries	Sodium-ion batteries	Significance
Cycle Life (Number of cycles)	2,000 – 6,500	3,500 – 6,000	The comparable cycle life of SIBs makes them well suited for repeated charging and discharging.
Round Trip Efficiency (%)	92 – 97	80 – 85	Lower round-trip efficiency means greater energy losses during battery operations. However, improvements are expected for SIBs with further R&D.
Calendar Life (Years)	10 – 15	10 – 15	Comparable calendar life for SIBs means they can operate for around the same number of years as LIBs.
DoD (%)	80	100	100% DoD is a benefit, allowing SIBs to be transported at 0% charge, improving safety.
Self-discharge rate (%/Day)	0.1	0.1	The comparable self-discharge rate makes SIBs equally suited for long duration storage applications.

Source: S&P Global[21], Faradion[22], The Volta Foundation[23]

21 Alternative Battery Technology Review | S&P Global | Link
22 Technology Benefits | Faradion | Link
23 The Battery Report 2022 | The Volta Foundation | March 2022 | Link

The risks associated with both SIBs and LIBs also vary across various key parameters:

Table 4: Comparison of LIBs and SIBs based on various risk areas

Risk area	Lithium-ion batteries	Sodium-ion batteries
Technology	Well established technology	Nascent stage with further R&D required
Supply chain	Volatile and geopolitically concentrated supply chain	Underdeveloped supply chain, but potential to be distributed worldwide
Raw material availability	Reliant on critical minerals	Significantly less reliant on critical minerals
Manufacturing	Established manufacturing capacity and processes	Limited manufacturing capacity, but similar process to LIBs
Cost	Higher cost at cell level but lower cost at pack level	Lower cost at cell level but higher cost at pack level with potential for reduction through economies of scale
Sustainability	Uses cobalt, which is associated with environmental and human rights concerns	Does not rely on cobalt, mitigating sustainability concerns

It is important to recognise that SIBs are not direct replacements for LIBs and their suitability varies depending on various application specific requirements. Broadly, SIBs are well suited to applications where energy density is not a key consideration, and where cost, safety, and sustainability are more valuable. Based on these characteristics, SIBs are currently not well suited to widespread deployment in EVs except for short-haul applications but are increasingly being explored for grid-scale storage applications. However, the technology is relatively new and constantly undergoing R&D. Accordingly, new applications may become feasible as the technology progresses and improves.

2.3 SIB research and development

SIBs have become a focus area for R&D activities considering their performance characteristics and the pressing need to develop alternatives for LIBs. There has been a steady increase in transnational patent applications for SIBs since 2010, with more than 400 transnational patents filed in 2021.[24] A number of major institutions are active in the R&D space for SIBs, including:

- **European Institutions:**
    - The Faraday Institution (UK)
    - The Austrian Institute of Technology (AIT) (Austria)
    - The Federal Institute for Materials Research and Testing (BAM) (Germany)
    - The French Alternative Energies and Atomic Energy Commission (CEA) (France)
    - Fraunhofer Institute (Germany)
- **USA National Laboratories,** such as Pacific Northwest National Laboratory and Argonne National Laboratory
- **Chinese universities and institutions,** such as Central South University in Changsha

24 Sodium-ion batteries 2023: Status quo and perspectives along a future value chain | Fraunhofer | September 2023 | Link (Translated from German)

Although universities continue to drive cutting edge research, SIBs are gradually entering the industry at large. A number of companies and startups are actively developing and improving SIBs, developing new chemistries and driving scale-up and commercialisation of the technology. These players are at the forefront of SIB development and are located around the world:

Figure 5: Select sodium-ion battery developers and manufacturers

India

- KPIT Technologies
- Sodion Energy
- Indi Energy
- Uneverse
- Cygni Energy

United Kingdom

- AMTE Power
- LiNa Energy

United State

- Natron Energy
- Acculon Energy

Europe

- Northvolt (Sweden)
- Altris (Sweden)
- Tiamat Energy (France)

Continued R&D will remain essential for the growth prospects of SIBs, allowing for improved battery performance, smoother manufacturing processes, and wider integration for EV and stationary storage applications. Focus areas for sodium-ion related research include improving battery energy density, optimising active materials and electrolytes, developing of Battery Management System (BMS) and "Cell to Pack" concepts, and scaling up manufacturing processes for commercialisation.

SIBs are a promising technology that can improve the sustainability and security of energy storage worldwide. There is significant potential for SIBs to co-exist with LIBs as per their specific strengths, and the market for SIBs is gradually developing as the technology continues to evolve.

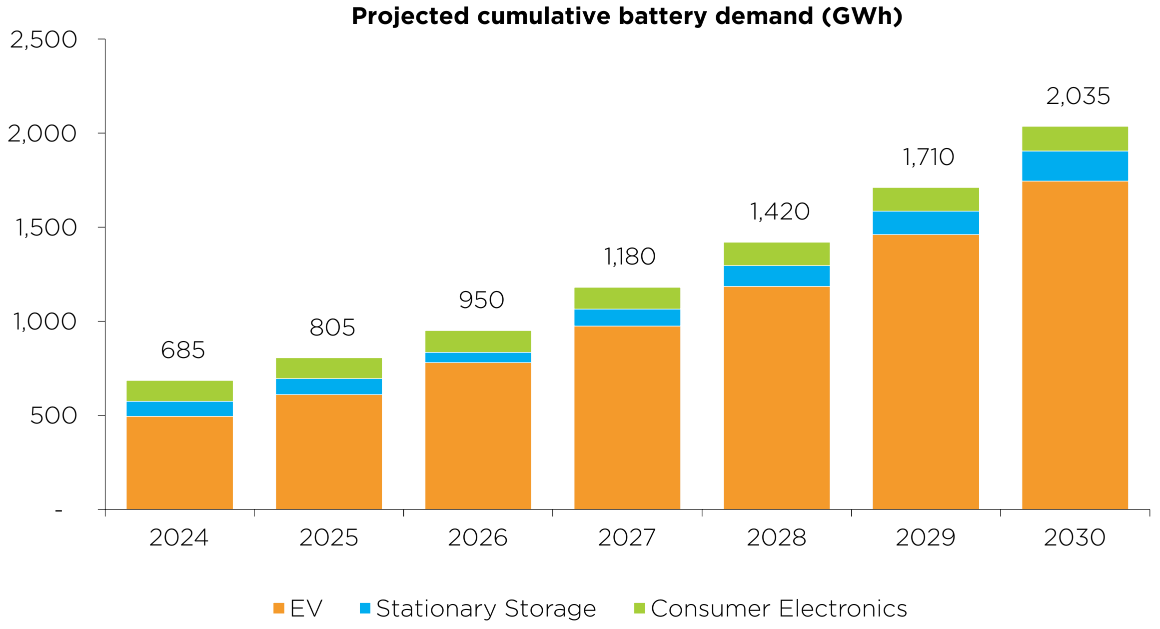
03

Market assessment and potential

3.1 Global demand for batteries

The global demand for batteries is on the rise, driven primarily by three major sectors: EVs, stationary energy storage solutions, and consumer electronics. Firstly, the shift towards EVs as a means to reduce carbon emissions and reliance on fossil fuels has propelled the demand for high-performance batteries to power them efficiently. Secondly, the integration of VRE sources like solar and wind power necessitates stationary ESSs to store surplus energy for later use, thereby enhancing grid stability and reliability. Thirdly, the ubiquitous use of consumer electronics such as smartphones, laptops, and wearables fuel the need for compact, long-lasting batteries with rapid charging capabilities to meet consumer expectations for convenience and performance. The convergence of these factors has created a significant surge in battery demand globally. In the year 2020, global battery demand was 185 GWh and has rapidly increased since and is expected to grow 11-fold by 2030.

Figure 6: Projected global battery demand (annual) till 2030



Source: Statista[25]

As technology continues to advance and environmental concerns drive innovation, the demand for batteries is expected to further escalate, prompting continued R&D efforts to enhance battery efficiency, capacity, and sustainability to meet the evolving needs of these diverse sectors.

25 Projected global battery demand from 2020 to 2030, by application | Statista | Link

3.2 Battery demand in India

India's battery market is experiencing substantial growth, mirroring global trends, due to the demand from three key sectors: EVs, stationary energy storage, and consumer electronics. The analysis of battery storage requirements for each sector by the year 2030 is outlined below.

- **EVs:** The current EV penetration in India leads to an estimated battery demand of ~27 GWh as per the battery size estimations done by The Council on Energy, Environment, and Water (CEEW).[26] With the constant policy push through the Faster Adoption and Manufacturing of Electric and Hybrid Vehicles (FAME) incentive, PLI scheme, and state-specific EV policies towards the growth in EV sales, NITI Aayog estimates that by the year 2030, the cumulative battery demand for EVs would be ~381 GWh.[27]

- **Stationary battery energy storage system:** As of March 2024, India had already installed approximately 219 mega watthours (MWh) of grid-scale BESS,[28] with tenders for about 18 GWh of grid-scale BESS either active or awarded.[29] Further, there are plans for a significant expansion in grid-scale BESS, with CEA projecting a capacity requirement of 208 GWh by 2030.[30]

- **Consumer electronics industry:** Market growth in the consumer electronics sector is largely attributed to the growth in sales of mobile phones and power banks, increasing from annual sales of 300 million devices today to 1.2 billion devices annually by 2030. Additional demand from the consumer electronics sector includes Internet of Things (IoT) devices and telecom towers.[31] The current battery demand for consumer electronics is 10 GWh which is projected to reach 30 GWh by 2030.[32]

Cumulatively, with these three sectors, battery demand in India is expected to increase to ~619 GWh by the year 2030.

26 India's Electric Vehicle Transition | CEEW | 2019 | Link
27 Advanced Chemistry Cell Battery Reuse and Recycling Market in India | NITI Aayog | May 2022 | Link
28 India's installed battery storage capacity hits 219 MWh | Mercom | July 2024 | Link
29 KPMG analysis
30 Report on Optimal Generation Mix 2030 Version 2.0 | CEA | April 2023 | Link
31 Need for advanced chemistry cell energy storage in India Part I | NITI Aayog | February 2022 | Link
32 Consumer electronics battery demand in India in 2022 with estimates up to 2030 | Statista | January 2024 | Link

3.3 Suitable applications for SIBs

It is important to recognise that SIBs are not direct replacements for LIBs and their suitability varies depending on various application-specific requirements. SIBs exhibit characteristics such as wider operating temperature ranges, stable anode-electrolyte mixtures, excellent capacity retention even in freezing temperatures, potential for safe transportation and lower susceptibility to thermal runaway, making them a safe and reliable choice of battery. Broadly, SIBs are well suited to applications where energy density (Wh/kg or Wh/L) is not a key consideration, and where cost, safety, and sustainability are more valuable. The below table provides a summary of the mapping of the required performance characteristics of various applications with SIBs.

Table 5: Cell chemistry trade-off (application requirements)

Sector applications		SIB suitability
Stationary storage (Grid-scale)	Grid balancing	Good
	Residential storage, Smart Grid	Very Good
Consumer electronics	Computer, tablets, smart phone, smart watch	Poor
EV	E-bikes	Good
	Moped	Poor
	Motorcycle	Not Suitable
	Sports car	Not Suitable
	Sedan	Average
	Sports utility vehicle	Not Suitable
	Pick-up trucks	Not Suitable
	Heavy duty trucks	Not Suitable

Source: Volta Foundation[33]

Based on these characteristics, SIBs are currently not well suited to widespread deployment in EVs (except for short-haul applications) and consumer electronics but are increasingly being explored for grid-scale storage applications. Stationary energy storage for grid balancing is a kind of application where energy density, size and weight are not critical considerations for the selection of batteries.

3.3.1 Suitability of SIBs for various grid-scale storage applications in India

SIBs can be a more viable option for grid-scale applications due to their cost effectiveness, long cycle life and safety parameters. The below section provides a mapping of the suitability of SIBs for various grid-scale storage applications in the Indian context.

1. Forward capacity or resource adequacy

System operators need to ensure an adequate supply of generation capacity to reliably meet demand during the highest demand periods in a given year, or the peak demand. This peak demand is typically met with high-cost generation capacity, such as gas plants. While VRE resources can also be used to meet this requirement, through pairing with BESS. This can enable these VRE resources to shift their generation to coincide with peak demand, improving their capacity value and system reliability. Fulfilment of these demand

33 Battery report | Volta Foundation | January 2023 | Link

variations from resource generation or storage is called resource adequacy, forward capacity or demand management.[34]

- **Technical considerations:** An ESS suitable for forward capacity applications should have a long cycle life and long discharge duration. In this application, energy storage system capacity needs to be large enough to store sufficient energy to meet the peak demand. Also, these applications involve frequent charging and discharging cycles, which can lead to battery degradation over time. Accordingly, long cycle life is preferred to ensure reliability and longevity, minimising maintenance costs and downtime.

- **Adequacy of SIBs:** The technical considerations required for forward capacity are broadly aligned with the technical specifications provided by SIBs. SIBs have a long cycle life and long discharge duration and are thus suitable for forward capacity applications.

2. Distribution upgrade deferral and voltage support

Distribution upgrade deferral involves using storage to delay or avoid investments that would otherwise be necessary to maintain adequate distribution capacity to serve all load requirements. When a transformer is replaced with a new, larger transformer, its size is selected to accommodate future load growth over the next 15-year to 20-year planning horizon. Thus, a large portion of this investment is underutilised for most of the new equipment's life. The upgrade of the transformer can be deferred by using a storage system to offload it during peak periods, thus extending its operational life by several years.

- **Technical considerations:** A BESS suitable for distribution upgrade deferral in grid-scale should have a moderate energy density, long discharge duration, moderate to high cycle life and moderate to large capacity with potential for further scalability. Energy density is not a critical consideration here as compared to other grid applications, but high cycle life batteries with minimum degradation over time are preferred to minimise maintenance costs and maximise return. Also, scalability is essential to accommodate future growth in energy demand or changes in grid requirements, ensuring that the system remains effective in deferring distribution upgrades over the long term. Additionally, lower-cost batteries are much more suitable if future scalability of capacity is required.

- **Adequacy of SIBs:** The technical considerations required for distribution deferral are aligned with the technical specifications of SIBs. SIBs have long cycle life, and long discharge duration and have high potential for capacity ramp-up along with being of low cost, thereby making them highly suitable for distribution upgrade deferral and voltage support.

3. Transmission congestion relief

Transmission congestion occurs when, despite being available, least-cost energy cannot be delivered to all or some loads because transmission facilities are not adequate to deliver that energy. Energy storage can be used to avoid congestion-related costs and charges. In this service, storage systems would be installed at locations that are located downstream from the congested portion of the transmission system. Energy would be stored when there is no transmission congestion, and it would be discharged (during peak demand periods) to reduce peak transmission capacity requirements.

- **Technical considerations:** A BESS suitable for transmission congestion relief applications should have long discharge hours, long cycle life, and large capacity with the potential of further scalability and low cost to effectively alleviate congestion and enhance grid stability.

- **Adequacy of SIBs:** The technical considerations required for transmission congestion relief are aligned with the technical specifications of SIBs. Technical considerations such as long cycle

34 Grid scale battery storage | NREL | September 2019 | Link

life, suitability for large capacity with high potential of scalability, and cost-effectiveness are supporting parameters for SIBs. Hence, SIBs are highly suitable for transmission congestion relief.

4. **Transmission upgrade deferral**

Transmission upgrade deferral involves delaying and, in some cases, avoiding entirely the utility investments in transmission system upgrades to meet projected load growth in specific regions of the grid, by using relatively small amounts of storage.

- **Technical considerations:** A BESS suitable for transmission upgrade deferral at grid-scale should have a long discharge duration, moderate to high cycle life and moderate to large capacity with a high potential for scalability. Similar to distribution upgrade deferral, high energy density is not a critical consideration but high cycle life batteries with minimal degradation over time are preferred to minimise maintenance cost and maximise return. Also, scalability is necessary to accommodate future growth in energy demand or changes in grid requirements, ensuring that the system remains effective in deferring transmission upgrades over the long term. Additionally, low-cost batteries are much more suitable if future scalability of capacity is required.

- **Adequacy of SIBs:** Similar to distribution deferral, the technical considerations required for transmission deferral are aligned with the technical specifications of SIBs. Technical considerations such as long discharge duration, long cycle life, suitability for large capacity along with potential scalability and lower cost than prevalent LIBs, are supporting parameters for SIBs. Hence, SIBs are suitable for transmission upgrade deferral.

5. **Energy arbitrage (daily)**

Electric energy arbitrage involves purchasing inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so that the stored energy can be used or sold at a later time when the price or costs are high. Alternatively, storage can provide similar time-shift duty by storing excess energy production, which would otherwise be curtailed, from RE such as wind or solar. The functional operation of the storage system is similar in both cases, and they are treated interchangeably.

- **Technical considerations:** For energy arbitrage, the target discharge duration is less than an hour, which can be termed as moderate response time. Other preferred technical considerations include large system capacity, long cycle life, and scalability (to capitalise on differences in energy prices). Energy arbitrage requires moderate response times to capitalise on the fluctuations in energy prices and respond to changes in market conditions, allowing for timely charging and discharging to maximise arbitrage opportunities.

- **Adequacy of SIBs:** Some of the technical considerations of energy arbitrage are aligned with the technical specifications of SIBs such as longer cycle life, large capacity and potential of scalability. SIBs have a slower response time as compared to LIBs. SIBs can be used in energy arbitrage applications if the instantaneous response is not critical for storage. Hence SIBs are moderately suitable for energy arbitrage.

6. **Frequency regulation**

Frequency regulation is the immediate and automatic response of power to a change in locally sensed system frequency, either from a system or from elements of the system. Regulation is required to ensure that system-wide generation is perfectly matched with system-level load on a moment-to-moment basis to avoid system-level frequency spikes or dips, which create grid instability.

- **Technical considerations:** A BESS used for frequency response should ideally have rapid response time, long cycle time, and capacity should have potential for scalability. The BESSs used for frequency response require high power density to respond rapidly to fluctuations in grid frequency. High power density enables storage systems to inject or absorb power quickly to balance grid conditions and stabilise frequency deviations.

- **Adequacy of SIBs:** Only some of the technical specifications of SIBs are aligned with frequency regulation such as long cycle life and potential for scalability. Higher energy density and rapid response time are the two important criteria for the frequency response application. SIBs have low to moderate energy density and long response time, which does not align with the requirement of application. Hence, SIBs are less suitable for frequency response applications.

7. Reserves

Operation of an electric grid requires reserve capacity that can be called upon when some portion of the normal electric supply resources become unavailable unexpectedly. There are three types of reserves that can be present in an electric grid. Spinning reserves comprise of generation capacity that is online but unloaded and that can respond within 10 minutes to compensate for generation or transmission outages. 'Frequency- responsive' spinning reserve responds within 10 seconds to maintain system frequency. Spinning reserves are the first type used when a shortfall occurs. Non-Spinning reserves comprise of generation capacity that may be offline or that comprises a block of curtailable and/or interruptible loads and that can be available within 10 minutes. Finally, supplemental reserve comprises of generation capacity that can pick up load within one hour. Its role is, essentially, a backup for spinning and non-spinning reserves.

- **Technical considerations:** The energy storage system used for reserve should have high power density, and fast response time, ranging from 10 minutes to 1 hour.

- **Adequacy of SIBs:** Fast response time is an important criterion for the reserve application while SIBs have a longer response time which does not align with the requirement of reserves. Hence, SIBs are less suitable for reserve applications.

8. Voltage support

Voltage regulation ensures reliable and continuous electricity flow across the power grid. The voltage on the transmission and distribution system must be maintained within an acceptable range to ensure that both real and reactive power production is matched with demand.

A requirement for electric grid operators is to maintain voltage within specified limits. In most cases, this requires management of reactance, which is caused by grid-connected equipment that generates, transmits, or uses electricity and often has or exhibits characteristics like those of inductors and capacitors in an electric circuit. To manage reactance at the grid level, system operators need voltage support resources to offset reactive effects so that the transmission system can be operated in a stable manner. Normally, designated power plants are used to generate reactive power to offset reactance in the grid. The nominal time needed for voltage support is assumed to be 30 minutes–sufficient time for the grid system to stabilise and, if necessary, to begin orderly load shedding to match available generation.

- **Technical considerations:** A BESS used for voltage support should ideally have high power density, and fast response time. Energy storage used for voltage support should be able to respond in a very short time around 30 minutes, which is a very important criteria for the application.

- **Adequacy of SIBs:** Higher energy density and rapid response time are the two important criteria for the voltage support application while SIBs have low to moderate energy density and longer response time which does not align with the requirement of the application. Hence, SIBs are less suitable for frequency response applications.

9. Black start

In the event of a grid outage, black start generation assets are needed to restore operation to larger power stations to bring the regional grid back online. Storage systems provide an active reserve of power and energy within the grid and can be used to energise transmission and distribution lines and provide station power to bring power plants online after a catastrophic failure of the grid.

- **Technical considerations:** The energy storage system used for a black start should have a fast response time and it should be able to respond in minutes, which is a very important criteria for the application.

- **Adequacy of SIBs:** Fast response time is the important criteria for the black start application. SIBs have longer response time which does not align with the requirements of the application. Hence, SIBs are less suitable for the black start application.

10. Renewable firming (daily and seasonal)

Renewable firming is when fast-response resources effectively smooth or firm up renewable generation, creating a more traditional dispatchable resource that can be easily integrated into the existing grid. As intermittent renewable generation increases, the need for fast-responding resources that match real-time generation and demand will increase. In addition, there is some uncertainty in weather forecasts and some undesirable electrical effects caused by some sources of RE generation.

Additionally, RE such as wind and solar can fluctuate in output both at the daily scale and the seasonal temporal scale. Seasonal storage is required at very high levels of renewable penetration to store large amounts of energy for weeks to months to bridge the gap between seasonally variable RE output.

- **Technical considerations:** A BESS used for renewable firming has two types of requirements. For daily RE firming, energy storage is needed to provide rapid response time while for seasonal storage, it can take a moderate response time. Based on the specific case requirement, an appropriate battery technology can be used.

- **Adequacy of SIBs:** For daily RE firming, SIBs might not be suitable as they do not have rapid response time but for seasonal RE firming, SIBs can play a role as they will have sufficient time for response during the seasonal change. Hence, SIBs are moderately suitable for RE-firming applications.

The suitability of SIB for different applications is summarised in the table below.

Table 6: Summarisation of SIB's suitability for grid-scale applications

Grid application	Suitability of SIB
Forward capacity or resource adequacy	High
Distribution upgrade deferral	High
Transmission congestion relief	High
Transmission upgrade deferral	High
Energy arbitrage (daily)	Moderate
Frequency regulation	Low
Reserves	Low
Voltage support	Low
Black start	Low
Renewable firming (daily and seasonal)	Moderate

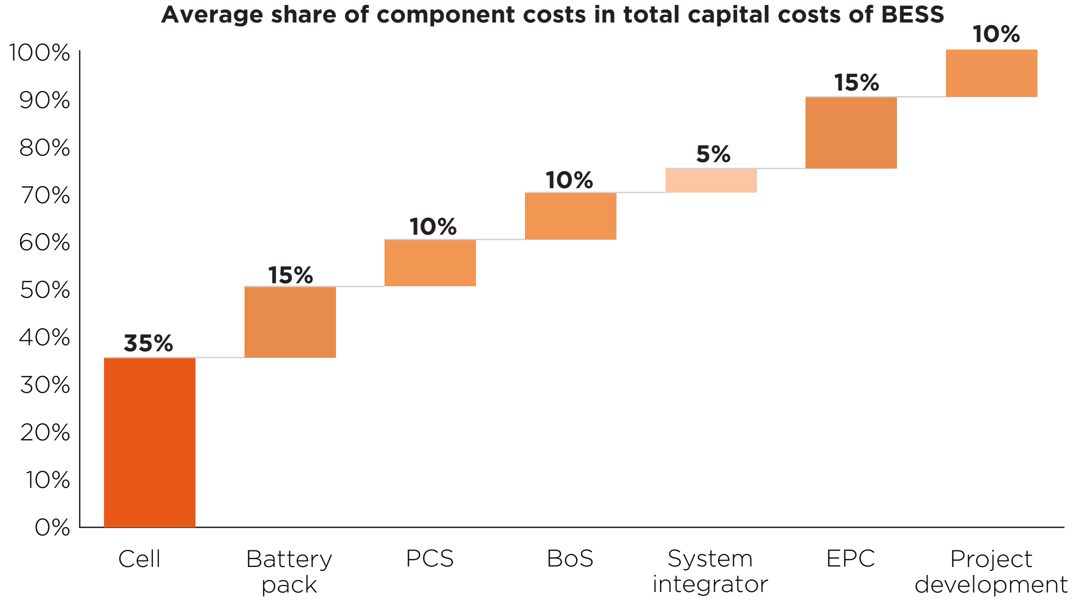
With higher discharge time at rated power and feasibility for large storage system, SIBs have more applicability towards bulk power services such as forward capacity, transmission and distribution support, RE firming, energy arbitrage and less suitability for applications requiring rapid response time i.e., frequency regulation, black start, or voltage support. Overall, batteries with long storage duration but moderate-low energy density are well suited for grid-scale storage applications. Here, energy storage capacity and duration are required over the compactness or higher output and SIBs are examples of such kinds of batteries.

3.4 Cost considerations

BESSs consist of multiple system components including cell (electrodes, electrolyte, collectors, and housing), pack/rack (structure and electronics), BMS and thermal management system, Power Conversion System (PCS) (inverter, transformer, energy management system and others), Balance-of-System (BoS) (container, fire suppression), system integration, Engineering Procurement Construction (EPC), project development (expenses) etc.

The figure below illustrates how capital expenditure is distributed among different components of BESS, showing their estimated cost contributions. The cumulative cost may differ slightly in terms of components included, depending on the storage duration of the system. It is emphasised that the cell is the most expensive component of a BESS. Cell price will vary depending on the chemistry, which in turn leads to changes in its percentage share of total BESS cost. It is also important to note that installation costs and project development costs are both highly location-dependent and may vary significantly among various projects.

Figure 7: Cost components of BESS



Source: Oxford Academic[35]

Thus, the cell and battery pack costs are major determinants of overall BESS project costs. Bringing down these costs is crucial for achieving financial feasibility of a BESS technology.

3.4.1 Comparative cost analysis of lithium and sodium-ion batteries

The current battery energy storage market is dominated by LIBs. However, cost remains a significant barrier to their widespread adoption despite notable reductions over the past decade. While advancements in manufacturing processes, materials, and economies of scale have led to substantial cost declines, there are two major factors that could hamper further significant reductions in LIB costs. Firstly, the raw materials required for LIBs, such as lithium, cobalt, and nickel, are subject to price fluctuations and supply chain constraints, impacting costs. Secondly, the complexity of LIB manufacturing processes and the need for stringent quality control measures add to production expenses.

Due to these factors, and the increasing demand for energy storage, the pursuit of alternative, cheaper battery technologies like SIB has gained significant momentum. SIBs offer a promising alternative due to the abundance and the low cost of sodium compared to lithium, which translates into a potentially lower raw material cost, making SIBs potentially more economically viable for widespread deployment.

35 Monetizing Energy Storage: A Toolkit to Assess Future Cost and Value | Oxford Academic | September 2023 | Link

Table 7: Comparative analysis of SIB vs LIB and their techno-economic parameters

Battery Technology	Global unit cost ($/kWh), year 2022	Global unit cost ($/kWh), year 2030 projected	LCOS (INR/kWh), year 2022	LCOS (INR/kWh), year 2030
SIB	77 (£60) (Cell)	40 (£31) (Cell)	5.4 (£0.05) (India)	4.3 (£0.04) (India)
LIB	128 (£101) (Cell)	47.8 (£37.8) (Cell)	4-hr: 7.0 (£0.06) (India) 10-hr: 5.9 (£0.05) (India)–LFP Or 9.7 (£0.08) (India)- NMC	4-hr: 4.5 (£0.04) (India) 10-hr: 3.5 (£0.03) (India)–LFP Or 6.2 (£0.05) (India)- NMC

Source: Lawrence Berkeley National Laboratory, Goldman Sachs

LIBs hold a cost advantage due to their established market presence and mature technology and manufacturing process. However, due to high critical mineral prices in 2022, sodium-ion cells, at $77 (£60) per kWh[36], were cheaper than lithium-ion cells, at $128 (£101) per kWh.[37] Since then, critical mineral prices have declined, coinciding with overcapacity in battery manufacturing capacity. Thus, lithium-ion cell prices have decreased massively in the last 2 years, to around $70 (£55) per kWh.[38]

Various forecasts suggest that SIB cost will further steadily decline over the next decade, driven by advancements in technology, and economies of scale. By 2030, SIBs are expected to achieve costs that are 15-20% lower than those of LIBs, making them increasingly competitive for various applications.[39,40]

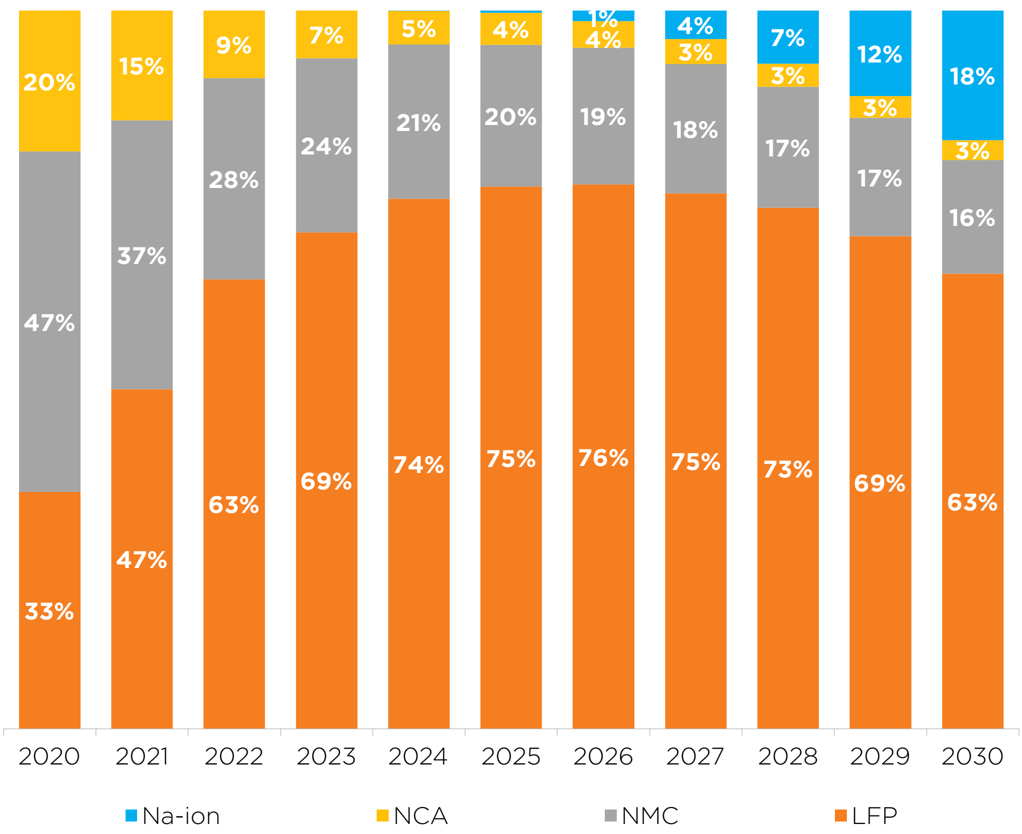
3.5 Projected demand for SIBs globally and in India

Evaluating future battery technology mix is a challenging task due to the changing landscape of performance, cost, and raw material limitations. While the forecast for the near future, up to 2030, can be predicted with confidence, uncertainties increase as we look further ahead. Some expectations include the ongoing prevalence of LFP, the rise of NMC with lower cobalt content, and the shift towards more advanced LIBs, SIBs and other alternative chemistries over time. The present and projected distribution of stationary storage battery chemistry is given in the figure below.

36 1 GBP (£) to INR: 109, 1 GBP (£) to USD ($): 1.29 | OANDA | 01 November 2024
37 Electric vehicle battery prices are expected to fall almost 50% by 2026 | Goldman Sachs | October 2024 | Link
38 Electric vehicle battery prices are expected to fall almost 50% by 2026 | Goldman Sachs | October 2024 | Link
39 Review of Grid-Scale Energy Storage Technologies Globally and in India | Lawrence Berkeley National Laboratory | August 2023 | Link
40 Electric vehicle battery prices are expected to fall almost 50% by 2026 | Goldman Sachs | October 2024 | Link

Figure 8: Projected evolution of stationary storage battery chemistry by 2030

Current and projected distribution of BESS chemistry



Source: BloombergNEF[41]

As mentioned in the graph above, the current prominence of LIBs in stationary energy storage is poised to undergo a transformative shift towards SIBs by 2030. In 2020, LIBs had captured almost 100% of the total stationary storage market. SIBs on the other hand are expected to occupy ~1% market share by 2026, with this figure growing to ~18% of the market share by 2030.[42] In India, based on estimations by NITI Aayog, it is estimated that SIBs will contribute ~4% to the overall battery technology mix in 2030, equivalent to approximately 24 GWh of storage capacity across various applications.

Due to their favourable technical characteristics and suitability for grid-scale applications, coupled with the growing overall global and Indian battery demand, SIB deployment will scale rapidly up to 2030. In order to meet this growing demand, a suitable supply chain of input materials, as well as sufficient manufacturing capacity, is a necessity.

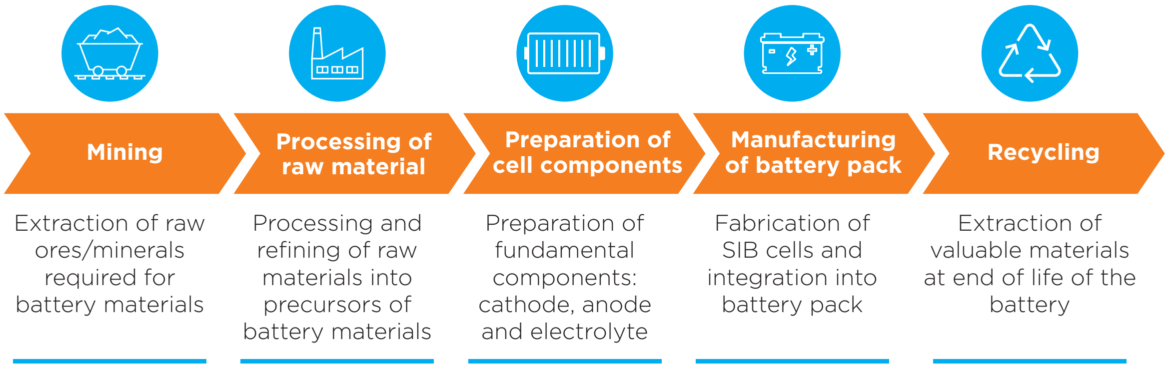
41 The Secret to a Greener, Longer-Lasting Battery Is Blue | Bloomberg | September 2020 | Link
42 The Secret to a Greener, Longer-Lasting Battery Is Blue | Bloomberg | September 2020 | Link

04

Manufacturing capabilities and sourcing of critical minerals

The value chain of SIB manufacturing involves several key steps and processes, comprising various stages and stakeholders, from the extraction of raw materials to the manufacturing of cells. The key processes of the value chain are depicted in the figure below and explained.

Figure 9: Schematic representation of SIB manufacturing value chain

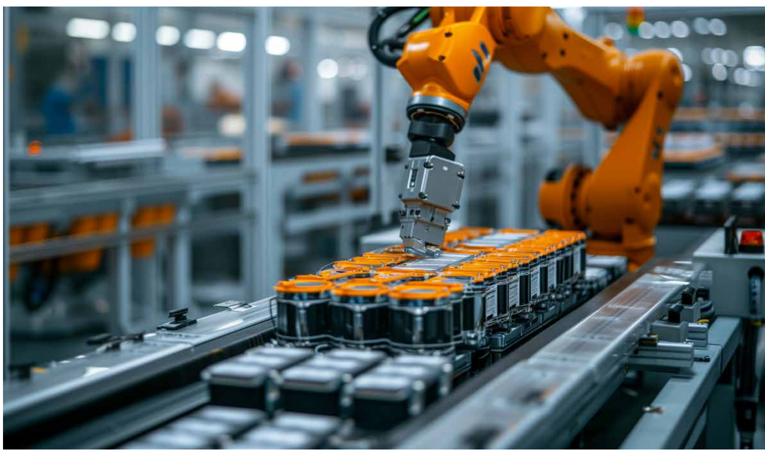


- **Mining or raw material extraction:** The supply chain begins with the extraction of raw materials required for SIBs. These materials typically include ore or rock from which metal is extracted and naturally occurring solids-minerals.

- **Processing of raw material:** Once the raw materials are sourced, they undergo processing, refinement, and purification to isolate the metal from raw material ensuring the specific requirements for battery production are being fulfilled.

- **Preparation of cell components:** Sodium-ion cell components preparation involves gathering and preparing all the necessary components required for the construction of a sodium-ion cell. This includes primarily active materials such as cathode, anode, and electrolytes which are synthesised according to the cell chemistry employed.

- **Manufacturing of cells:** The manufacturing process for SIB closely resembles that of LIB, allowing the production line for LIB to be utilised for SIB manufacturing purpose.[43] Generally, the cells, fundamental components of batteries, are produced in three distinct types, namely pouch, prismatic, and cylindrical cells. The production process of sodium-ion cells can be classified into three phases:[44] electrode manufacturing; cell assembly; cell finishing.



43 Course on Electrochemical Energy Storage | National program for technology enhancement learning | May 2021 | Link
44 The research and industrialization progress and prospects of sodium ion battery | ELSEVIER | October 2023 | Link

The manufacturing of electrodes and the finishing of cells are not dependent on the type of cell. However, certain processes in cell assembly are specific to each cell type.[45] The prepared cell components are utilised to manufacture electrodes. The electrodes manufactured along with the electrolyte and other materials such as separators, current collectors, and battery housings are integrated to form individual cells.

- **Recycling:** At the end of the useful life of the battery, select raw materials are extracted at recycling facilities to mitigate waste generated by the sector and recover valuable materials for reuse as inputs in the battery sector or other manufacturing processes. The recycling ecosystem for SIBs is currently non-existent due to the nascent stage of development of the sector and the limited presence of valuable materials in SIBs.

4.1 Metals and minerals required in the SIB manufacturing

In the case of SIB, the key elements in the cathode are sodium, iron, manganese, phosphorus, sulfur, vanadium, and nickel. The anode is primarily made up of hard carbon or expanded graphite. Elements like tin and antimony are also incorporated into the anode material. The electrolyte typically contains a sodium salt dissolved in solvents primarily based on carbonates. Moreover, the collector foils of both the anode and cathode in SIB are made of aluminium. Hence, key elements employed in SIBs consist of sodium, iron, manganese, phosphorus, sulfur, aluminium, graphite, tin, antimony, nickel and vanadium.

The table given below provides the details of resources, reserves and production of required minerals.

Table 8: SIB input mineral availability

Key elements	Source mineral	Global				Indian			
		Total resource[46]	Reserve[47]	Production	Top three producing countries	Total resource	Reserve	Production	Top three producing states
Sodium	Sodium chloride (Salt)	Extensive	Extensive	270 MT (2023)	China (19%), US (15%), India (11%)	Abundant	Abundant	26.5 MT (2021)	Gujarat (82%), Tamil Nadu (9%), Rajasthan (8%)
Iron	Iron ore	800 billion tonne (BT) (2023)	190 BT (2023)	2.5 BT (2023)	Australia (38%), Brazil (17%), China (11%), India (11%)	35 BT (2021)	6.4 BT (2021)	0.2 BT (2021)	Odisha (51%), Chhattisgarh (18%), Karnataka (17%)
Manganese	Manganese ore	Large and irregularly distributed	1,908 MT (2023)	20 MT (2023)	South Africa (36%), Gabon (23%), Australia (15%)	504 MT (2021)	75 MT (2021)	2,688 thousand tonnes (kT) (2021)	Madhya Pradesh (34%), Maharashtra (24%), Odisha (18%)
Phosphorus	Phosphate	300 BT (2023)	74 BT (2023)	220 MT (2023)	China (41%), Morocco (16), US (9%)	311 MT (2021)	31 MT (2021)	1,455 kT (2021)	Rajasthan (93%), Madhya Pradesh (7%)
Sulfur	Sulfur and pyrites	600 BT (2023)	Large	82,000 kT (2023)	China (23%), US (10%), Saudi Arabia (10%)	1,674 MT	Nil	737 kT (as byproduct) (2021)	Odisha (28%), Kerala (19%), Haryana (19%)

46 Comprised of mineral reserve and remaining resources.
47 Economically viable portion of the measured and/or indicated mineral resource.

Key elements	Source mineral	Global				Indian			
		Total resource[46]	Reserve[47]	Production	Top three producing countries	Total resource	Reserve	Production	Top three producing states
Aluminium	Bauxite	55-75 BT (2023)	30 BT (2023)	70,000 kT (2023)	China (59%), India (10%), Russia (6%)	4,958 MT (2021)	646 MT (2021)	3,619 kT (2021)	Odisha (64%), Chhattisgarh (16%), Uttar Pradesh (10%)
Graphite	Graphite	800 MT (2023)	263 MT (2023)	1,600 kT (2023)	China (78%), Madagascar (6%), Mozambique (6%)	212 MT (2021)	9 MT (2021)	30 kT (2021)	Odisha (42%), Tamil Nadu (33%), Jharkhand (19%)
Tin	Cassiterite	Limited	4,900 kT (2023)	300 kT (2023)	China (23%), Myanmar (19%), Indonesia (18%)	103,757 tonne (2021)	963 tonne (2021)	17 tonne (2021)	Chhattisgarh (100%)
Antimony	Stibnite	Limited	2,100 kT (2023)	83.3 kT (2023)	China (48%), Tajikistan (25%), Turkey (7%)	255 kT (2021)	75 kT (Probable reserve[48]) (2021)	Nil	NA
Nickel	Oxides	350 MT (2023)	131 MT (2023)	3,500 kT (2023)	Indonesia (50%), Philippines (11%), New Caledonia (6%)	198 MT (2021)	Nil	Nil	NA
Vanadium	Deposits of phosphate, bauxite, crude oil etc	63 MT (2023)	19 MT (2023)	104 kT (2023)	China (66%), Russia (19%), South Africa (9%)	25 MT (2021)	Nil	Nil	NA

Source: U.S. Geological Survey[49], Indian Bureau of Mines[50]

48 Economically mineable part of indicated, or in some case, a measured mineral resource.
49 Mineral Commodity Summaries | U.S. Geological Survey | January 2024 | Link
50 Indian Mineral Yearbook 2021 | Indian Bureau of Mines | January 2023 | Link

4.2 Existing manufacturing capabilities across the globe and predicted pipeline

The SIB manufacturing sector is experiencing rapid growth. While currently dominated by a handful of established companies, the global SIB industry is expanding across continents, with frequent introduction of large-scale deployments. The Global EV Outlook 2023 report[51], published by IEA, reveals that, almost 30 SIB manufacturing facilities are currently in operation, in the planning stages, or being built, with a total capacity of ~100 GWh, predominantly located in China. These manufacturers are currently in the final stages of product development and are on the verge of commercialising their products.[52] Detailed information on the key manufacturers of SIBs is given in the table below:

Table 9: Key manufacturers of SIBs

S. No.	Manufacturer	Details
Global players		
1	LiNa Energy Limited (UK)	LiNa Energy Limited was established in 2017 and specialises in the development and provision of solid-state sodium batteries. Currently, LiNa is developing a distribution scale 10 kWh sodium Battery Energy Storage System. As of January 2024, LiNa has enhanced its internal capacity to produce 6,000 cathodes each month.
2	AMTE Power (UK)	AMTE Power, founded in 1997, focuses on the development and manufacturing of lithium-ion and sodium-ion cells specifically designed for specialised applications in global markets. Their batteries are engineered for high-performance vehicles, with an annual production capacity nearing 0.5 GWh.
3	Transimage (China)	Transimage was founded in 2007. As of March 2023, the total production capacity stands at 4.5 GWh, with ongoing expansion efforts. The company has also established an SIB research institute in 2022 to drive SIB technology development.
4	Natrium Energy (China)	Natrium Energy was founded in 2018. They are planning to inaugurate a specialised mass production line for SIBs with a capacity of 2.5 GWh. The company provides solutions focused on cathode materials and electrolytes. Natrium is also focused on R&D activities and has established a research institute for the same.
5	CATL (China)	CATL was founded in 2011, and in 2021, the company introduced its first-generation SIBs, which had an energy density of 160 Wh/kg. CATL is developing second-generation SIBs with an energy density of 200 Wh/kg. CATL is also exploring the potential of SIBs in EV market.

51 Global EV Outlook | International Energy Agency |April 2023 | Link
52 Sodium Ion (Na-Ion) Battery Market 2023 The Next Technology on Battery Mass Production | Shmuel De-Leon Energy Ltd | May 2023 | Link

S. No.	Manufacturer	Details
6	HiNa Battery (China)	HiNa Battery was established in 2017. The company is dedicated to developing sodium-ion battery technology for EVs and industrial energy storage systems. By 2022, it reached an initial production capacity of 1 GWh.
7	Natron Energy (US)	Natron Energy was founded in 2012 and introduced its UL-listed SIB product in 2021. Currently, Natron's batteries are mainly utilized in stationary applications within data centres and telecommunications networks. The company has established an annual production capacity of 600 MW.
8	Acculon Energy (US)	Acculon Energy commenced operations in 2009, and has started production of its SIB modules and packs. The company focuses on battery systems architecture as well as battery modules for commercial and industrial applications. The company has unveiled plans to scale its production to 2 GWh by mid-2025.
9	Tiamat Energy (France)	Tiamat Energy started its operations in 2017, focusing on the development of sodium-ion storage solutions for both mobility and stationary energy storage applications. The first phase of the plant, which will have an annual capacity of 0.7 GWh, is scheduled to be commissioned by the end of 2025, with a target of reaching 5 GWh by 2029.
Indian players		
10	Indi Energy (India)	Indi Energy, founded in 2019 and headquartered in Roorkee, Uttarakhand, is a startup that specialises in energy storage. The primary focus of the firm is on the R&D of cutting-edge battery technologies such as SIBs. The major products of Indi Energy include hard carbon, sodium-ion cathode and electrolyte, and customised SIB packs.[53]
11	Sodion Energy Private Limited (India)	Sodion Energy Private Limited was established in the year 2020 and is based in Coimbatore, Tamil Nadu. Sodion Energy has recently unveiled its range of SIBs. Moreover, Sodion Energy has created a BMS designed specifically to enhance the efficiency of SIBs.[54]
12	KPIT Technologies (India)	KPIT Technologies started operations in 1990 and is located in Pune, Maharashtra. KPIT has collaborated with the Indian Institute of Science Education and Research (IISER) in Pune to develop SIB technology. In collaboration with IISER Pune, the company utilises earth-abundant materials for battery manufacturing to ensure supply chain security and reduce import reliance.[55]

53 Indi Energy | Website | March 2024 | Link
54 Sodion Energy launches indigenously developed sodium-ion battery for EVs | Express mobility | February 2024 | Link
55 KPIT Technologies | Website | March 2024 | Link

S. No.	Manufacturer	Details
13	Uneverse (India)	Uneverse commenced its operations in 2023, focusing on clean energy and mobility solutions, with its headquarters located in Kolkata, West Bengal. Uneverse and IIT Kharagpur have entered into an exclusive Memorandum of Understanding (MOU) to commercialise and enhance the patented sodium-ion technology. As part of this initiative, a range of SIBs, incorporating various cell form factors and electrode raw materials, will be introduced to the Indian market.[56]
14	Cygni Energy (India)	Cygni Energy, founded in 2014, is an energy generation, storage, and processing technology solutions enterprise based in Hyderabad, India. Their primary areas of focus encompass EVs, smart battery BMS-controlled batteries, and rooftop solar hybrid solutions.[57] Cygni has recently introduced a certified sodium-ion 2-wheeler battery pack.[58]

Source: Company announcements and media publications

While SIBs benefit from reduced need for critical minerals as input materials, and industry efforts to scale manufacturing capabilities and improve technological parameters are ongoing, it is equally important to develop a supportive policy and regulatory framework that can provide financial and non-financial benefits to support overall deployment of BESS. Such policy and regulatory frameworks can help promote innovative BESS technologies such as SIBs.

56 Uneverse | Website | March 2024 | Link
57 Cygni Energy | Website | May 2024 | Link
58 Cygni launches sodium-ion battery packs for e-2Ws | EV Reported | May 2024 | Link

05

Policy and regulatory environment

5.1 Regulatory and policy measures taken by countries across the world

Across the globe, countries are enacting policy and regulatory changes to foster the development of advanced battery chemistries and battery storage infrastructures. These initiatives aim to accelerate the transition towards a sustainable energy system by promoting research, incentivising investments, and streamlining the regulatory processes. Some of the global policy-level initiatives are mentioned below:

Table 10: Global regulatory and policy initiatives

S.No.	Country	Regulatory and policy initiatives
1	UK	1. The Department for Business and Trade UK issued a 'UK Battery Strategy' which sets the government's activity to support the strategic objective towards battery ecosystem in UK. Some of the import points are mentioned below: • UK Government will invest £12 million[59] in the Advanced Materials Battery Industrialisation Centre (AMBIC), a new world-class battery materials scale up facility in the West Midlands and North-East to bridge the gap between laboratory research and commercial production • Government will invest £11 million in 20 competition winners developing technologies across the battery value chain in areas such as artificial intelligence and digital tools to increase battery performance, future technologies such as Lithium-metal anodes and Sodium-ion batteries, and improved recycling technologies • UK will expand market access for the trade of critical minerals and promote high international standards in supply chains when negotiating new Free Trade Agreements. 2. The Faraday Institution is the UK's flagship programme for electrochemical energy storage research, skills development, market analysis and early-stage commercialisation.
2	Japan[60]	On 19 April 2022, the New Energy and Industrial Technology Development Organisation (NEDO) of Japan announced the allocation of Japanese Yen (JPY) 151 billion ($1.2 billion or £0.93 billion) for the 'Development of Next-Generation Storage Batteries and Next-Generation Motors' project. The support was granted under the Green Innovation Fund launched in 2021.

59 UK Battery Strategy | Department of Business & Trade | November 2023 | Link
60 Japan: NEDO allocates USD 1.2 billion for the development of next-generation batteries and motors under the Green Innovation Fund | Global Trade Alert | April 2022 | Link

S.No.	Country	Regulatory and policy initiatives
3	South Korea	1. South Korea is home to three of the world's leading domestic battery manufacturers: LG Energy Solution, Samsung SDI, and SK Innovation. These companies have formed a "grand alliance" to build a long-standing industrial network and establish a fund to support battery technology, parts, and materials development in collaboration with other companies and academia. 2. The government also provides significant support for battery development through tax incentives, R&D, and capital investments, and this has been the case since the development of South Korea's battery industry in the late 80s/early 90s.
4	US	1. The passage of the Inflation Reduction Act in 2022 has mobilised investments, consumer subsidies and private sector mobilisation in battery manufacturing with multiple companies announcing at least 50 new manufacturing projects across the EV supply chain, totalling over \$500 billion (£387.6 billion) in investment since the passage of the legislation. 2. The Inflation Reduction Act has significant incentives for a domestic battery value chain to be built in the United States. The 'Advanced Manufacturing Production Tax Credit' provides a tax credit equal to 10% of the cost of production to the producer of the critical minerals that are found in batteries, including lithium, cobalt, graphite, and nickel. 3. Additional legislation like the Bipartisan Infrastructure Act, promotes the development and commercialisation of advanced battery technologies with \$2.8 billion (£2.17 billion) in funding for a portfolio of 21 projects that support new, retrofitted, and expanded commercial-scale domestic facilities to produce battery materials, processing, and battery recycling and manufacturing demonstrations.

5.2 India's energy storage key policy and regulatory developments

India has been actively promoting the use of ESSs to increase RE integration, enhance grid stability, and improve overall energy efficiency. The ability of storage to fulfil these requirements relies on various factors, such as the physical attributes of the power system and the policy and regulatory landscapes within which these investments would function. Select major policy and regulatory interventions at the national level in India are listed below:

- **National Mission for Transformative Mobility and Advanced Battery Manufacturing (2019):** In 2019, NITI Aayog developed a National Mission for Transformative Mobility and Advanced Battery Manufacturing to help create a cohesive framework for conducive policies with emphasis on supporting infrastructure and cost-effective options for BESS. The mission aimed to drive uptake EVs and BESS while developing the overall ecosystem to improve self-reliance and energy security. Furthermore, it is multi-disciplinary and involves an inter-ministerial steering committee comprising key officials from the Ministry of Road Transport and Highways, the Ministry of Power, the MNRE, the Department of Science and Technology (DST), the Department of Heavy Industry

(DHI), the Department for Promotion of Industry and Internal Trade (DPIIT), and the Bureau of Industrial Standards (BIS).[61]

- **Guidelines for round-the-clock (RTC) tenders (2019):** To allow firm and uninterrupted supply of RE electricity, India has focused on the use of hybrid capacities (typically wind-solar hybrids) coupled with ESSs or conventional generation sources to ensure RTC power supply. The tenders do not necessitate the use of ESSs, but indirectly provide a demand-side push due to the natural advantages that ESS provides towards meeting the RTC tender requirements of capacity utilisation and meeting peak demand.[62] The guidelines for RE RTC tenders issued by MoP were amended in 2021 to directly mention the use of storage by a generator to achieve the required minimum annual availability of 90%, further providing a push to the use of ESS for RTC tenders.[63]

- **Notification on Production Linked Incentive scheme, 'National Programme on Advanced Chemistry Cell (ACC) Battery Storage' (2021):** In order to promote the domestic manufacturing sector, India developed PLI schemes for 10 key sectors, including for ACC batteries. The scheme aims to enhance India's ACC battery manufacturing capabilities with a budgetary outlay of INR 18,100 crores (£1,660.5 million)[64] for achieving a manufacturing capacity of 50 GWh of ACC batteries and 5 GWh of 'niche' ACC batteries. Bidding for the original ACC PLI program was concluded in March 2022, with 30 GWh allocated across 3 bidders. The remaining 20 GWh of ACC capacity that remains unallocated has been divided into two tranches of 10 GWh each. One of these tranches is being managed by the Ministry of Heavy Industries (MHI), Government of India, while the other – is being developed by MHI in conjunction with MNRE.[65] The 10 GWh allocated to MHI was recently awarded in September 2024.[66]

  The ACC Battery PLI aims to drive direct investment of ~INR 45,000 crores (£4,128.4 million) in the ACC Battery storage manufacturing project[67], fostering domestic manufacturing and reducing import dependence. One of the benefits of developing domestic ACC battery manufacturing capacity is the associated impetus to R&D to improve battery parameters and promote the uptake of newer niche technologies such as SIBs.

- **Guidelines for procurement and utilisation of battery energy storage systems as part of generation, transmission and distribution assets, along with ancillary services (2022):** The MoP has notified the guidelines to support the procurement of BESS as part of RE projects or on a standalone basis. The guidelines are applicable for both intra and inter-state projects above 1 MW and 50 MW respectively. The guidelines identified seven key business cases for BESS for energy supply and grid maintenance. Additionally, it mentions that other suitable business cases identified by key stakeholders may also be considered. The guidelines serve to provide additional clarity to sectoral stakeholders on the requirements for procuring BESS for various applications and thus support the uptake of BESS in India.[68]

- **Order on renewable purchase obligation (RPO) and energy storage obligation**

61 E-Mobility: National Mission On Transformative Mobility And Battery Storage | Niti Aayog | Link
62 Understanding Round-the-Clock Tenders in India | JMK Research and Analytics and Institute for Energy Economics and Financial Analysis | November 2021 | Link
63 Amendments to the Guidelines for Tariff Based Competitive Bidding Process for Procurement of Round-The Clock Power from Grid Connected Renewable Energy Power Projects, complemented with Power from any other source or storage | Memorandum of Understanding | August 2022 | Link
64 Currency Converter | Foreign Exchange Rates | 31st May 2024 | OANDA
65 Re-bidding of 20 GWh Advanced Chemistry Cell (ACC) manufacturing under Production Linked Incentive scheme "National Programme on Advanced Chemistry Cell Battery Storage" | Press Information Bureau | July 2023 | Link
66 MHI awards 10 GWh capacity to one bidder under PLI ACC scheme | PIB | September 2024 | Link
67 Cabinet approves Production Linked Incentive scheme "National Programme on Advanced Chemistry Cell Battery Storage" | Press Information Bureau | May 2021 | Link
68 Guidelines for Procurement and Utilisation of Battery Energy Storage Systems as part of Generation, Transmission and Distribution assets, along with Ancillary Services | Ministry of Power | March 2022 | Link

(ESO) trajectory till 2029-30 (2022): In order to promote the uptake of RE in India, RPOs have been used to mandate that all distribution licensees should procure a minimum share of their electricity requirements from RE sources. In July 2022, the MoP specified the RPO and ESO trajectory till 2029-2030. For the first time, an obligation to procure energy storage was incorporated to further promote the uptake of grid-scale ESS in India. The ESO requires a percentage of total energy consumed from wind and/or solar energy along with or through energy storage. The obligated entity can only count this energy towards meeting ESO if at least 85% of the energy stored in ESS is procured from renewable sources The ESO begins from financial year (FY) 2023-24 with a 1% obligation, growing by 0.5% each year to reach 4% by FY 2029-30.

- **Bidding process for procurement of firm and dispatchable power from grid-connected renewable energy power projects with energy storage systems (2023):** In June 2023, MoP issued the guidelines for the bidding process which provided a framework for designing grid-scale ESS tenders that are demand-following. These FDRE tenders build on the guidelines for RTC and peak power tenders and further promote the deployment of ESS for providing reliable and predictable RE power. The guidelines provide the tender and project requirements, the bidding process to be followed, qualification criteria, timelines, and other relevant information for FDRE tenders. The guidelines were amended in February 2024 to streamline the mechanisms for commencement of power supply from FDRE projects to address potential delays.[69]

- **National Framework for Promoting Energy Storage Systems (2023):** In August 2023, MoP released the National Framework for Promoting Energy Storage Systems in order to support the development and deployment of ESS in India. The framework highlights the major policy and regulatory initiatives undertaken to support the ESS sector in India and charts a way forward for the sector, involving VGF for BESS, additional budgetary support for pumped storage, green finance initiatives, guidelines for resource adequacy plan, connectivity and grid access initiatives, technology agnostic bidding guidelines for procurement of ESS, facilitating Ease of Doing Business (EoDB), regulatory measures, fiscal waivers, and more. The framework underlined the importance of ESS to India's energy transition objectives and provided a clear market signal to drive further ESS deployment.[70]

69 Ministry of Power Amends Renewable Energy Bidding Guidelines for Streamlined Project Initiation | SolarQuarter | February 2024 | Link
70 National Framework For Promoting Energy Storage Systems | Ministry of Power | August 2023 | Link

- **Scheme for viability gap funding for Battery energy storage system (2023):** The GoI has recognised the importance of driving down the cost of BESS capacity to accelerate deployment alongside RE capacity. In September 2023, the Union Cabinet approved the Scheme for VGF for development of BESS. The approved scheme envisions the development of 4,000 MWh of BESS projects by FY 2030-31 and allows for financial support of upto 40% of capital cost in the form of VGF. The scheme has an initial outlay of INR 9,400 crores (£862.4 million) including budgetary support of INR 3,760 crores (£345 million). Through the VGF mechanism, the scheme aims to achieve a LCoS of INR 5.5-6.6 (£0.05–£0.06) per kWh. Achieving this LCoS will allow RE coupled with BESS to become a cost competitive option to reliably meet India's growing electricity demand. The VGF will be disbursed in five tranches, and a minimum of 85% of the BESS project capacity will be made available to distribution companies.[71]

In addition to the policy and regulatory measures undertaken by the central government, various states and union territories (UTs) are also actively promoting the adoption of ESS. Currently, 21 states and 2 UTs have established guidelines for the manufacturing and installation of various energy storage technologies, including BESS and pumped hydro storage (PHS) systems. Additionally, provisions related to the integration of ESS can be found within various state regulations such as green open-access regulations, net metering regulations, grid-connected rooftop solar regulations, and others. Thus, states and UTs are increasingly incorporating ESS as part of their plans in line with India's energy transition vision.

BESS has been recognised as a key technology for a successful energy transition, and this reflects in the policy and regulatory measures undertaken both globally and in India. Although each country will undertake its own set of activities to promote BESS and SIBs domestically, fostering international collaboration can lead to significant benefits and acceleration of BESS adoption. India may look to work closely with leading countries in the BESS sector, such as the UK, to support its own BESS and SIB sectors.

71 Cabinet approves the Scheme titled Viability Gap Funding for development of Battery Energy Storage Systems (BESS) | Press Information Bureau | September 2023 | Link

06

UK capabilities in the BESS sector

The SIB landscape in the UK encompasses a diverse array of organisations collaborating across sectors to advance research, development, and deployment efforts. Over the past decade, the battery ecosystem has witnessed significant innovation, enabling it to meet the necessary cost and performance requirements for widespread adoption. According to a recent study conducted by the Government Office for Science, the UK ranks among the top 5 global leaders in terms of research and patent output[72], underscoring its importance on the global stage. Experts have specifically highlighted the UK's strengths in solid-state and cathode research. Additionally, the UK holds a significant comparative advantage in BESS and SIBs for stationary storage applications, positioning it to lead in their commercialisation and industrialisation efforts potentially.

On December 6, 2023, the UK released its first battery strategy, in conjunction with the advanced manufacturing plan, acknowledging the crucial role of batteries in the country's energy transition and its commitment to achieving net zero emissions by 2050. The government has pledged to allocate over £2 billion in R&D funding for both battery technologies and their applications in the automotive industry.[73] This funding will be utilised to support the manufacturing and advancement of zero-emission vehicles, as well as their batteries and supply chain, for 5 years until 2030. The various support initiatives of the UK Government are depicted in the figure below:

Figure 10: Initiatives to support BESS ecosystem in the UK

Innovation

Creation of battery focused research institutions, innovation contests, and focused R&D initiatives

Financing

Improving access to public and private financing instruments for the BESS sector

Supply chain

Establishing estimates for critical mineral requirements and developing strategies to ensure accessibility

Manufacturing

Supporting scale up of manufacturing processes and providing manufacturing incentives

Skill development

Various initiatives to develop battery related courses, identify job roles, and address skill gaps

72 Rapid Technology Assessment: Novel batteries | March 2023 | Link
73 UK battery strategy | December 2023 | Link

The government is actively promoting the battery sector and fostering the advancement of future battery technologies through a variety of initiatives. These encompass a wide array of programs as discussed below:

Innovation

- **The Faraday Institution:** The Faraday Institution is a registered charity with an independent board of trustees, headquartered at Harwell Science and Innovation Campus. The Faraday Institution serves as the leading independent institute in the UK for researching electrochemical energy storage. It focuses on various aspects such as skill development, market analysis, and early-stage commercialisation. By harnessing the collective expertise of universities and industry, the Faraday Institution aims to establish the UK as the premier destination for advancing electrical storage technologies in the automotive and related sectors. The institution takes the lead in implementing research programs that are directly applicable to real-world scenarios. It collaborates with 27 universities, 85 industry partners, and over 500 researchers across 10 major projects, encompassing both current and future battery technologies.

- **Innovate UK:** Innovate UK is a UK government agency that supports business-led innovation. It has been involved in funding and supporting R&D in SIB technology. Innovate UK has funded a number of projects that have helped to develop new SIB materials, designs, and manufacturing processes. It has also supported the establishment of the United Kingdom Battery Industrialisation Centre (UKBIC), which provides support to businesses that are developing and commercialising SIB technologies.[74]

- **Advanced Propulsion Centre:** The Advanced Propulsion Centre (APC), formed in 2013, has received a substantial amount of industry investment and government grant funding, totalling over £1.4 billion. Its primary objective is to assist the automotive industry in addressing the decarbonisation challenges outlined by the government and the Automotive Council. As a result, the APC collaborates with both the automotive industry and academia on advanced R&D projects, specifically focusing on late-stage collaboration to expedite the industrialisation of technologies. In a recent announcement, the APC disclosed that it has secured £87 million in funding from both the government and industry partners. This funding will be utilised to advance cutting-edge EVs technology, encompassing projects related to luxury EV platforms, lithium refining, and solid-state battery manufacturing.[75]

- **High-Value Manufacturing (HVM) Catapult:** The HVM Catapult comprises the Energy Innovation Centre at Warwick Manufacturing Group (WMG) and The Centre for Process Innovation. These two centres play a crucial role in national research, focusing on the entire R&D process and battery material development, scale-up, and recycling support. Recently, they have secured substantial funding of £12 million for the establishment of an Advanced Battery Materials Innovation Facility. This state-of-the-art facility will enable the synthesis, scale-up, formulation, and validation of innovative active materials and solid-state electrolytes.

- **Faraday Battery Challenge (FBC):** The FBC's objective is to position the UK as a leading force in battery technology. FBC is dedicated to advancing innovations in the battery supply chain, from laboratory breakthroughs to large-scale production. The FBC, a program under the UK Research and Innovation (UKRI) Challenge Fund, has successfully established itself with the support of prominent delivery partners such as Innovate UK (lead), UK Battery Industrialisation Centre, and Faraday Institution.[76]

74 Innovate UK-UKRI | Link
75 Advanced Propulsion Centre | October 2023 | Link
76 Faraday Battery Challenge | UK Research and Innovations | February 2023 | Link

This initiative is dedicated to supporting research and innovation endeavours, as well as enhancing infrastructure, to foster the expansion of a robust battery industry in the United Kingdom. Its primary objective is to advance battery technologies that are not only cost-effective but also exhibit high performance and extended-range capabilities.

- **Automotive Transformation Fund:** The Automotive Transformation Fund (ATF), initially disclosed in 2020, has facilitated the UK in attracting several noteworthy original equipment manufacturers (OEM) and supply chain investments. This has expedited the UK's progress towards electrification, as the industry has established ambitious targets for inward investment. The ATF funding aids various companies involved in the EVs' supply chain, encompassing batteries, electric drive units, fuel cell systems, and other related technologies.[77]

- **Longer Duration Energy Storage Demonstration Competition:** The Longer Duration Energy Storage Demonstration (LODES) is a ground-breaking contest that seeks to expedite the commercialisation of cutting-edge energy storage projects with longer durations. Through LODES, the government has provided support for the advancement of BESS making a substantial capital funding of £69 million available to start-ups. This initiative was specifically open to novel battery technologies. In a significant move, the UK Government has recently announced an investment of £11 million in 20 winning projects from the competition. These projects focus on developing technologies across the battery value chain, including areas such as artificial intelligence and digital tools to enhance battery performance, future technologies like lithium-metal anodes and SIBs, and improved recycling technologies.[78]

77 UK battery strategy | December 2023 | Link
78 Longer Duration Energy Storage Demonstration (LODES) competition | April 2023 | Link

- **Ayrton Fund:** The Ayrton Fund aims to accelerate the clean energy transition in developing countries, by creating and demonstrating innovative clean energy technologies and business models. It also aims to demonstrate UK leadership and expertise in cutting global emissions through world-leading innovations. [79] Some of the international funding programmes as part of this initiative include the International Energy Storage Challenge, led by the Faraday Institution, the Clean Energy Innovation Facility (CEIF) programme funded by the Department for Energy Security and Net Zero (DESNZ) and Transforming Energy Access (TEA) which is a flagship programme of Foreign, Commonwealth and Development Office (FCDO).[80]

  The UKRI Ayrton challenge programme which is a grant programme part of the main Ayrton Fund has total funding of £25 million. It is an interdisciplinary, challenge-led research project enabling the transition to low-carbon energy in developing countries. The Ayrton Challenge Programme is a key part of the UK government's strategy to support the development of a low-carbon economy. One of the focus areas of the programme is to accelerate the development and commercialisation of new energy storage technologies.[81]

Financing

- **British Business Bank (BBB):** The BBB collaborates with industry players in the market to ensure that smaller businesses have the necessary financial resources and information to fund their innovative processes. By analysing the market and utilising evidence, they identify areas where support is lacking and take a commercially driven approach to address these gaps. They aim to maximise their impact on smaller businesses by combining private-sector capital with government funding. The BBB offers various finance programs, each tailored to address specific market failures and enhance access to finance for smaller businesses. Among these programs, several are dedicated to strengthening the battery supply chain in the UK.

- **UK Infrastructure Bank (UKIB):** The UKIB focuses on investing in projects that not only generate a financial return but also attract significant private capital over time. In September 2023, the UKIB released a strategy update that outlined its offerings for short-duration BESS. This included a mezzanine loan product that aims to encourage more banks to provide funding for such projects. Furthermore, the UKIB is committed to supporting the development of markets for long-duration storage by assuming greater risk than private investors. Additionally, the UKIB also invests in projects related to cell manufacturing and the critical minerals supply chain.[82]

Supply chain

- **Critical mineral demand modelling:** The future demand for critical minerals in the UK is highly uncertain as it depends on future battery chemistries, battery energy density, the EV market, costs, and technological developments. Multiple different scenarios could occur depending on when battery technologies become commercially available. Next-generation technologies including silicon anodes, solid-state batteries and SIBs may shift raw materials supply chains.

  The UK Critical Minerals Intelligence Centre (UK CMIC) offers estimates for critical mineral demand by 2030, derived from two distinct future battery technology scenarios. The first scenario anticipates that batteries produced in the UK will predominantly utilise NMC technology. In contrast, the second scenario predicts a significant transition towards LFP technology, with 50% of batteries being LFP. Additionally, the Faraday Institution releases findings from

79 Ayrton Fund | December 2023 | Link
80 Ayrton Fund |Energy Storage Challenge | Link
81 UKRI Ayrton Challenge | January 2024 | Link
82 UK Battery Strategy | November 2023 | Link

their modelling of the UK's critical mineral demand, considering factors such as, battery requirements, chemistry variations, and material intensity.

These demand modelling efforts and projections allow the UK to assess its critical mineral needs by 2030 across various scenarios, facilitating the development of strategies to ensure the availability of these essential minerals to satisfy battery demand.[83]

- **Guaranteeing the accessibility of critical minerals:** The UK government is preparing for a significant increase in critical mineral demand by 2030. However, there are concerns about potential supply shortages. To tackle this, the government has outlined its Critical Mineral Strategy, which aims to accelerate domestic capabilities, foster international collaboration, and improve international markets.

  To support domestic mining capabilities, the government offers direct assistance to firms in the sector. The ATF is a key initiative that provides support for critical minerals used in the transport sector, and production process.

  Overall, the UK government is committed to ensuring a sustainable and reliable supply of critical minerals. Through support and collaboration, they aim to address the challenges posed by increasing demand while promoting responsible practices in the industry.

Manufacturing

- **Competitive electricity price for battery manufacturing:** Battery production, along with its associated activities, requires a significant amount of energy and relies on substantial power connections. The APC predicts that the largest giga-factory in the UK will consume more than 2 terra watt hour (TWh) of electricity annually once it is fully operational.[84] To enhance the competitiveness of the UK's business environment, the government has consistently implemented various programs to reduce energy costs.

  The Energy Bill Relief Scheme aimed to alleviate the burden of high gas and electricity prices for non-domestic consumers. The scheme offered a discount on wholesale gas and electricity prices from 1 October 2022 to 31 March 2023.[85] Furthermore, the Energy Bills Discount Scheme has been introduced, extending the benefits of the Energy Bill Relief Scheme until April 2024.[86]

  Furthermore, the Net Zero Growth Plan, released in March 2023, aims to ensure that Britain's wholesale electricity prices become one of the most affordable in Europe by 2035. This plan outlines the government's strategies to enhance energy independence, security, and resilience in the UK.[87]

- **UK Battery Industrialisation Centre:** The UK Battery Industrialisation Centre (UKBIC) serves as a hub for manufacturing development. With its state-of-the-art facility spanning 20,000 m^2, UKBIC offers open-access infrastructure and expertise in manufacturing and scale-up. Renowned worldwide, UKBIC plays a crucial role in supporting the advancement of battery technologies in the UK. By mitigating risks associated with commercialisation and facilitating technology development, UKBIC paves the way for seamless expansion and increased investment opportunities for firms in this sector.[88]

Skill development

- **Fostering requisite skills for battery sector development:** A thriving battery industry in the UK necessitates a highly skilled workforce that possesses expertise across the entire battery value chain and at all levels. The availability of skilled

83 UK battery strategy | December 2023 | Link
84 UK battery strategy | December 2023 | Link
85 Energy Bill Relief Scheme: help for businesses and other non-domestic customers | March 2023 | Link
86 Energy Bills Discount Scheme | July 2023 | Link
87 Powering Up Britain: Net Zero Growth Plan | April 2023 | Link
88 UK battery strategy | December 2023 | Link

individuals is becoming increasingly crucial for companies seeking to invest in battery development and manufacturing on a global scale. According to the Faraday Institution, meeting the domestic demand for EV batteries could potentially create around 270,000 full-time equivalent jobs in the UK by 2040.[89]

In recent years, various organisations such as the Automotive Council Skills group, the Faraday Institution, and HVM Catapult have collaborated to gain a comprehensive understanding of the job roles and corresponding skill levels required in this industry. Additionally, the government has placed employers at the core of the skills system to ensure that the provision of skills aligns with both current and future demands. They offer a wide range of high-quality training options, including apprenticeships and flexible courses like Skills Bootcamps.

In September 2023, the FBC selected three leading universities to receive £3.2 million in funding. These universities will support the UK's battery-related sectors by identifying and addressing skills gaps. This program includes the establishment of two Battery Workforce Training Initiatives, focusing on up-skilling, re-skilling, and new-skilling for cell production staff.[90]

The National Electrification Skills Framework and Forum (NESFF), funded by the FBC, strives to establish a unified and reliable platform for specialised courses that cater to the evolving skill requirements in the sector. NESFF will advocate for the implementation of workforce development programs in electrification across various skill levels.

India can gain significant benefits in developing its domestic BESS and SIB sectors by fostering partnerships with UK government and business entities. In addition to commercial and research partnerships, India can also look to international best practices on how to develop the GESI ecosystem for SIBs in India, as the nascent nature of the sector provides opportunities to drive a just transition through SIB deployment.

89 UK electric vehicle and battery production potential to 2040 | June 2022 | Link
90 UK battery strategy | December 2023 | Link

07

Recommendations for India

Energy storage, particularly at the grid-scale, has been recognised as a vital aspect of both the global energy transition as well as India's energy transition ambitions, and demand for grid-scale BESS is expected to grow steadily in the coming years. SIBs, thanks to their cost and technological benefits, can play a key role in meeting the demand for the same. Allowing SIBs to meet their potential will require a variety of supporting activities, including R&D support, policy and regulatory measures, manufacturing support, supply chain development, amongst others.

In India, in addition to the clear demand for grid-scale BESS, the potential for SIB deployment is supported through its supply side benefits such as abundance of raw material and reduced reliance on imports, as well as existing central and state policy measures such as the PLI scheme, the ESO mandate, and the provision of VGF for BESS capacity. The clear demand push coupled with the supply-side support on offer means that innovative BESS chemistries like SIBs can see deployment in India. While these measures have laid a strong foundation, several areas need to be addressed to fully harness the potential of SIB technology.

7.1 Areas to address for SIB deployment in India

The key areas to address for SIB deployment in India are summarised in the figure below and subsequently explained:

Figure 11: Areas to address to scale up SIB technology in India

1. Technology

Although efforts to create a robust technology ecosystem for BESS and SIBs are already taking place in India, further efforts are required for development of indigenous technological capabilities in the country. Primarily, the following areas need to be addressed:

- **Domestic manufacturing capabilities:** Despite some growth in battery pack assembly capacity in India, further efforts are required for development of domestic manufacturing capacity and capabilities for battery cells and packs. Addressing this will help reduce reliance on imports, which in turn would bring down BESS costs and improve supply chain security.

- **R&D and industry partnerships:** There is a significant need for further R&D in alternative battery technologies such as SIBs which promise higher DoD, safety, and life cycles. India has the opportunity to strengthen its R&D for the SIB ecosystem by promoting international collaboration and industrial partnerships.

India can explore academic collaborations with notable UK R&D institutions such as The Faraday Institution. The British Standards Institution (BSI) has developed a standards roadmap for technical and quality standards for battery manufacturing, which can be leveraged to develop standards for SIBs in India.

2. Policy and regulatory

India's SIB ecosystem faces a few policy and regulatory challenges that can hold back its potential as a key player in the global BESS market. Further efforts are required to develop comprehensive government policies and incentives to drive research, development and commercialisation. Additionally, specific state level policies and regulations to promote and govern the incorporation of BESS into the power grid for various applications are also necessary. Policy and regulatory frameworks should also be cohesive across states/UT and central level to ensure alignment of all stakeholders and support rapid sectoral growth.

India can obtain learnings and best practices from the comprehensive UK Battery Strategy, which outlines financial support for the development of various battery technologies, including SIBs. Additionally, learnings may also be obtained from the collaboration between the Scottish Government and the UK Government for the establishment of a new battery prototyping facility at The University of St. Andrews.

3. Demand

A global shift towards innovative energy storage technologies has supported increased SIB demand worldwide. In a similar manner, India can seek to directly support innovative technologies such as SIBs through technology-specific tenders, financial support through technology-specific VGF schemes, development of common infrastructure for BESS and SIB projects, and other activities to develop a smooth project development process. Efforts can also be made to encourage deployment of BESS for grid-scale storage applications for which SIBs are well suited, which in turn would drive demand for the technology.

4. Supply chain

India's SIB battery supply chain needs to be scaled up to enable widespread adoption. The supply chain for essential materials such as hard carbon needs to be established within India to reduce import reliance and address challenges due to cost fluctuations. Developing a domestic supply chain for such essential input materials for SIBs will support scaling up of manufacturing capabilities and the overall uptake of the technology. The supply chain for various balance of system components can also be developed to ensure overall availability of SIB project components, which will in turn support project deployment.

Support from the UK Government's Ayrton Fund, which supports clean energy research, development, and demonstration in developing countries, may be leveraged to help address this challenge.

5. Skill development

Considering the nascent nature of the BESS sector in India, as well as the overall SIB technology, the country needs to make efforts to develop a skilled workforce for the SIB sub-sector. The government can develop initiatives to promote training and education in critical fields such as material science, cell manufacturing, battery pack assembly, and project deployment. Additionally, educational and research institutions may be encouraged to develop SIB specific trainings and courses, which in turn would promote sectoral growth.

India can obtain best practices from major skill development initiatives in the UK, including the FBC, The UKBIC, Innovate UK training initiatives, and The Faraday Institution's Battery Career Portfolio.

6. Gender equality and social inclusion (GESI)

Due to the widespread availability of raw materials for SIB production, particularly relative to LIBs, SIBs present an opportunity for India to establish an indigenous energy storage ecosystem. However, while doing so, it is important to ensure that the socio-economic benefits of such an environment are fairly distributed amongst diverse gender and social groups. India can obtain significant benefits from incorporating GESI considerations into the emerging SIB ecosystem in India. These can include creation of new employment opportunities for women and marginalised communities, upskilling and reskilling of the labour force, creation of localised economies, formalising workers from coastal communities, health and safety benefits through improved battery sustainability, and avenues for women empowerment.

India can obtain best practices and learnings for incorporating GESI from guidelines and frameworks developed in various countries, including in the UK. Innovate UK and UK Aid have developed guides to support incorporation of GESI considerations in the clean energy and manufacturing sectors. Additionally, UK Aid and Work and Opportunities for Women (WOW) have developed a report covering key net zero trends across three sectoral value chains, including energy, and providing key recommendations for a Gender Just Transition.

7.2 Recommendations for India

Targeted measures across the areas identified above will help develop the overall ecosystem in India for accelerated SIB uptake. Some of these measures can be listed below:

1. **SIB-specific VGF:** SIBs have the potential to be cheaper than LIBs, but the nascent nature of the sector means that it is yet to achieve economies of scale in manufacturing and supply chain that would drive down costs. Additionally, as a new technology, it may have limited access to finance due to a perception of high risk amongst potential financiers. By closely monitoring the SIBs development and cost trends, India can leverage VGF to accelerate its adoption and create a more robust and holistic energy storage ecosystem. Currently, the Indian government is providing VGF for BESS, but with the oversupply situation of LIBs, costs are declining drastically. Thus, the Indian government may consider reallocating some of the funds from the VGF support for BESS towards SIB specific initiatives. The provisions of VGF to facilitate the development and adoption of SIBs by GoI can encourage R&D efforts and enhance manufacturing capabilities. VGF has the potential to be a key factor in advancing SIB technology. VGF support for a pre-determined capacity of SIBs deployed in India would help establish the sector and improve the viability of initial projects. This initiative has the potential to promote the use of SIBs, thereby decreasing the dependence on imported lithium and strengthening the availability of environmentally friendly energy storage alternatives in India.

2. **State-specific support:** The majority of states do not have specific policies and regulations in place to promote and govern the incorporation of BESS into the power grid for various applications. This is primarily due to the absence of storage considerations in the existing frameworks, requiring states to establish their objectives, targets and strategies ESS to develop supportive regulations. The state governments can release guidelines to promote the utilisation of BESS with targets established individually for various BESS technologies. Also, they can offer incentives for the establishment of BESS manufacturing facilities and the installation and interconnection of BESS with the grid. Additionally, it is imperative to grant utilities and private developers the opportunity to invest in storage.

3. **Demand side support:** In order to promote the deployment of SIBs and other new and innovative technologies, technology-specific tenders can be developed. These tenders will help create a clear demand side driver to support manufacturers that have borne the initial risk of investing in a nascent technology. Developing such demand side assurances can allow manufacturers to be confident that the manufacturing capacity will not remain underutilised, while also driving the market towards the adoption of SIBs.

4. **Manufacturing support:** SIBs have a similar manufacturing process to LIBs and utilise raw materials that are abundant in India. Thus, they are an attractive option to support the development of battery manufacturing in India. Achieving economies of scale and technological advancements will make SIBs a more cost-effective option compared to LIBs. The PLI scheme for promoting domestic manufacturing for ACC batteries is already active, with 40 GWh awarded and a further 10 GWh to be allocated. Additionally, 5 GWh of capacity has been reserved for 'niche' technologies. A share of this upcoming PLI capacity can be allocated for the development of SIB manufacturing facilities. This will support the development of the overall SIB ecosystem. Additionally, SIB-specific components should also be included in

any future PLI schemes that are focused on specific sub-components such as cathodes and anodes.

5. **Skills development initiatives:** Developing a workforce that is familiar with SIBs and has the requisite sectoral skills is essential for the long-term viability of the SIB sector. SIB-related training and capacity building can be covered under relevant ESS schemes issued by the GoI. These training measures can include awareness creation to improve knowledge of the technology and its capabilities, an overview of use cases and applications, and specific technical sessions where applicable. Training of technicians for the ESS sector at large should incorporate SIB-specific considerations as well to ensure the availability of a workforce for SIB project maintenance. Additionally, learnings from UK BESS skilling and innovation initiatives such as the FBC, which also funded the NESFF, can also be leveraged to help meet sectoral skill requirements.

6. **Development of R&D and industry partnerships:** The SIB technology remains at a nascent stage, and significant developments are expected that could further improve their performance and viability. India can augment its domestic SIB capabilities and ecosystem by supporting international collaboration on SIB R&D. This can be carried out by making BESS R&D activities, including those focused on SIBs, a key focus area under various energy-related bilateral and multilateral agreements. Additionally, R&D partnerships between relevant entities working on developing SIBs can be promoted. The establishment of collaborative partnerships will accelerate technological progress particularly in the areas of SIB cell cathode development and its stability, ultimately enhancing the lifespan and energy efficiency. This will consequently drive down the cost per kWh of SIBs, thereby reducing overall costs for BESS projects.

7. **Development of technical and quality standards:** Ensuring SIBs manufactured in India meet relevant technical and quality standards will be critical to ensure that they are trusted in the market. To enable this, clear technical and quality standards for SIBs will need to be developed. These standards should be accompanied by clarity on testing methodology and evaluation criteria and should be developed in conjunction with inputs from industry bodies and academic institutions to ensure relevant technology considerations are incorporated and the standards developed are as comprehensive as possible. Collaboration with organisations such as Faraday Institution and the British Standards Institute could be taken forward.

8. **Technology demonstrations:** The GoI can support pilot initiatives that integrate SIBs in applications, such as grid storage. These demonstrations will gather crucial data on performance, scalability, and the establishment of trust among potential investors and users. By merging research funding with hands-on experimentation, policymakers can greatly bolster confidence in the technology and accelerate its adoption. Moreover, public awareness campaigns that emphasise the advantages of SIB technology can further enhance confidence and advance acceptance of this promising innovation.

SIBs represent a promising avenue for the future of global and Indian energy storage solutions. With its usage of abundantly available raw materials, affordability, and potential for scalability, SIBs offer a viable alternative to LIBs. SIBs are poised to play a significant role in supporting RE integration, grid stability, and electrification efforts worldwide. With ongoing research, development and investments, SIBs are well positioned to unlock their full potential and contribute to cleaner, more sustainable energy future on global scale.