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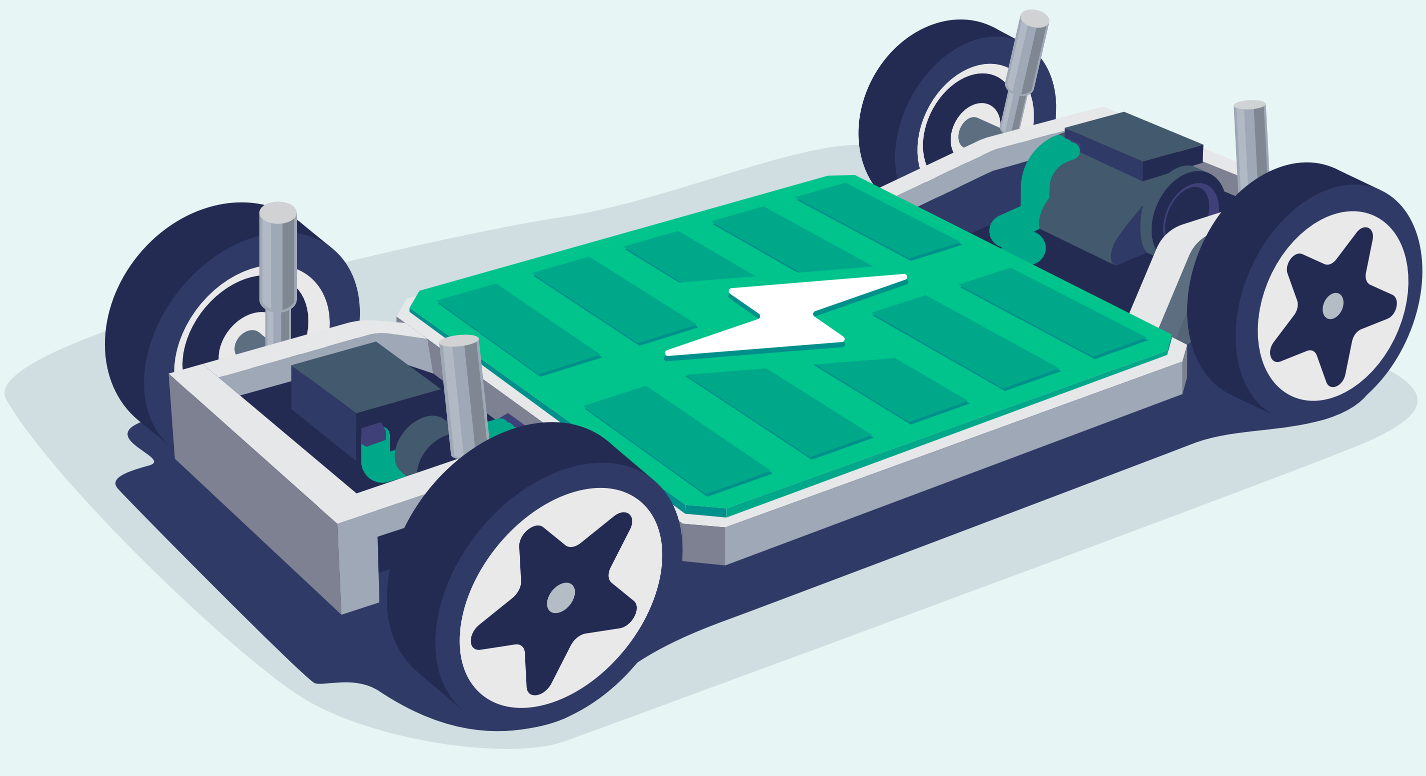
DEPARTMENT OF
SCIENCE AND TECHNOLOGY
सत्यमेव जयते

R&D Roadmap on

Tropical EV Battery

TECHNOLOGIES TO OVERCOME HINDRANCES TO E-MOBILITY



VOLUME No. 1

R&D Roadmap on

Tropical EV Battery

TECHNOLOGIES TO OVERCOME HINDRANCES TO E-MOBILITY

[Note: Thematic report based on DST's White Paper on Catalysing Technology-Led Ecosystem for e-Mobility].

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प्रो. अभय करंदीकर
Prof. Abhay Karandikar

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भारत सरकार
विज्ञान एवं प्रौद्योगिकी मंत्रालय
विज्ञान एवं प्रौद्योगिकी विभाग
Secretary
Government of India
Ministry of Science and Technology
Department of Science and Technology

17th October, 2024

MESSAGE

India's commitment to achieve a Net-Zero emission target by 2070 and reducing carbon emissions by one billion tonnes by 2030 underscores the critical need for a transition to electric mobility. India aims to achieve 30% EV market share by 2030. Spurred by encouraging initiatives by the Government of India, EV industry is growing at faster pace and automotive industry is gearing up to ramp up their operations to meet domestic demand. Many innovative start-ups have also ventured into this domain.

While there is significant growth in this sector, there are still many challenges that needs to be addressed for effective EV adoption in the country. At present, the industry depends heavily on imported materials/components due to lack of domestic supply chain and manufacturing capabilities in the country. This calls for a strategy and intervention in developing indigenous R&D capabilities to strengthen the capacity and capability of Industry for long term sustainability and end-to-end value creation across the value chain.

In this context, the Department of Science and Technology (DST) has prepared EV R&D Roadmaps to assess existing technology gaps and propose viable solutions. These documents aim to establish an industry-focused R&D roadmap for the development of indigenous components, processes, and technologies that will benefit the sector. Two year-long intensive consultation process involving over 200 stakeholders has culminated in these R&D Roadmaps, which focus on Tropical EV Batteries, Power Electronics, Machines and Drives and EV Charging Infrastructure.

With the establishment of the Anushandhan National Research Foundation (ANRF), DST is well-positioned to concentrate on clean energy and decarbonization pathways, under EV Mission, which has been recently launched, guiding India's energy transition and working towards the goal of Net Zero by 2070.

I would like to commend the DST team for their tremendous efforts and acknowledge the invaluable contributions of domain experts from academia, industry, and ecosystem partners in producing these crucial insights for e-Mobility.

I am confident that this document will serve as an important reference guide for the R&D community and will drive new advancements in industry-oriented R&D initiatives for e-Mobility in India.

(Abhay Karandikar)

Technology Bhavan, New Mehrauli Road, New Delhi - 110016
Tel: +91 11 26511439 / 26510068 | Fax: + 91 11 26863847 | e-mail: dstsec@nic.in | website: www.dst.gov.in

सत्यमेव जयते
डा. अनिता गुप्ता
Dr. Anita Gupta

सलाहकार एवं प्रमुख/वैज्ञानिक 'जी'
जलवायु, ऊर्जा व सतत् तकनीक
विज्ञान और प्रौद्योगिकी विभाग
भारत सरकार
ADVISOR & HEAD / SCIENTIST 'G'
Climate, Energy and
Sustainable Technology (CEST)
Department of Science & Technology
Government of India

MESSAGE

In the effort to decarbonise India, the mobility sector is undergoing significant transformation, with Electric Vehicles at the forefront as a sustainable solution for the future. India aspires to become a global manufacturing hub for electric vehicles.

To achieve this ambitious goal and foster an environment conducive to innovation, Department of Science and Technology (DST) had launched a pioneering initiative to prepare R&D Roadmaps on three key areas: Tropical EV Batteries, EV Power Electronics and Machine and Drives and EV Charging Infrastructure. These documents analysed current capabilities, identify gaps and challenges and proposed actionable strategies to accelerate advancement in indigenous technologies while building a robust R&D and manufacturing eco system.

A key focus is establishing self-reliant battery ecosystem which include setting up of pilot production facilities for battery cell manufacturing. In case of power electronics and machine drives, it is envisaged to develop market driven products through creation of Centres of Excellence (CoEs). These R&D Roadmaps also address supply chain challenges related to essential materials like lithium salts and rare earth oxides under scoring the need for standardized processing technologies to support extraction, product development and recycling of end-of-life products. Further, low cost, innovative solutions have been proposed to enhance the ease of doing business in EV charging infrastructure sector.

I would like to extend my heartfelt thanks to the Advisory Committee led by Prof. B.G. Fernandes from IIT Bombay, and to the expert members for their invaluable contributions in crafting these R&D Roadmaps with high quality content, in-depth analysis and actionable framework. Lastly, I appreciate the efforts of my colleague, Mr. Suresh Babu Muttana, Scientist-E, DST in engaging with industry experts and stakeholders which has resulted in rich insights that shaped these R&D roadmaps.

I am hopeful that these documents will not only promote technological advancements but also cultivate vibrant R&D eco-system for electric mobility in the country.

(Dr. Anita Gupta)

Room No.8, S&T Block-I, Technology Bhavan, New Mehrauli Road, New Delhi-110016
Tele.: 011-26523977, 26590213 Website: www.dst.gov.in / www.nstedb.com
E-mail : anigupta@nic.in / anitagupta2004@gmail.com

भारतीय प्रौद्योगिकी संस्थान मुंबई
पवई, मुंबई - 400 076, भारत

Indian Institute of Technology Bombay
Powai, Mumbai - 400 076, India

दूरभाष/Phone : (+91-22) 2572 2545
फैक्स/Fax : (+91-22) 2572 3480
वेबसाईट/Website : www.iitb.ac.in

IIT Bombay

MESSAGE

Electric Vehicles are sustainable alternatives to Internal Combustion Engines (ICEs) as they produce zero local emissions and reduce dependence on imports of fossil fuels thereby ensuring energy security. Spurred by favourable schemes and policies by the Government of India, Indian Electric Vehicle sector has shown remarkable growth over the last few years.

With growth, there are still many challenges that need to be addressed for effective adoption of EVs in the country. These include the high cost of vehicles, limited range, concern about vehicle safety and lack of adequate charging infrastructure. In addition, innovation, design and development to increase efficiency and performance of the EVs and testing competency are also need attention. In this context, Department of Science and Technology (DST) in consultation with various stakeholders brought out a consolidated White Paper on *EV Evolution: Catalysing Technology led Ecosystem for e-Mobility,* which was released in the month of February, 2024. This document highlighted both hindrances being faced and also provided technology solutions to address these issues to strengthen Indian EV industry through R&D intervention.

DST is now bringing out three R&D roadmap documents on EV battery, EV motors and power electronics, and EV charging infrastructure, which have been prepared after extensive consultations with the stakeholders over a period of two years. These documents are crucial for setting up R&D targets and work towards developing indigenous products/systems that conform to international standards to help industry to meet domestic market and as well increase export potential in this domain.

I extend my sincere gratitude to Dr. Abhay Karandikar, Secretary, DST for giving me the opportunity to Chair the Advisory Committee. I also thank Dr. Anita Gupta, Head, Climate, Energy and Sustainable Technology (CEST), DST for her support in this endeavour. Special thanks to members of the Advisory Committee, especially Prof. Siddhartha Mukhopadhyay, for their valuable contributions in shaping these documents.

I hope that these documents are of use for planning and implementation of R&D programmes in promoting research and advancing domestic manufacturing competencies in achieving the targets of Atma Nirbhar Bharat (Self-Reliance).

Prof. B.G. Fernandes
Chairman, Advisory Committee
White Papers on e-Mobility, DST

CENTRE FOR SCIENCE AND ENVIRONMENT

LEAVES OF IMPORTANT SURVIVAL TREES IN INDIA —MAHUA, KHEJDI, ALDER, PALMYRA AND OAK

Sunita Narain
Director General
Centre for Science and Environment

Anumita Roychowdhury
Executive Director
Research and Advocacy
Centre for Science and Environment

MESSAGE

For a scalable and ambitious electric vehicle programme and manufacturing to meet the climate mitigation goals, India needs a strong ecosystem for local development of electric vehicle technologies to make the transition cost effective, high quality and also maximise economic gains from the local value chain. This requires an effective framework and a roadmap for local innovation in the areas of battery storage, electric propulsion, new materials, processes and advanced manufacturing capabilities. Strong research and development (R&D) ecosystem can enable development and production of batteries that are safe and appropriate for operation in the Indian climate.

The Centre for Science and Environment therefore deeply appreciates this opportunity to engage with a wide spectrum of industry stakeholders and sector experts to assess and frame this white paper. This has enabled collective assessment of the potential for a national battery development program that can facilitate large scale cell production and commercialisation of mature cell technologies, development of new cell chemistries to minimise import dependence, localise value chain, strengthen material security through circularity, and enable technology development to reach the higher levels of technology readiness for commercialisation.

This R&D Roadmap therefore identifies the critical pathways for the ecosystem and a strategy for aligned action by diverse technical bodies, research laboratories, and industry partners. This can enable a R&D consortium for knowledge, skills and resource mobilisation to support cell component development and commercialization for a mature market.

Sunita Narain

Anumita Roychowdhury

MAIN OFFICE: 41, Tughlakabad Institutional Area, New Delhi-110 062 INDIA
Tel: +91 (011) 4061 6000, 2995 5124, 2995 6110 **Fax:** +91 (011) 2995 5879
BRANCH OFFICE: Core 6A, Fourth Floor, India Habitat Centre, Lodhi Road, New Delhi-110 003, **Tel:** +91 (011) 2464 5334, 2464 5335
Email: cse@cseindia.org **Website:** www.cseindia.org

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Suresh Babu Muttana
Scientist E
Coordinator, EV R&D Roadmaps

GENESIS AND KEY CONTRIBUTORS

NITI Aayog entrusted DST to work on technologies to overcome hindrances in e-Mobility. Over the last two years, DST conducted a series of interactions with stakeholders viz. vehicle OEMs, battery manufacturers, electrical & electronics industry, R&D labs, academia and think tanks to identify key challenges and potential R&D solutions to address these issues. These deliberations led to preparation of a White Paper on Catalysing Technology led Ecosystem for e-Mobility, which was released on 28.02.2024 by Dr. Jitendra Singh, Hon'ble Minister of State (I/C) for Science & Technology, GoI.

As an extension to the above effort, DST has now come up with detailed R&D Roadmaps in key thrust areas of electric mobility viz. (a) Tropical EV battery, (b) Power electronics, Machines and Drives; and (c) EV charging infrastructure. These reports have gone through several iterations and inputs received from major auto industries and other stakeholders from the entire EV ecosystem have been incorporated.

I would like to express sincere gratitude to Prof. Abhay Karandikar, Secretary, Department of Science & Technology (DST), GoI for his kind support and overall guidance. I would like to thank Dr. Anita Gupta, Head, CEST Division, DST for her concerted efforts and guidance in shaping the recommendations as well as program plans aligned with national goals.

I also extend deeper appreciation to the Advisory Committee led by Prof. B.G. Fernandes, IIT Bombay, and the noteworthy contributions by domain experts namely: Dr. K Raghunathan, IIT Madras; Prof. Siddartha Mukhopadhyay, IIT Kharagpur; Mr. Sajid Mubashir (former), DST; Dr. Z.V. Lakaparampil (former), CDAC ; Mr. Suuhas Tendulkar, ERF Global; Ms. Veena Koodli, Robert Bosch; Mr. N. Mohan, CESL; Mr. Kiran Deshmukh, Sona Comstar, who have extensively contributed in preparation of these R&D Roadmaps with quality content and in-depth analysis and actionable framework.

I would like to express sincere thanks to the lead authors: Ms. Moushumi Mohanty, Ms. Mrinal Tripathi, Mr. Rohit Garg, Ms. Anannya Das, Centre for Science and Environment (CSE); Dr. Raghunathan, IIT Madras; Mr. Sajid Mubashir (retired), DST; Mr. Arghya Sardar, TIFAC; Dr. Parveen Kumar, WRI India; Mr. Suuhas Tendulkar, ERF Global; Ms. Veena Koodli- Robert Bosch; and Mr. N Mohan, CESL, who have put together initial drafts and also immensely contributed in finalisation of these documents. I would like to acknowledge especially Dr. Reji Mathai, Director, ARAI for reviewing R&D Roadmap on EV Charging Infrastructure.

(Suresh Babu Muttana)

Technology Bhavan, New Mehrauli Road, New Delhi -110016; Email: sureshbabu.muttana@gov.in
+91-11-26590593; www.dst.gov.in

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SCIENCE AND TECHNOLOGY

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EXECUTIVE SUMMARY

India's Long-Term Low Carbon Development Strategy (LT-LEDS) was launched in the 27th session of Conference of Parties (COP-27) in 2022, with the target of meeting net-zero emissions by 2070. India is a signatory to the global pledge for 100 per cent electrification target in the time frame of 2030-40 with special focus on two and three wheelers.

To drive this program, the Department of Science and Technology (DST) has framed a series of White Papers in three volumes to address the key technical barriers to scaling up of the EV programme and to identify a roadmap and pathways on the critical aspects of battery technology development and its manufacturing ecosystem and charging systems. They aim to support and enable decision making and consensus building among the decision makers in the Government on supporting the electric vehicle transition in India with the help of this program. The White Paper volumes have focussed on the following themes: i) Tropical EV Batteries; ii) Electric vehicle motors, drives and power electronics; and iii) Electric vehicle charging infrastructure. This report addresses the first, Tropical EV Batteries.

Tropical EV Batteries

The paper is designed as a proposal and a roadmap for such a focused development program that builds competence and capability as well as capacity that attempts to solve problems specific to India. Key programme imperatives are outlined below, and the details can be found in the full document.

Battery performance metrics: The critical battery performance metrics are energy and power (and the trade-off between the two), cycle life, thermal stability, raw material availability, and the cost. This report provides a discussion on these metrics, their relative importance and interdependence in the Indian context.

Battery cell technology and materials: As for battery technology, the focus is divided into two large areas based on the TRL (Technology Readiness Level). TRL 1-3 is concept development in a laboratory scale, TRL 4-6 is scale up to prototype demonstrating proof of concept, design validation, and manufacturability, and TRL 7-9 is full-scale commercial production:

1. High TRL: Short-to-medium term where the target is to enable quick vehicle electrification especially in the low cost and low load two and three wheeler segments, with further extension to four wheelers. The battery chemistry will involve on the cathode side, Nickel Manganese Cobalt (NMC) at varying nickel and cobalt contents

and Lithium Iron Phosphate (LFP) and its variant Lithium Manganese Iron Phosphate (LMFP); candidates on the anode side include Lithium-Titanium-Oxide (LTO), graphite, silicon-based anodes, and supercapacitors.

2. Low TRL: Long-term technologies that are promising but not yet matured to large-scale production. The candidates discussed in depth are Sodium Ion Batteries (SIB), Solid State Batteries (SSB), as well as Lithium-Sulfur, and Lithium metal chemistries. In SIB, lithium is replaced by sodium which is significantly more abundant and cheaper. However, it is a heavier element, resulting in low energy density batteries. SSBs enjoy superior thermal stability and energy density but cycle life, cell resistance, and manufacturability are challenges.

Material sourcing and production will need to focus on cathode active material (CAM) which is the most expensive single component in a battery cell. Additional development work may also focus on indigenous manufacturing of other raw materials such as anode active materials, current collectors, electrolyte, etc. Opportunities exist, for example with CAM, for tailoring the material for superior thermal performance and stability. It will also be useful to explore metallurgical processing of lithium to produce CAM precursors if we gain access to lithium.

Commercial cell manufacturing: Indigenous cell manufacturing is another important imperative. The paper describes the entire battery production value chain starting with cell components all the way to pack manufacturing. Main aspects of LIB (and SIB) as well as SSB cell manufacturing processes are described. For SSBs, process steps transferable from the common LIB manufacturing line are discussed. There is also a need to optimize existing processes and develop new ones while reducing manufacturing costs under Indian conditions. A cell manufacturing plant requires clean rooms, process automation, and on-line process and quality control. Most of the manufacturing equipment is imported and needs to shift to domestic development.

Battery cell R&D and prototype facilities for scale up: Taking a technology concept proved in the lab (TRL 1-3) to full scale production (TRL 7-9) requires intermediate scaling steps (TRL 4-6), achieved through R&D and prototype cell fabrication facilities. The R&D Cell Fab facility fabricates multi-layer pouch cells with small capacity and requires its own cell testing facility. The test data from such a cell is representative of (not the same as) production-size cells and establishes technology proof-of-concept (POC). Several such facilities are needed, located at key R&D centres in India. Some already exist (at IITs, CECRI, etc.) and may require enhancement of existing capabilities. After successful POC, the next step is evaluation with full capacity cell builds in a prototype facility.

The Prototype Cell Fab centre is a larger facility that mimics a commercial manufacturing process but at a lower throughput; it should have the capability to build production size cells at multiple formats (cylindrical, prismatic, pouch). An extensive testing lab with multiple cyclers/thermal chambers as well as analytical and safety labs may be co-located. The purpose of such a centre is to demonstrate techno-commercial viability of a candidate cell technology for full-scale cell manufacturing and subsequent implementation in EVs.

The data and knowledge derived will enable cell manufacturers to rapidly translate a cell technology into full-scale production. This is envisioned as a centre that is accessible to various R&D activities across India with streamlined operation and administration (including scheduling).

Safety and durability are major concerns for Indian conditions. Spate of fire incidents have plagued two wheelers largely and a few light-duty cars. Poor quality cells, inadequate thermal management, and deficient battery management system (BMS) are major causes of these incidents. Thermal runaway typically initiates at a single cell (Cell 0) and proceeds through three stages: (1) internal short caused by dendrite formation, (2) separator melting, electrolyte decomposition and anode oxidation, and (3) cathode and electrolyte oxidation and steep temperature rise. The energy released from Cell 0 then propagates throughout the battery pack through multiple heat transfer modes, setting the entire battery on fire.

Durability of the battery is reflected by the decline in battery capacity due to cell degradation. Higher temperatures and improper battery operation, often the case under Indian conditions, are some of the major causes for poor cycle life. The resulting cell internal mechanisms in play are growth of solid electrolyte interphase (SEI), loss of active material, electrode delamination and lithium plating. Along with battery capacity, which is a measure of energy, power degradation also may be connected to durability of battery depending upon the application. While the problem of poor quality cells may be satisfactorily tackled through rigorous supplier qualification processes and checks, inadequate thermal management and deficient BMS are more of design problems that need the attention of battery manufacturers.

Battery diagnostics and modelling: Cell diagnostics techniques for early warning against thermal runaway and battery capacity failure can enhance the safety and save OEMs from the high battery replacement costs. Physics and machine learning based battery models can render optimum battery performance and accurate prediction of battery life; pack models incorporating thermal behaviour are needed for mitigating thermal runaway. The diagnostics and models may also be deployed on board by incorporating into the battery BMS.

Battery Management System (BMS): An effective BMS can protect the battery from damage, ensure safety, predict battery life, and maintain the battery operation in order to keep efficiency high. The BMS architecture is designed, developed and calibrated for each type of battery system. The BMS relies on the battery voltage data and Coulomb count and keeps track of battery state of charge (SOC), state of health (SOH). Cells with LFP exhibit a flat voltage profile, making it challenging to estimate SOC from voltage data. Along with a flat Open Circuit Voltage (OCV) curve, LFP and Sodium Batteries also show high levels of hysteresis which need to be accounted for. Advanced techniques incorporating EIS, Kalman filters, physics-based models and machine learning tools need to be developed and deployed via the BMS.

Battery Thermal Management System (BTMS) is responsible for controlling the temperature of the battery under high ambient temperatures, high power discharge and fast charge. Battery cooling strategies vary with application (two to four wheelers), cell chemistry, and cell type. They include air cooling, indirect liquid cooling, direct liquid immersion cooling, tab cooling and phase change materials.

Building safety standards: Taking cognizance of the gap in the regulatory framework with the assembly of light electric vehicle batteries, the government set up an expert committee to build safety standards for battery, BMS, and related components in electric vehicles. Standards and regulations would need to drive the terms of technology development. For example, adherence to standards will require outstanding manufacturing practices and quality control, reducing thermal runaway incidents. The Automotive Industry Standards (AIS) issued by the Ministry of Road Transport and Highways (MoRTH) enforce testing and evaluation of Electric Vehicles and Hybrid Electric Vehicles, including AIS 156 and AIS 038, the two main standards pertinent to EV batteries. The current standards and test protocols require a deeper investigation to assess the gaps in addressing the critical safety parameters and interface with the climatic conditions.

Battery raw material security: Raw materials comprise over 60% of the cost of a lithium ion cell, and India has very limited known reserves of lithium and there is not enough cobalt, nickel and graphite to hedge against uncertainties in the battery supply chain driven by global politico-economic changes. It is imperative that India builds a concrete plan to address uncertainties in battery material sourcing with an alternative plan to offset potential tightening of the supply chain. More innovation is needed to improve battery chemistries to substitute or minimise the use of materials that face the problem of unstable supply chains and higher costs. This would call for focus on LFP, LMFP, LMO and LTO-LMO cells as well as a major shift towards sodium-ion chemistry.

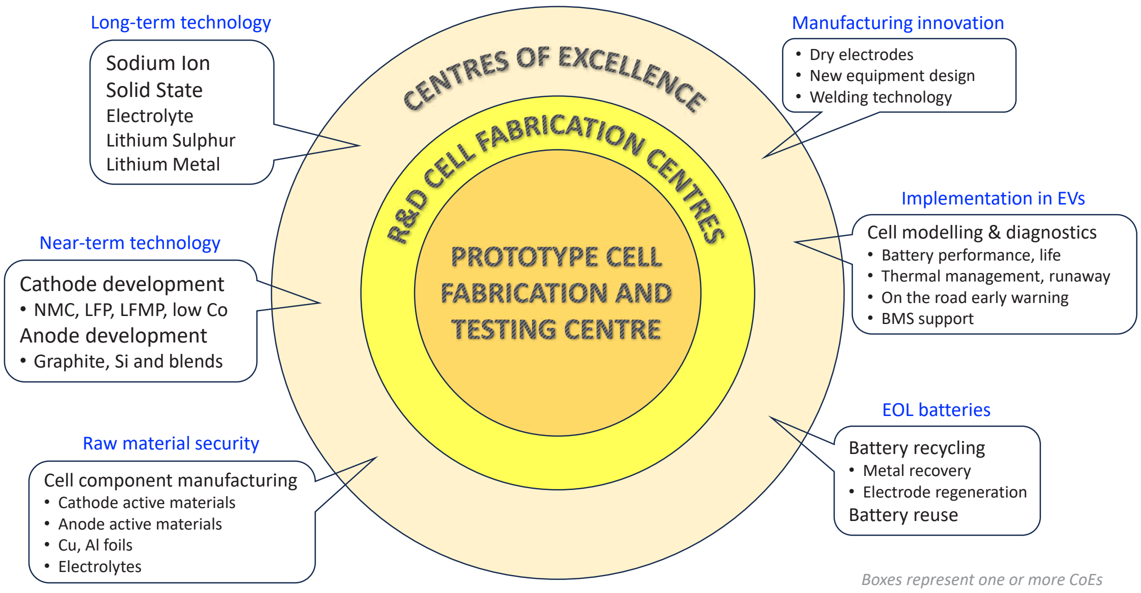
International partnership initiatives are also essential for access to raw materials. India is now part of the coveted critical minerals club, MSP (Mineral Security Partnership) consisting of 13 members. More international and private-public partnerships will need to be fostered.

Battery reuse presents another opportunity. End of life for an EV battery is when the battery capacity drops to 80 per cent of the rated capacity. However, batteries can still deliver usable power below 80 per cent charge capacity, although they will produce shorter run-times. For a reuse case, however, it is essential to determine the residual value of the battery using accurate State of Health (SOH) prediction tools.

Battery recycling: Even though the EV market in India is in its nascent stage, early action towards battery recycling can partially offset the material scarcity and cost and reduce waste. Within a cell, the recyclability of each of the components varies. Recycling is a challenging process and recycling-friendly battery design would need innovation but can yield benefits critical for the Indian ecosystem. Sorting based on chemistry and later processing strictly according to the said process of the particular chemistry may help ease the challenges.

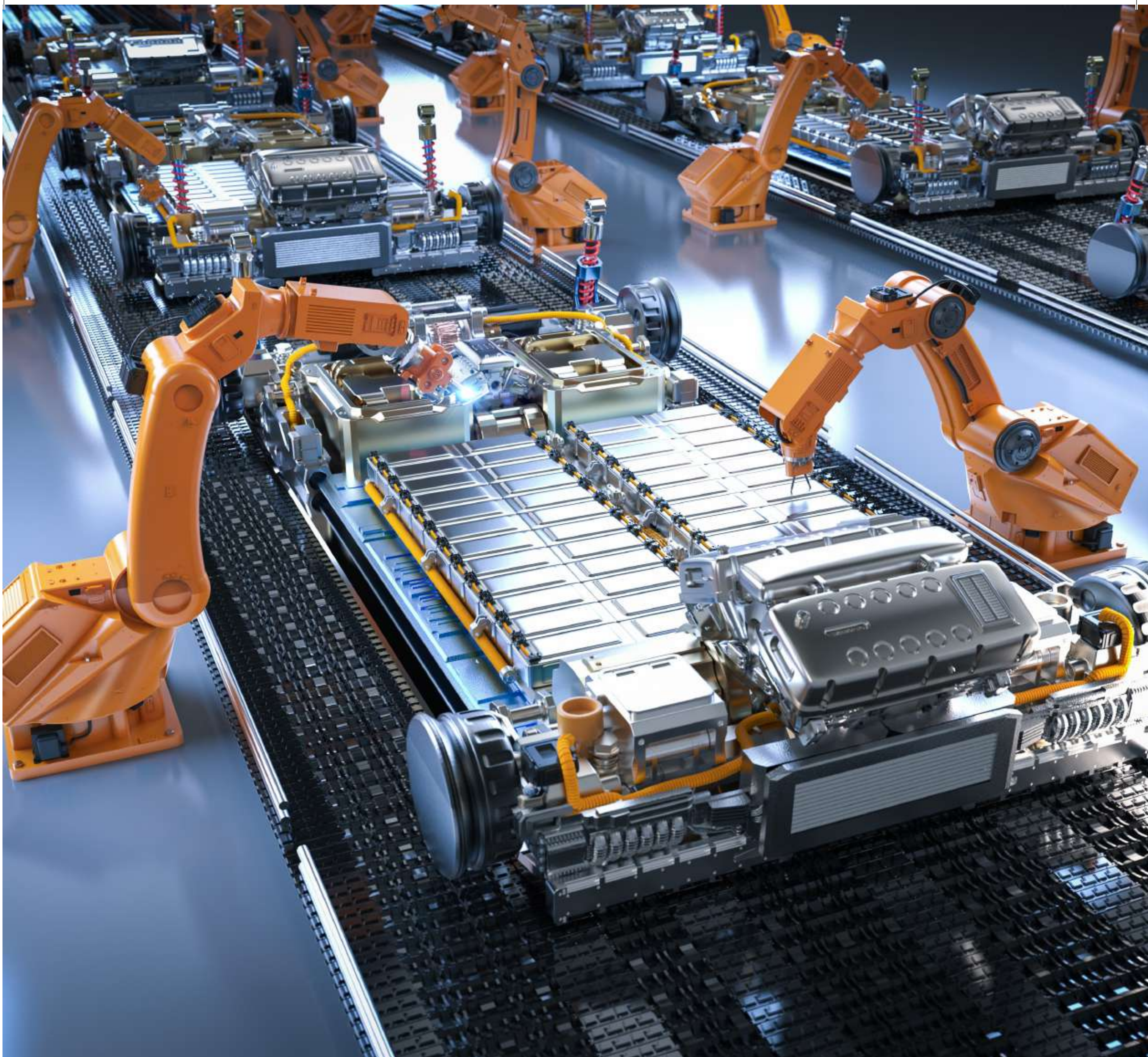
There is an opportunity in incorporating regulations for an indigenous version of the battery passport (in context of the recent EU battery passport regulations) at the outset of building a domestic battery value chain. India can leverage its experience and know-how of deploying scalable digital solutions across stakeholders in the battery value chain to enable more robust reuse and recycle.

Possible Centres of Excellence/Themes



Clusters for battery research: It is suggested that Centres of Excellence/ Innovation Clusters (see suggestion below) may be established for R&D in the priority areas of EV Batteries described above. Each Centre must serve as a collaboration network for solving industry level challenges & opportunities with public-private partnerships connecting the stakeholders, industry and academia.

The White Paper has been prepared in collaboration with selected lead agencies and along with a network of experts. The paper addresses specific issues in each thematic area in the context of emerging challenges in the manufacturing supply chain, infrastructure development, and constraints of climatic conditions and proposed a technology development program spanning the entire battery value chain.



INTRODUCTION

Imperatives of battery development in India

With India transitioning to electric vehicles, the need to build its own electric vehicle cells and batteries is now more urgent than ever. India depends on imports for all of its lithium ion cells. The imports, however, more often than not, are littered with manufacturing defects and have had dubious grade quality with low resilience to abuse and operating conditions typical of tropical Indian climate. These cells have a higher tendency to catch fire, jeopardising the lives of drivers and riders. It is therefore imperative for India to develop India-specific cells and manufacture its own cells and batteries that address issues of quality and suitability to the Indian climate and road conditions, as well as to consumer charging habits.

The White Paper brings focus on the following determinants for battery technology development.

Diverse requirements of vehicle segments: In India, we have diverse and highly stratified vehicle segments including small and light two and three wheelers, four wheelers and the heavy duty electric buses and trucks. The battery capacity can range from 2 to 300 kWh, and gross vehicle weight can vary from 100 kg to 16 tons (see Table 1: Categories of electric vehicles in India). Customers of light electric vehicles (two and three wheelers) are extremely price sensitive and need more customised solutions.

Table 1: Categories of electric vehicles in India

Vehicle Category	Battery Pack Capacity (kWh)	Gross Vehicle Weight (kg)	Type of Motor Used	Motor Maximum Power (kW)	Motor Torque (Nm)
Electric Scooter	1.30 to 4.50	100 to 275	BLDC	0.25 to 8.5	33
Electric Motorcycle*	2.3 to 5.2	265 to 290	BLDC	5.0 to 7.5	95 to 170
Electric Rickshaw	3.5 to 6.0	600 to 725	BLDC	1.0 to 1.9	22 to 42
Electric Auto Rickshaw	4.0 to 8.0	689 to 990	BLDC/ Induction	4.3-8.0	42
Electric Car (Mini)	15	1250 to 1700	PMSM/ Induction	19 to 30.5	91
Electric Car (Compact)	19.3 to 30.2	1260 to 1800	PMSM	55 to 105	110 to 270
Electric Car (Mid-Size Sedan)	50.3 to 60.5	2060 to 2160	PMSM	130 to 150	280 to 310
Electric Car (Executive)	77.4 to 90	2425 to 2670	PMSM	168.4 to 294	180 to 350
Electric Car (Premium)	71.0 to 84.0	2605 to 3114	PMSM, Induction	240 to 300	345 to 430
Electric LCV (2T)	14.4 to 21.3	1840 to 1920	Induction	25 to 27	90 to 130
Electric LCV (7.5T)	62.5	7000-7490	PMSM	150 to 220	1200 to 2800

Vehicle Category	Battery Pack Capacity (kWh)	Gross Vehicle Weight (kg)	Type of Motor Used	Motor Maximum Power (kW)	Motor Torque (Nm)
Electric Bus (7.5- 12T)	60 to 124	10200	PMSM	180 to 245	
Electric Bus (16.2T)	151 to 204	12800	PMSM	180 to 235	800 to 3250
Electric Bus (>16.2T)	186 to 250	17800 to 19500	PMSM	180 to 250	800-3250

Source: Compiled by Centre for Science and Environment

Battery technologies to meet a range of performance criteria: The program for battery technology development has to address a range of performance parameters related to energy density, safety, electrochemical stability and durability under real world operations. Cell chemistries need to be identified, optimised and further innovated to meet a range of these criteria but in a cost effective manner. They have the potential to minimise or eliminate the use of imported strategic materials like cobalt and nickel in order to reduce supply side risks and price volatility.

The current paradigm of lithium-ion batteries in varying combinations of cathode chemistries include Lithium Iron Phosphate (LFP) and Lithium Nickel Manganese Cobalt (NMC). These are an improvement over the conventional lead-acid batteries for their higher energy density and hence capacity to store more energy in less weight and volume. While cell chemistry will continue to see more modifications, more advancements and innovation are underway to develop future cell chemistries. There is already a move towards solid-state electrolytes and sodium ion batteries to address performance and safety gaps and cost challenges in the currently used batteries. But India requires a clear trajectory for supporting research and their commercialisation. White paper I evaluates some of these aspects.

Battery cell manufacturing and scale-up: Currently, the battery cells in locally manufactured EVs are imported. By 2025 Indian cell manufacturing is expected to evolve, focusing on NMC and LFP chemistries. Most of the battery cell technology research activity in India is with small, lab-scale coin cells and India needs the capability to rapidly scale up from lab to commercial production of battery cells. The scale-up requires at least two stages: (1) small-format multi-layer cell fabrication and testing and (2) large-format prototype cell fabrication and testing. These fabrication and test facilities need to be developed so that cell manufacturing in India is able to catch up and then stay abreast of countries that already are producing cells at large scales.

Safety of EV batteries in the tropical climate of India: After a spate of fire incidents reported mostly in the two-wheeler and three wheeler segment and also a few cars, adequacy of the current safety regulations and testing protocols came under the spotlight. In view of fire incidents, the Ministry of Road Transport and Highways set up a committee to suggest safety standards for battery, battery management system (BMS), and related components.

The committee has suggested additional requirements for the existing testing standards for battery and related components of L, M, and N category vehicles. Automotive Industry Standards AIS 156 [Specific requirements for L category electric powertrain vehicles] and AIS 038 (Rev 2) [Specific Requirements for M, N Category electric powertrain vehicles] have been revised and are effective from March 31, 2023.

Li-ion batteries are sensitive to high temperature and voltage. Several conditions including overheating, over charging, exposure to high temperature, short circuiting, and rise in cell temperature can lead to thermal runaway if not detected and mitigated. Standards, regulations and testing methods for batteries are expected to address these issues as well as the bearing of climatic parameters including high temperature conditions, etc.

Review of global regulations show that testing procedures for vehicle certification include abuse tests to simulate thermal abuse, thermal shock cycling and rapid charge/discharge; electrical abuse including overcharge/overvoltage, short circuit, over discharge/voltage reversal, and partial short circuit; and mechanical abuse that includes controlled crush, nail penetration, drop, immersion, roll-over simulation, vibration, and mechanical shock. This also includes heat generation within a battery cell. Materials used in the anode and cathode affect thermal response of the cell.

What is needed is a deeper dive into materials research and develop processes to manufacture cells that are non-flammable. It will also be important to conduct investigation into the adequacy of the current testing protocol to address the range of issues and failure modes to inform the roadmap in India.

Battery durability: Battery capacity degradation with usage affects battery life in an EV. Cycle life of a battery is degradation with charge/discharge cycling and calendar life is degradation during storage. Factors responsible for poor cycle and calendar life include higher temperatures, charging the battery above its recommended voltage limit as well as charging at a high rate (current). There is also a strong dependence on cell chemistry, specifically anode and cathode active materials in the cell. Thermal management of the battery plays a major role in prolonging the battery life.

Battery modelling and implementation in EVs: Modelling battery performance and aging can provide in-depth understanding of lithium ion and non-lithium-ion batteries. Physics-based models are constantly evolving, and there is a great potential in using data analytics/ artificial intelligence/ machine learning techniques to build a robust model that can predict various battery phenomena. Each battery chemistry will have its own specific signature and behaviour pattern, and significant research is required to abstract the model that can be applied to different situations. Models can also help the automakers to rapidly implement technologies into EVs, in a cost effective fashion. It is therefore important for relevant software tools and data banks to be developed and made available to a variety of actors in the energy storage industry in India.

Critical minerals and resource security pose yet another challenge for the current technology. Rapid increase in demand for critical minerals and the prices has made the supply chain more unreliable and volatile. According to the estimates of International Energy Agency (IEA)[1], in a scenario analysis that meets Paris Agreement goals, the share of total demand for critical minerals will rise significantly over the next two decades to over 40 per cent for copper and rare earth elements, 60-70 per cent for nickel and cobalt, and almost 90 per cent for lithium. EVs and battery storage have already displaced consumer electronics to become the largest consumer of lithium and are set to take over from stainless steel as the largest end user of nickel by 2040, according to the IEA.

Even though the cost of batteries has reduced due to economies of scale and innovation, material costs are increasing. They are sourced from a few geographies and processing is largely concentrated in China. According to the International Energy Agency, China's share in refining is around 35 per cent for nickel and 50-70 per cent for lithium and cobalt.[2]

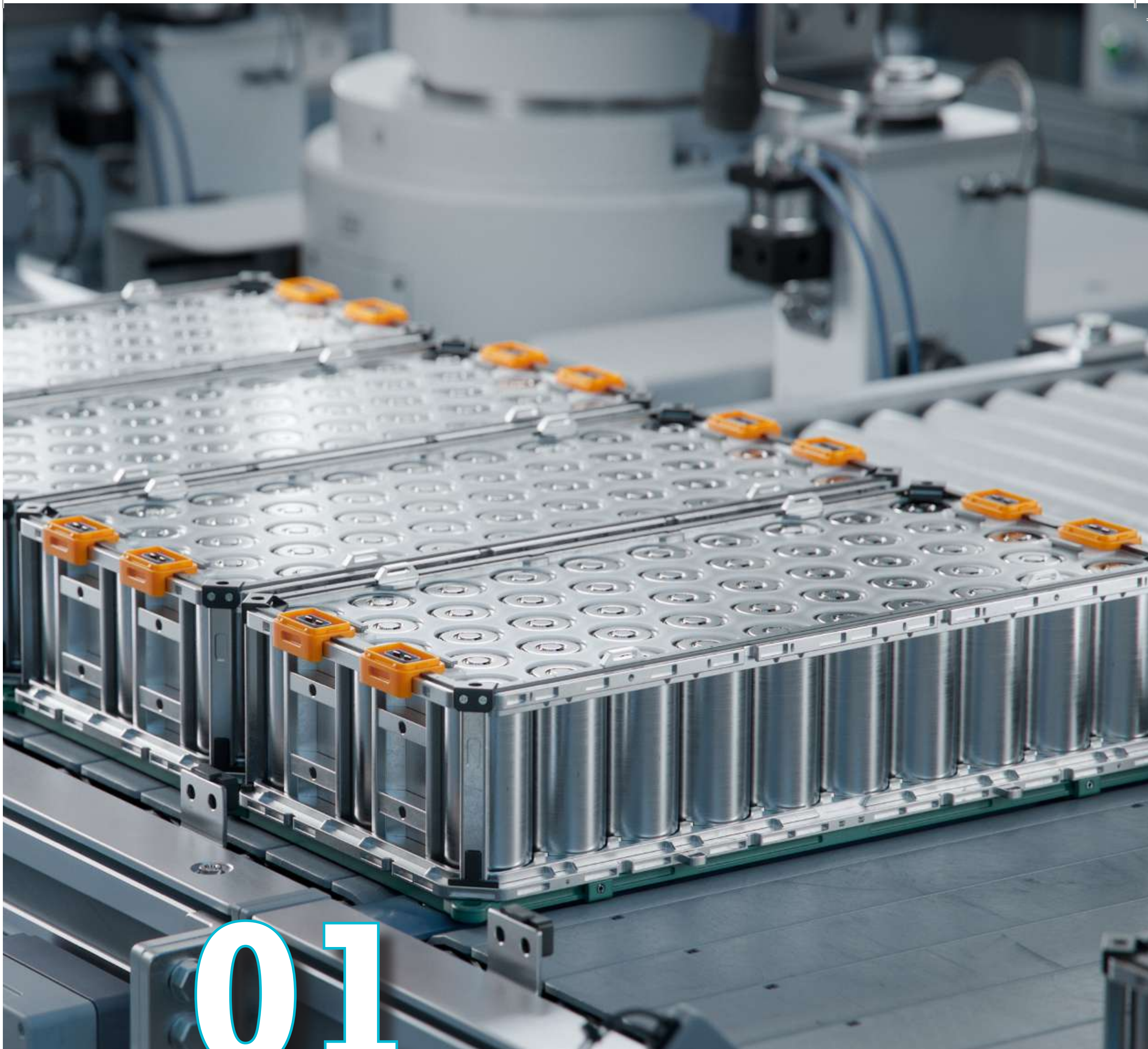
The prices for critical battery metals used in battery technologies fluctuate as a result of supply-demand economics, supply chain disruptions, political instability, pandemics, and global political uncertainties, which could directly affect the price of batteries and associated materials. Cobalt prices have been highly volatile between 2016 and 2019 because of political instability in Congo (DRC), where 70 per cent[3] of global cobalt mining occurs. Thus, it becomes necessary for India to secure access to raw and refined materials and discover and develop alternatives.

This supply risk will also have to be combated with R&D efforts to minimise or eliminate cobalt and nickel in Li-ion batteries through developing innovative cathode materials and processing R&D. This will require support for developing domestic battery materials processing. If electrode, cell, and pack manufacturing sectors develop that can help to improve processing and assembly and reduce costs.

Material security can improve if material intensity can be reduced and material substitution can be achieved through technology innovation. It is also necessary to diversify supply sources.

End of life reuse and recycling of critical materials for resource security: To improve material security it is necessary to promote recycling and work towards a circular economy. The number of spent/used batteries will increase with time. According to IEA estimates, material recovered from spent batteries including copper, lithium, nickel and cobalt can meet the combined primary global supply requirements by around 10 per cent. This will require design of battery packs to enable second use and recycling. This needs to be backed by the supportive infrastructure for collection, sorting, transport, processing and recycling of lithium-ion battery materials. More improved processing technologies can bring back materials into the supply chain. Ambitious targets are needed for achieving maximum recycling. Implementing circular economy in EV batteries for long term sustainability and mandating that a large part of the starting materials must be utilized from minerals mined in India are useful steps.

Creating an ecosystem and mission for EV adoption: This White Paper discusses the above-mentioned imperatives in detail in the following chapters and provides recommendations for successful EV adoption in India. A mechanism has to be created to accelerate the connection between academic research and industry, in order to fast track development, adoption and deployment of new technologies in the market. This will require a strong R&D programme addressing specific strategies intended for technology design for a sub-system supply chain for larger adoption of electric mobility. This program will support ACC PLI Scheme & also FAME Scheme to promote incremental innovation in battery technology.



01

CELL & BATTERY DEVELOPMENT TO DRIVE E-MOBILITY IN INDIA

As India strives for vehicle electrification to meet decarbonisation goals, the battery technologies for India need to address the following:

- Development of cell technologies that are specific to vehicle segments and driving conditions in India
- Development of machinery and equipment for cell manufacturing
- Supporting and building small scale battery plants for prototype building to aid quicker graduation to manufacturing readiness levels for new technologies
- Building of battery information banks for understanding battery behaviour from which feedback loops can be used to build more safe systems in the future
- Minimise reliance on imports for cell component materials

Beyond what is in vehicles currently, the technology may be divided into two major focus areas. One involves short to medium term strategy with mature cell technologies such as LTO batteries, super capacitors and silicon based anodes. The other is a long term strategy of funding promising technologies such as Sodium ion, solid state and metal-air batteries. Other cells with ACC benchmarking may also be considered. The paper also offers discussions on near term solutions for manufacturing technologies and processes that require indigenous development in the country.

Cell technology options

Today's cell chemistries

As of now there is no clear roadmap or mechanism for promoting and funding R&D to support cell development. This requires a framework for funding, setting up of incubation centres and testing facilities facilitated by consortia and associations. This also requires a longer time horizon for material level R&D, new manufacturing processes, technology development with supportive funding strategy. Skill development and R&D agenda need to be in place.

Currently, the most popular application is the lithium-ion technology and is considered the most preferred option among the rechargeable battery technologies available today for electric mobility. The Lithium-ion battery has high energy density i.e., a small battery pack (both by weight and volume) can provide the desired driving range.

Diverse combinations of Lithium-Ion Battery technologies have evolved for commercial applications. These include LCO (Lithium Cobalt Oxide), LMO (Lithium Manganese Oxide), LFP, NMC, NCA (Lithium Nickel-Cobalt-Aluminium Oxide) and these are differentiated based on the cathode material used in the battery. Their varying performance levels have been characterised in the literature. Currently, the most prominent chemistries used in India are LFP and NMC. Between LFP and NMC chemistries, LFP has a lower decomposition temperature that provides better thermal stability, which is ideal for the tropical climate in India. However, there is a significant penalty in energy density with LFP chemistry, compared to NMC, which would limit the range of the vehicle.

LFP chemistry also has a supply side advantage. Apart from Lithium, all component materials such as iron oxide, phosphate and graphite can be developed and sourced domestically. Compared to NMC, where precursor materials are sourced from foreign reserves, LFP would offer a short, stable supply chain. It has a price advantage as raw materials for NMC such as Nickel and Cobalt are expensive and experience significant price volatility, creating a significant business risk for cell manufacturers. It is evident that Nickel prices have grown over 107 per cent over the last two years, reaching record levels in March 2022.[4]

Currently, the target is to achieve quick vehicle electrification especially in the low cost and low load two and three wheelers segment. A lot of these vehicles which were initially powered by NMC technology are now moving towards LFP battery technology. One of the alternatives to NMC and LFP batteries is LMFP, a variant of lithium iron phosphate in which manganese is introduced to stabilize the iron. LMFP offers 4 volts Open Circuit Voltage (OCV) with iron stabilised (because Manganese has Jahn Teller problem) with a higher energy density cell compared to LFP.

Globally, batteries continue to get enhanced, and it is clear that batteries with high nickel content such as NMC811 and NCA could service passenger EVs in high-end passenger cars, while low-cost options such as LFP cells will find deployment in mass market vehicles. Batteries can be custom-built and aligned with applications that are India specific.

In India, priority may be given to LFP chemistry as the most widely commercialised Lithium-ion battery because it does not use metals with accessibility issues like nickel and cobalt. These are not only difficult to obtain but are also toxic to human health[5]

Raw material availability: For manufacturers, raw material security continues to be one of the biggest challenges to localization of cells in India and the industry continues to be dependent on imports. The electric mobility programme has also highlighted India's vulnerability to geopolitical complexities and uncertainties in the global supply of material and minerals and battery technology. Indian manufacturers are almost entirely dependent on global supplies of resources and technology. Self-reliance and localization are high on national priority but this needs firmer strategies.

It is believed that 60–70 per cent of the materials can be sourced locally. Given the uncertainties in the battery material supply chain caused by delays in the raw material supply chain, the assurance of material security is of huge significance to manufacturers. Securing the supply chain for cobalt, lithium, nickel, and graphite will be a challenge because of geopolitical uncertainty and price volatility issues. The race towards cobalt substitution has led to development of nickel-rich cathode chemistries. But this requires sustainable and economically viable methods to produce class 1 grade nickel in large quantities.

India does not have any meaningful reserves of key raw materials such as lithium and cobalt. The government has signed battery mineral sourcing agreements with Latin American countries and Australia. In order to ensure the mineral security of the country and to attain self-sufficiency, the Ministry of Mines has created a joint venture company, Khanij Bidesh India Ltd (KABIL). But the present policy regime reserves these minerals only for public sector undertakings. The country needs to encourage and incentivise private players in the sector to venture globally in parallel with KABIL.

India is currently a member of the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, which supports the advancement of good mining governance. In July 2022, India and Australia decided to strengthen their partnership in clean energy transition and create resilient supply chains for critical minerals. Australia committed AU$5.8 million[6] to the three-year India-Australia Critical Minerals Investment Partnership. India must proactively engage with global players to secure its place in international partnerships on critical minerals.

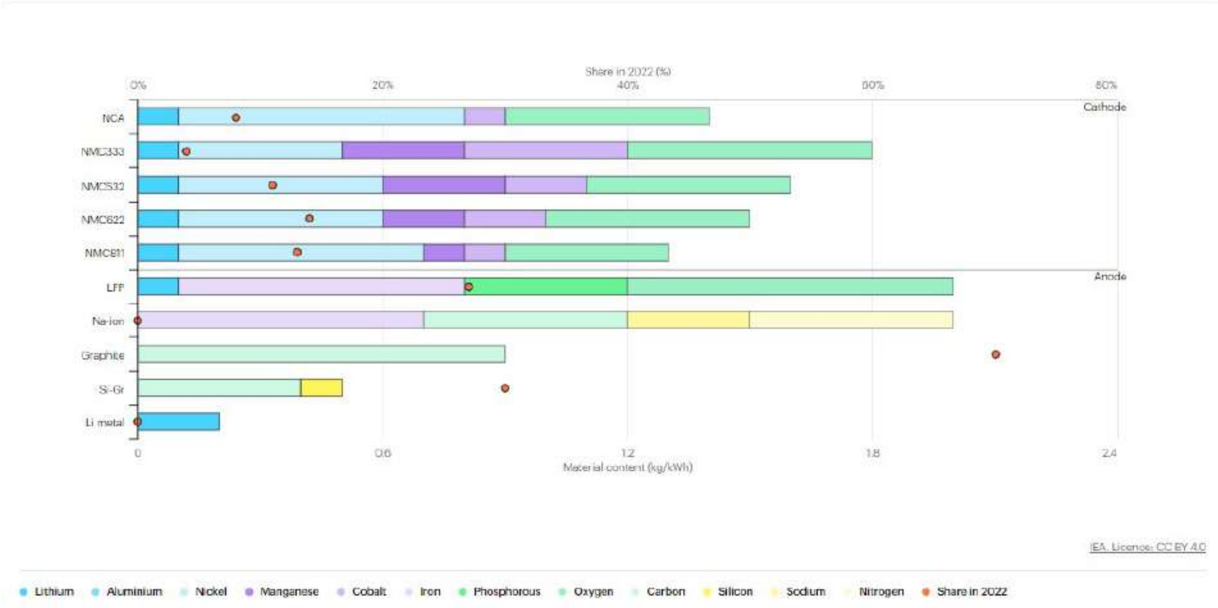
The United States Geological Survey (USGS) has stated in its 2023 reports that global consumption of lithium in 2022 was estimated to be 134,000 tons, a 41 per cent increase from 95,000 tons in 2021. Australia, Brazil, Argentina, Chile, and China accounted for the majority of world lithium production

In 2022, Congo (Kinshasa) continued to be the world's leading source of mined cobalt, accounting for about 70 per cent of world cobalt mine production. China is the world's leading producer of refined cobalt, most of which is produced from partially refined cobalt imported from Congo (Kinshasa).

Estimated global nickel mine production increased by about 20 per cent, with almost all of the increased production attributed to Indonesia at a gross mine production of 1.6 million metric tons in 2022.

The demand for chemical precursors of metals such Li, Ni and Co will depend on the cathode chemistry demand for various applications. LFP could be the dominant cathode chemistry in the near term. (See Figure 1: Material content in different anodes and cathodes)

Figure 1: Material content in different anodes and cathodes



Source: IEA, Material content in different anode and cathodes, IEA, Paris https://www.iea.org/data-and-statistics/charts/material-content-in-different-anode-and-cathodes, IEA. Licence: CC BY 4.0

Cell component cost breakdown

Globally, research agenda is being driven by the need to reduce costs while substituting targeted materials and improving performance. The battery value chain begins at the material stage. In the manufacturing of lithium-ion cells, material costs account for a majority of total cost. According to a study conducted by RWTH Aachen University and German Engineering Federation Verband Deutscher Maschinen- und Anlagenbau (VDMA), material costs in an NMC LIB cell account for 72 per cent of the total cell cost with the cathode and separator capturing a lion's share at 61 per cent of the material cost (See Figure 2 Cost overview of a cell).

Figure 2: Cost overview of a cell

Source: Heiner Hans Heimes, et al. 2019, PEM der RWTH Aachen and VDMA 1st Edition

With increased demand for LFP cell chemistry because of the advantages it offers with regard to cost as well as thermal stability, its cost has been on a rise in the last few years.

Cathode: Within the NMC LIB cathode, which is preferred currently because of its higher energy density, cobalt is the most expensive material on a $/kg basis but the amount of cobalt in a cell is small compared to Li and Ni. In absolute terms, Ni and Li are more expensive components in the cell because of the sheer volume of their composition in the cell. Cathode, or the positive electrode of the battery, is made up of a lithium metal oxide, such as lithium cobalt oxide, lithium iron phosphate, or lithium nickel manganese cobalt oxide.

Anode: The negative electrode is typically made of graphite or another form of carbon. However, anode manufacturers prefer synthetic graphite to natural graphite mainly because of its better performance. Producing synthetic graphite, however, is costly, power-intensive and environment unfriendly. Natural graphite enjoys a cost advantage relative to synthetic graphite, with natural graphite available at less than half the cost of synthetic graphite with its cost expected to further reduce.

The increased use of silicon in anodes is still largely under development and anode technology with about 5 per cent silicon oxide is starting to appear in commercial cells. In the future, if this technology is more widely adopted, it could expand the market for natural graphite as this form of graphite performs better than synthetic graphite with silicon in the anode, according to Fastmarkets[7]. The supply of both natural and synthetic graphite is dominated by China. In 2020, at least 62 per cent of the natural graphite's global supply came from China.

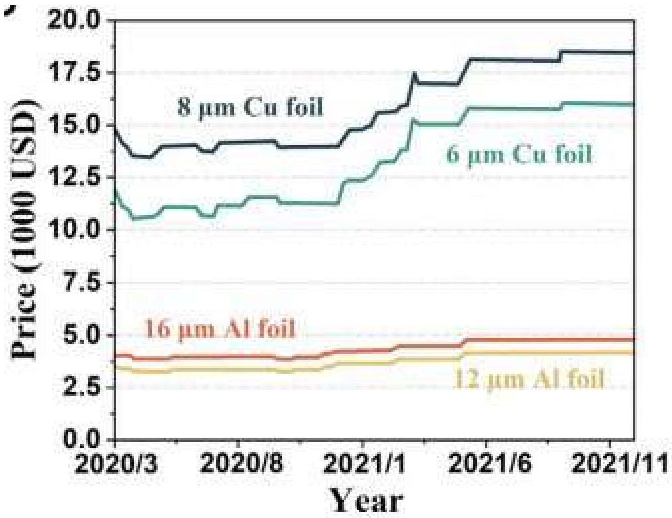
Electrolyte: The medium that allows movement of lithium ions between the cathode and the anode is usually a lithium salt dissolved in an organic solvent. It consists of a conductive salt (e.g. Lithium hexafluorophosphate) and a solvent (e.g. Dimethyl carbonate, ethylene carbonate, diethyl carbonate, or ethyl methyl carbonate). Additives like vinylene carbonate improve the long-term stability of the cell.

Electrolyte contributes 6-10 per cent to the total cost of a cell. One of the biggest issues with the electrolyte is the presence of moisture as an impurity. It causes a decomposition reaction of LiPF6. Hence, presence of water in cell components has to be avoided. This requires setting up dry rooms with moisture content below 100 parts per million, incurring high operating costs.

Separator: A thin, porous membrane that physically separates the cathode and the anode, the separator allows the flow of ions between the electrodes. At a material cost share of 17 per cent (see Fig 2: Cost overview of a cell), the separator also has a significant influence on total costs. The main raw materials used in different types of separators are Polyethylene, Polypropylene and Ceramics.

Current collectors: Made of conductive materials, current collectors transfer the electrical current generated by the battery to the external circuit. For the LIB anode, the current collector is typically copper because of its compatibility with most of the anode materials but is a significant contributor to cell cost. For the cathode, aluminium is preferred as the current collector because of its low price and good electric conductivity. Aluminium also offers corrosion resistance at cathodic conditions due to the formation of passive layers in the LIB electrolyte. The cost of the aluminium current collector is much less compared to that of copper (see Figure 3 The price of battery-grade Al foil is much lower than that of copper foil).

Figure 3: The price of battery-grade Al foil is much lower than that of copper foil



Source: Tingzhou Yang, et al 2023, Anode-free sodium metal batteries as rising stars for lithium-ion alternatives, iScience, CellPress; available at https://www.cell.com/iscience/pdf/S2589-0042(23)00059-7.pdf

Hardware (Cell Case)

The case can be made of nickel coated mild steel, stainless steel or pure aluminium and its alloys. Manufacturers who can supply such cases need to be available in the country. Deep drawing or reverse extrusion is used for cell cases. Standardisation of cell size will help to produce cases in volume which will bring down the cost and improve viability for a manufacturer.

With the above background, it is recommended that, for immediate and prolonged success of the EV industry in India, the strategy is to develop both short-term and long-term battery cell technology as outlined below.

Short-Medium term cell chemistry options

LTO Batteries (Anode)

Lithium titanate (LTO) has emerged as a promising alternative anode material for Lithium ion batteries, offering advantages like superior thermal stability, fast charging ability, and long cycle life potential.

LTO anodes have higher intercalation potential (~1.55 V vs. Li+/Li) compared to graphite anodes (~0.1 V vs. Li+/Li). Although this results in lower cell voltage and hence low energy density, it also eliminates dendrite formation, thus providing better safety. LTO anodes have also demonstrated excellent cyclic stability (~20000 cycles[8]) due to its negligible volume change during intercalation.

Furthermore, these cells also achieved the highest specific power, up to 950 W/kg, which corresponds to current rates of up to 20C.[9] The main reason for superior charging rates is that LTO nanocrystals have increased surface area for lithium ions to flow in and out at a much faster rate compared to a graphite anode.

Silicon-based anodes

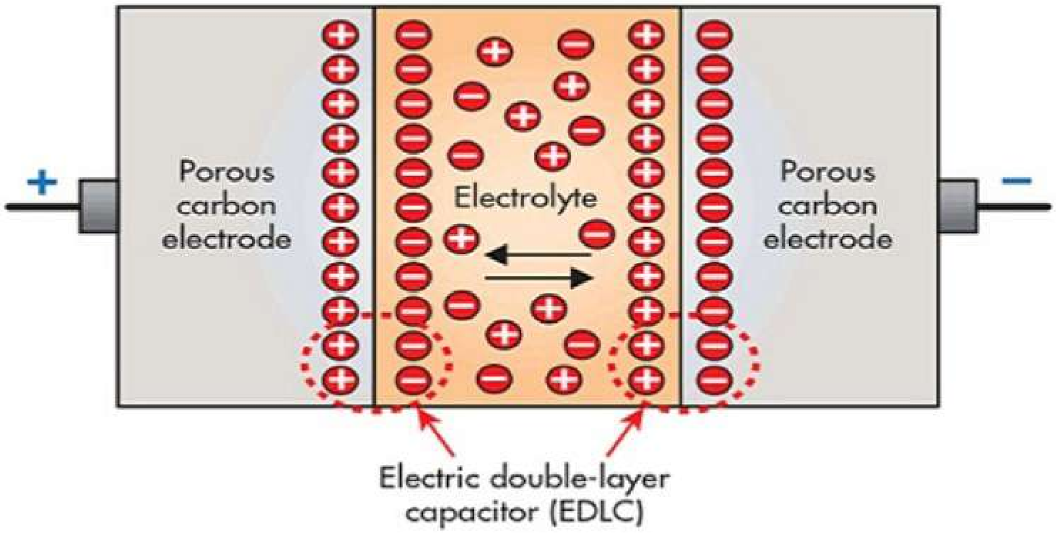
Considering the high abundance, environment friendliness, low cost, high capacity, and low operation potential of silicon-based anode, it has been intensively studied as one of the most promising anode materials for high-energy LIBs. Pure silicon has 10 times the capacity of graphite while silicon oxide (SiOx) capacity is about 5 times. However, the widespread application of silicon anode is impeded by the poor electrical conductivity, large volume variation, poor first-cycle efficiency, and unstable solid electrolyte interface (SEI) films.[10] Silicon is a promising anode material for lithium-ion and post lithium-ion batteries but suffers from large volume change upon lithiation and delithiation. The resulting instabilities of bulk and interfacial structures severely hamper performance and obstruct practical use. For anodes with 100 per cent active silicon (Si or SiO), cycle life still remains a challenge.

To take advantage of the higher capacity of silicon materials, industry is using a blend of silicon (especially SiO) with graphite in the anode. Currently, these anodes contain about 5 per cent SiO (rest is graphite), and this is expected to increase to 10 per cent or more in the coming years. The silicon-graphite anode technology is a drop-in for the existing cell manufacturing plants with pure graphite anodes, requiring no additional investment at the plant.

Supercapacitors

Like batteries, supercapacitors are electrical energy storage devices, however their working principle is fundamentally different. While batteries store energy through chemical reactions at the electrodes, supercapacitors store energy in the form of electric fields through charge accumulation at the electrodes by means of an electric double layer effect[11] (See Figure 4: Working principle of a Supercapacitor).

Figure 4: Working principle of a Supercapacitor



Source:https://www.kynix.com/Blog/Electronic-Tutorial-Supercapacitor-s-Basic-Working-Principle-and-Applications-related-video.html

Therefore, supercapacitors are also referred to as Electrochemical double layer capacitors (EDLC). This operating principle bestows them with complementary characteristics with respect to batteries.

Supercapacitors have a specific power 5 to 10 times greater than that of batteries. For example, while Li-ion batteries have a specific power of 1 - 3 kW/kg, the specific power of a typical supercapacitor is around 10 kW/kg. The gains in power density come at the cost of reduced energy density. The energy density of batteries is higher (50-150 Wh/kg) due to the bulk of the electrode being able to contribute to charge storage, whereas in supercapacitors (1-10 Wh/kg), only the surface can be exploited.

Thus, the supercapacitor is a power device and is ideal for applications that require quick bursts of energy to be released from the storage device. They can be used for EV applications like peak current requirements (high torque) and for harvesting regenerative braking energy in conjunction with the primary traction battery.

Supercapacitors are safer than ordinary batteries in abuse situations. They possess low internal resistance, do not undergo thermal runaway and do not explode in the event of a short circuit. Supercapacitors can be charged and discharged millions of times, while charge-discharge cycles of lithium-ion batteries range between 500 to 10000 cycles. This makes supercapacitors very useful in applications where frequent storage and release of energy is required.

The most commonly used material in modern supercapacitors is activated charcoal. Another exciting material used in supercapacitor research is graphene. Energy densities achievable using graphene in supercapacitors are comparable to energy densities found in batteries and are the most promising candidates for future supercapacitor technology advances. Efforts are also on to improve supercapacitor energy density by using next-generation electrolytes and battery-supercapacitor hybrids.

Long term cell chemistry options

Sodium Ion Batteries (SIBs)

Rechargeable sodium-ion batteries (SIBs) are attractive large-scale energy storage systems compared to Li-ion batteries due to the advantages it offers with easy material accessibility and low cost of resources. The recent rapid development of SIBs will no doubt accelerate the commercialization process. Sodium is the seventh most abundant element and 1,200 times more common than lithium[12]. Sodium compounds are synthesised from sea water and limestone, via established processes. In the future, secure supply and predictable and lower price seem likely. Another advantage with SIBs is the absence of copper and cobalt in the chemistry. SIBs use aluminium as current collectors in place of copper. Second, the cathode composition does not have cobalt, which is difficult to obtain (mined mainly in Democratic Republic of Congo) and often comes with dubious environmental, social and governance (ESG) parameters in the supply chain. (See Table 2: Comparison of sodium-ion and lithium-ion cell)

Table 2: Comparison of sodium-ion and lithium-ion cell

Parameter	Sodium ion cell	Lithium-ion cell
Energy Density	17-160 Wh/kg - potential of 200 Wh/kg	160 ± 10 Wh/kg LFP to 275 Wh/kg NMC
Safety	low risk of thermal runaway	can overheat and catch fire
Cycle Life	still not proven	high number of cycles
Low Temperature Performance	>90% performance at -20 degrees Celsius	drops considerably in cooler temperatures
Electrolyte	Na salt (NaPF6, NaClO4) in organic solvent	Li salt (LiPF6, LiTFSI) in organic solvent

Source: TCG Crest

SIBs can be a good candidate for large segments of the Indian market, if an adequate life cycle can be achieved. It can work well at elevated temperatures and can be stored and transported at a state of charge (SoC) close to 0 V (zero Volt). In comparison, lithium-ion batteries have to be transported at a predefined charge state (30 per cent) to prevent dissolution of the copper current collector. This makes lithium-ion batteries unsafe for air transportation. However, SIBs lag behind LIBs in terms of energy density and specific capacity because sodium is three times as heavy as lithium and has a lower standard electrochemical potential despite having a similar outer atomic structure.

SIB Cathode: While abundance of sodium will enable India to become self-sufficient in terms of SIB production, its overall operating costs still need to be optimised in comparison to LIB. There is a large body of research on SIB, most of which is focussed on achieving long cycle life and high energy density in the cathode material. Other challenges with SIBs include inconsistencies in chemical composition during large-scale manufacturing of the salts which have displayed consistent laboratory performance. Research is also focused on devising more sustainable means to produce hard carbon, the preferred anode material for SIBs. Over the past 20 years, research for cathode materials in SIBs has been mainly centred around layered oxides, polyanions[13], and PBAs (Prussian Blue analogues[14]). On average, layered oxides exhibit a higher specific capacity and energy density compared to polyanions and PBAs, owing in part to their lower molar mass, but they typically suffer from shorter lifetimes.

SIB Anode: Most SIB researchers and now even manufacturers are using graphite and graphene as anode materials. Most importantly, carbon allotropes are used as anodes because of their high valency[15] of 4. Graphite has layers of carbon spatially arranged in the densest form, whereas graphene is a two-dimensional carbon allotrope. However, unlike the application in LIBs, sodium ions can hardly electrochemically intercalate into graphite layers because of its larger radius, so it is accepted that graphite does not exhibit a desirable intercalation ability for sodium ions.

Alternative anode options to graphite include synthetic graphite and hard carbon. Of the two, hard carbon is cost effective because of its lower energy requirement during manufacturing. Synthetic graphite needs manufacturing temperatures of around 2000 °C, while hard carbon can be manufactured at temperature ranges of 1200 °C-1300 °C. In general, hard carbon cannot be graphitised even at very high carbonisation temperatures due to the high oxygen and disordered structure of the precursors. They are disordered structures with randomly-oriented graphitic domains, higher interlayer spacing and some remaining heteroatoms (mainly oxygenated groups).[16] Scientists in India are also exploring cost-effective and sustainable raw materials (such as sugarcane residue and other bio-waste) for manufacturing hard carbon.

SIB Electrolytes: These play a key role in the cell with impact on the overall lifetime, rate capability and safety of the battery. The current range of sodium ion battery electrolytes have significant drawbacks, such as, moisture sensitivity, cost, and toxicity. There is an urgent need to develop novel electrolytes to overcome these shortcomings. Electrolytes can cause unwanted side reactions and degradation products that significantly affect the overall performance and lifetime of the battery. Similar to LIBs, the most promising salt to date for SIBs is sodium hexafluorophosphate (NaPF6). However, its high moisture sensitivity can promote the formation of hydrogen fluoride (HF) via hydrolysis, leading to further electrolyte degradation and major safety concerns. In recent times, the use of computational modelling and simulation has become a much more powerful method for the development of high-performance electrolytes.[17]

Lithium Metal Batteries

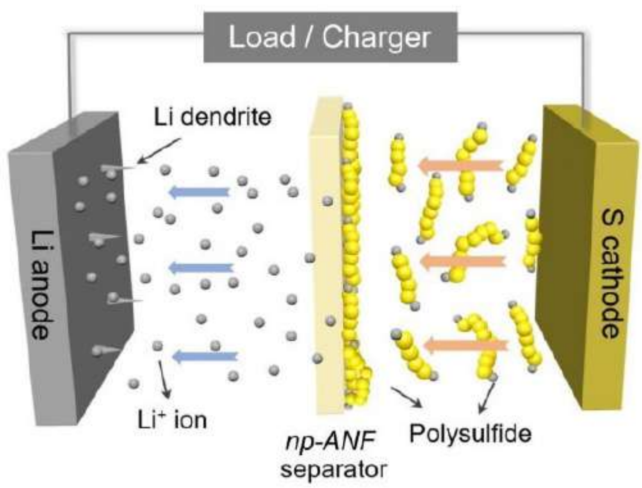
In general, Li metal battery refers to any type of battery that utilizes Li metal as the anode. Lithium metal is an ideal anode with the highest specific capacity (3,860 mAh/g) and the lowest electrochemical potential (−3.04 V versus standard hydrogen electrode [SHE]) [18]. Having ten times the theoretical specific capacity of graphite anodes (372 mAh/g), Lithium metal anodes can potentially enable batteries with the highest specific energy. However, this technology has not yet been commercialized due to issues which arise during cycling like dendrite formation, corrosion of lithium, dead lithium and volume expansion.

Lithium Sulphur Battery

The lithium-sulphur battery (LSB) is one of the most promising candidates of the lithium metal battery family. It has a high theoretical specific capacity of 1675 mAh/g[19]. Sulphur is the raw material of the LSB cathode (see Figure 5: Schematic configuration of a Lithium Sulphur cell). It is inexpensive, abundantly available and non-toxic thus proving to be a more economical and environment friendly option compared with Lithium-ion batteries. This makes it particularly suited for India specific applications like electric 2W and 3W.

The obstacles to commercialization include the low conductivity of the sulphur element and discharge product lithium sulphide, the shuttle effect of lithium polysulphides in the electrolyte, sluggish electrochemical reaction kinetics of the sulphur cathode, and the huge volume changes for both electrodes upon lithiation and delithiation[20]. The use of inorganic solid electrolyte to prevent polysulphide dissolution presents exciting possibilities as a step towards achieving technology commercialization. This is expanded further in the next section on Solid State Batteries.

Figure 5: Schematic configuration of a Lithium Sulphur cell



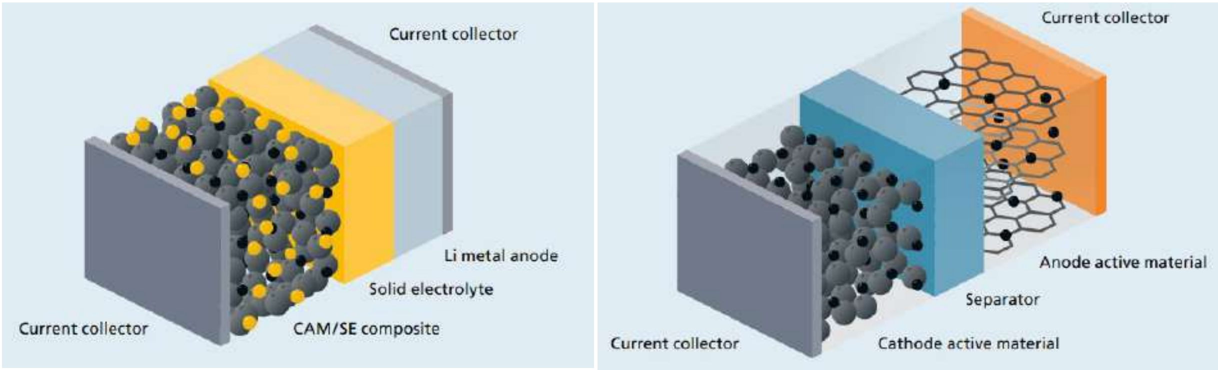
Source: Wang, M., Emre, A.E., Kim, JY. et al 2022 Multifactorial engineering of biomimetic membranes for batteries with multiple high-performance parameters. Nat Commun 13, 278, available at https://doi.org/10.1038/s41467-021-27861-w

Solid State Batteries

Solid State batteries are the frontier technology for achieving safe and high energy density storage. They provide a pathway to integrate high capacity lithium metal anodes. This is enabled by utilizing a solid electrolyte separator instead of conventional liquid electrolytes. Organic liquid electrolytes are widely used for their high ionic conductivity and wettability but pose safety and performance challenges.

Moreover, solid electrolytes exhibit improved temperature tolerance, do not leak and are non-flammable. Studies have shown that solid electrolytes can adapt to higher-than-ambient temperatures (603–120°C), which may make them more suitable for Indian conditions[21]. (See Figure 6: Solid-state Cell (L) vs Liquid electrolyte cell(R))

Figure 6: Solid-state Cell (L) vs Liquid electrolyte cell(R), The difference is the replacement of the separator and liquid electrolyte (at least partial) with a solid electrolyte (SE). The ionic conduction between solid electrolyte and Active Material has to be established by creating intimate contact.



Source: Fraunhofer ISI 2022, Solid-State Battery Roadmap 2035+

There are several material level issues which need to be overcome for successful commercialization of SSB. Interfacial properties between the solid electrolyte and the electrodes play a major role in determining the performance of an SSB. While in all-solid-state batteries, the liquid electrolyte is completely replaced, several solid-state battery concepts have initially used liquid electrolytes as catholyte or anolyte to guarantee sufficiently high ionic conductivity, especially at the interface between the electrolyte and the active materials.

Currently, three groups of solid electrolyte (SE) materials offer promise, namely oxide electrolytes, sulphide electrolytes and polymer electrolytes. Oxide electrolytes generally exhibit high mechanical and chemical stability, but require high-temperature processing (sintering), are brittle and have relatively poor ionic conductivity. The production of oxide SSBs is much easier when compared to sulphides. The garnet-type is one of the best known and most promising material sub-class within the oxides.

Sulphide electrolytes are mechanically softer and more malleable than oxide electrolytes and easier to process since they do not require sintering. Sulphides offer high ionic conductivity among solid electrolytes. The superior conductivity of sulphides compared to oxides is due to greater polarizability of sulphur atoms compared to oxygen atoms. As a result, the Li-ions have a weaker interaction with the sulphur atoms and exhibit higher mobility. Amorphous nature of sulphide allows for good wettability. But the sulphide electrolyte materials are currently available only at a research scale and the chemical compatibility with Li metal and high-potential Cathode Active Material (CAM) is limited. It is not stable against metallic Lithium. A small amount of moisture is sufficient to produce H2S gas. Therefore, scalability of sulphide SSBs is a challenge.

Polymer electrolytes are the most established among all SE in terms of material availability and production technologies. They are considered as an intermediate technology between liquid electrolytes and solid electrolytes. But they have limited ionic conductivity at room temperature and poor chemical compatibility with high-potential CAMs. Other types of SE are being developed (e.g., halides[22]), but they are still in an early state of research.[23]

Although solid electrolyte cells offer much better thermal stability than liquid electrolyte cells, several challenges including low ionic conductivity, poor wettability, low stability/ incompatibility between electrodes and electrolytes, etc., may degrade performance, hindering the development of practical applications.

Several companies have invested in solid state battery technology. For example, Volkswagen announced investment of USD 200 million[24] in Quantum Scape with expectations of producing a million electric vehicles by 2025. BMW released details of a US$ 20 million[25] deal in 2022 with Solid Power to scale up the production of solid-state batteries. Toyota[26] and Hyundai have announced the launch of their solid-state battery EV in 2025.

Development of indigenous cell & battery manufacturing

While at one level, demand focused incentives like the FAME I and FAME II are expected to catalyse the market and strengthen charging ecosystem, on the other hand, production linked incentives (PLI) for Advanced Chemistry Cell (ACC) are expected to promote localisation of battery cell manufacturing and increase its domestic availability.

There is strong interest by the government in developing and expanding local manufacturing capacity which helps to reduce the cost of energy storage, enable scaling up of the electric vehicle (EV) industry and reduce imports. Given the constraints of inadequate access to raw material for cell production, import dependence is high, which increases procurement costs. It is estimated that in FY20, India had spent nearly US$865 million to import ~450 million units of lithium-ion batteries.[27] Active policy interest in promoting manufacturing of lithium-ion (Li-ion) cells started around 2020. Resource availability is a challenge but India is negotiating procurement of ores or concentrates. At the same time material recovery from end of life batteries can further improve resource security.

Typically, the battery raw material lithium comes either from spodumene ore or from salt flats (hard rock mining or brine pools) which is processed into lithium carbonate or hydroxide. Lithium carbonate or hydroxide is combined with metals like Nickel, Cobalt or

Iron (depending on the cell chemistry) by precursor manufacturers to produce the cathode active material (CAM). The Anode Active Material (AAM) involves production of graphite.

The CAM and AAM are combined with binders for mechanical stability and with carbon additives to enable electronic conductivity. These are then coated on current collector metals (aluminium or copper) to build the electrodes. Cell manufactures source other cell components like electrolyte, separators and external casing material to assemble the cells.

In May 2021, the Cabinet approved the Production Linked Incentives (PLI) Scheme on 'National Programme on Advanced Chemistry Cell (ACC) Battery Storage' for achieving manufacturing capacity of 50 Giga Watt hours (GWh) of ACC with an outlay of Rs.18,100 Crore. The first round of the Advanced Chemistry Cell (ACC) PLI bidding was concluded in March 2022, and three beneficiary firms were allocated a total capacity of 30 Giga Watt hours (GWh). These companies were Reliance New Energy Limited, Ola Electric Mobility Private Limited and Rajesh Exports Limited. Since one of the allotees withdrew from the effort, it was retendered and received seven bids for 10 GWh ACC manufacturing with maximum budgetary outlay of Rs. 3,620 crores.

Typically, in a giga-factory, as proposed in the ACC (Advanced Chemistry Cell) PLI scheme, the entire cell manufacturing value chain is expected to be integrated in a single facility to manufacture at a large scale.

The process is underway to set up the first few Li-ion battery-manufacturing plants in states including Tamil Nadu and Gujarat. Planned as an investment incentive, the PLI scheme has influenced private investments to flow into the battery manufacturing sector. According to estimates by Ernst and Young, India's EV industry had attracted investments to the tune of USD 6 billion in 2021, and the industry expects this to reach USD20 billion by 2030. [28]

There is also considerable traction due to emerging state level electric vehicle policy. Several states have proposed incentives for establishing manufacturing hubs for EV and EV components, and R&D. The policies also offer opportunities for recycling and enable circular economy.

India has the opportunity to optimize existing processes and develop new manufacturing processes to implement EV battery design while reducing manufacturing costs and the environmental footprint. Along with scaling up the Technology Readiness Levels (TRL), India needs to simultaneously scale up the Manufacturing Readiness Levels to demonstrate manufacturing preparedness and capability.

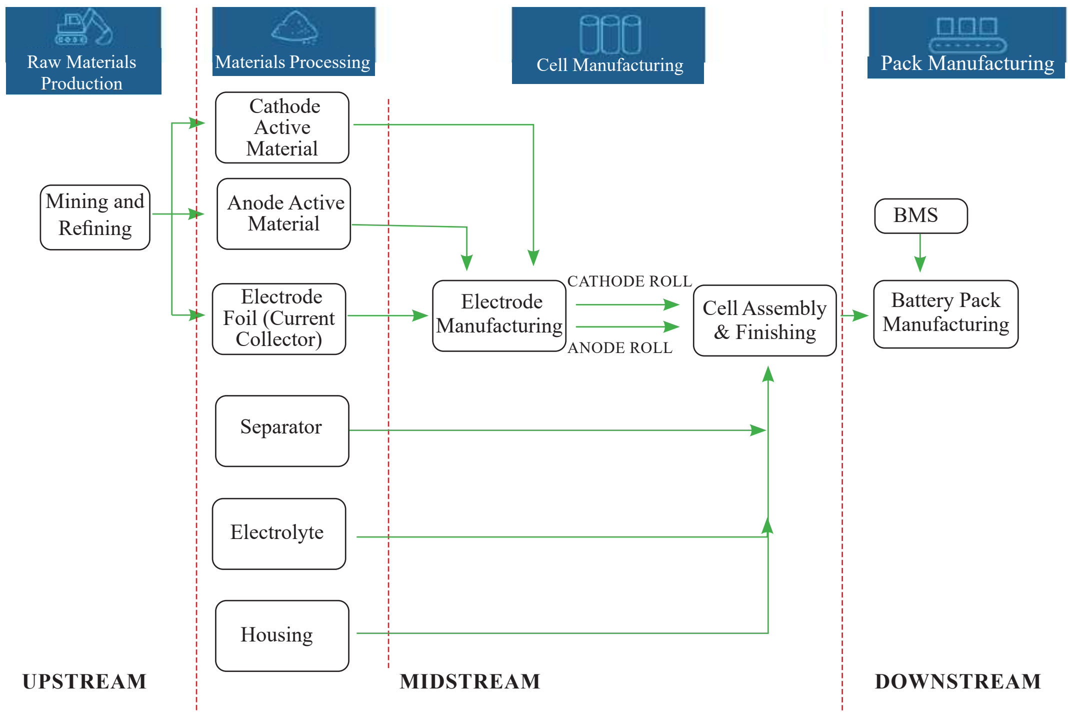
Battery production value chain

Figure 7 shows the value chain in battery production. Cell active materials, especially cathode, are metals oxides. The metals are mined and processed to produce the active materials. Other cell components are produced from various process industries. All these cell components are shipped to a cell manufacturing plant.

Cell manufacturing involves electrode production which involves anode/cathode slurry preparation, coating and drying, and calendaring. The calendared electrodes then go through a cell assembly step to produce pouch, prismatic, or cylindrical cells. The cells are filled with electrolyte and undergo a formation step where the cells are activated and stabilized for their performance.

The cells are assembled into modules and packs and integrated with the battery management system (BMS). The above steps are typical at a cell manufacturing plant. These cells are then shipped by the cell supplier to battery plants for module/pack manufacturing.

Figure 7: Sub-processes of a battery production value chain



Source: Centre for Science and Environment

Challenges with setting up battery ecosystem

How the supply chain and value chain around battery manufacturing will evolve in India will depend on the development of each aspect of the battery ecosystem that consists of sourcing of battery materials and critical minerals, chemical processing of raw material to intermediate compounds, active material production, cell production, assembly of battery packs, secondary use of battery and recycling of battery materials.

All these stages have not yet developed adequately or uniformly in India. Battery module and pack assembly is currently the only activity in the battery value chain which is established at an industrial scale. Cell production has taken place only at research and pilot facilities. This makes India highly import-dependent on raw materials and cells from

China, Japan and Korea, increasing vulnerability to a volatile global market. Currently, local capacity for assembly of the cell modules, battery packs and battery management systems are evolving but at much lower volumes.

It is noteworthy that Indian battery manufacturers find it challenging to even negotiate competitive terms with suppliers in the global cell market because of lack of scale. Indian manufacturers have explored the option of starting with smaller production goals to streamline processes before graduating to multiple assembly lines. The most basic components (battery-grade Copper and Aluminium sheets) are not available in India. They too need to be imported. Hindalco, a leading Indian aluminium manufacturer makes battery grade Aluminium through its subsidiary, Novelis in the US but does not have an equivalent in India. Lack of sufficient demand could be cited as a reason for this anomaly, but with upcoming cell manufacturers in India this situation will likely change.

Graphite is manufactured in the country but not at the scale required by India's aspirations in battery manufacturing. Additionally, it must be noted that given the uncertainty of critical minerals like Lithium, economies like the US are introducing protectionist policies like the US' Inflation Reduction Act 2022[29]. In such a scenario, the barriers to entry in the global EV market are only rising higher and higher.

Key Considerations for building indigenous cell manufacturing capability

Material Sourcing

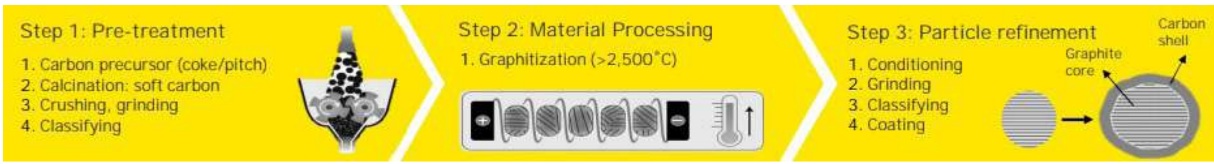
The vision of battery gigafactories requires equivalent 'material gigafactories' to scale material supply capacity. According to the Ministry of Mines, India imports nearly 70 per cent of its Li-ion cell requirements from China and Hong Kong[30]. Looking at the current scenario of the battery production value chain, policies for localization of upstream processes like raw material sourcing, manufacturing & refining are missing from the discourse. To have a strong hold of the supply chain capacity, building of upstream material manufacturing cannot be ignored. In this context, a thrust on SIB manufacturing can allow India to build self-sufficient upstream supply chains which are free from critical metals such as Lithium, Nickel and Cobalt.

The CAM makes up for a large part of cell weight and cost. The CAM supply chain is long and expensive with a significant environmental footprint. The CAM production process is complex and requires multi-chemical transformation stages to get a pure mix of active materials. It involves sub-processes like transition metal sulphate precursor production, hydroxide-driven precipitation, the addition of lithium salt using solid-state mixing and high-temperature calcination over extended timeframes.

It is important to ensure that the starting materials are of high purity to finally enable the smooth transport of lithium ions in the finished cell. Quality metrics like particle size distribution, particle shape and morphology are ensured using spectroscopy and x-ray diffraction techniques. Equipment required include stirred tank reactors, ploughshare mixers, jet mills and dryers.

Anodes for LIB cells are made of spherical graphite or battery-grade graphite. Its production involves processing/refining natural or synthetic graphite to have the optimum shape, particle size, and crystalline properties suitable for lithium intercalation chemistry. India has a notable Petroleum Coke production capacity which can be used to produce synthetic graphite (See Figure 8: Synthetic graphite to battery grade graphite processing). Companies like Epsilon Advanced Materials are engaged in graphite anode material production. India can take the lead in Silicon and graphite based composite anodes which has potential to increase energy density in an LIB.

Figure 8: Synthetic Graphite to battery grade graphite processing



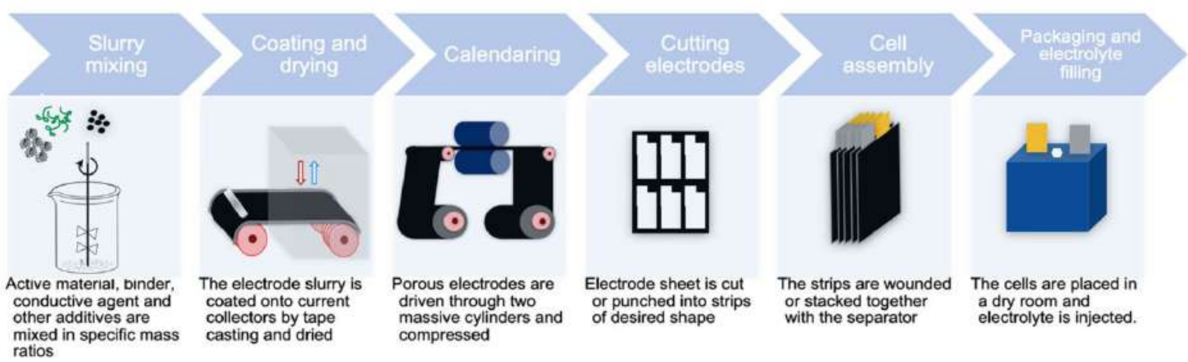
Source: Niti Ayog[31]

Even in electrolyte supply, China dominates global supply chains. India has an opportunity for electrolyte manufacturing, leveraging its substantial industry experience in pharmaceutical manufacturing.

Cell Production

To deliver desirable electrochemical performance, the multistep manufacturing process of cells needs to be closely controlled (see Figure 9: Production steps of a lithium-ion battery cell from electrode manufacturing to battery packaging). Annexure 1 shows a list of equipment used in cell manufacturing.

Figure 9: Production steps of a lithium-ion battery cell from electrode manufacturing to battery packaging



Source: Bryntesen, et al. 2021, Opportunities for the State-of-the-Art Production of LIB Electrodes—A Review. Energies

To drive indigenous manufacturing of batteries, R&D for manufacturing equipment and special purpose machines also needs to be incentivized to develop modular cost-effectiveness Significance of process quality and high precision equipment to mitigate safety risk in manufacturing are discussed below.

Electrode Manufacturing

The electrode is at the heart of a lithium-ion cell, and its performance depends on the quality of materials used and the manufacturing process. Below are the steps:

Slurry preparation: This uses raw materials such as active materials, conductive additives, solvents and binders. The mixture needs to have consistent physical properties (homogeneity, rheology and stability of dispersions) and formation of agglomerates

Coating and drying: This involves coating the electrode material on current collector foils with the slurry that contains the active material, binder, and conductive additives. The coated electrode is passed through heating zones and dried and rolled. Coating on foils has to be even across the width of the foil and adhere well to the substrate foil.

Calendaring is the densification [compression] stage for the active materials on the foil. This process results in the increase in volumetric capacity of the battery, improved electrode adhesion and rate capability of the battery (due to an improvement in particle-to-particle contact between the active material and the conductive carbon additives). It reduces layer porosity induced by the evaporated solvent during the drying process.

Slitting is a separation process in which a wide electrode coil (mother roll) is divided into several electrode coils (daughter rolls) to be used for cell assembly. The cut quality of the electrode edges and the cleanliness of the coils are the main quality criteria.

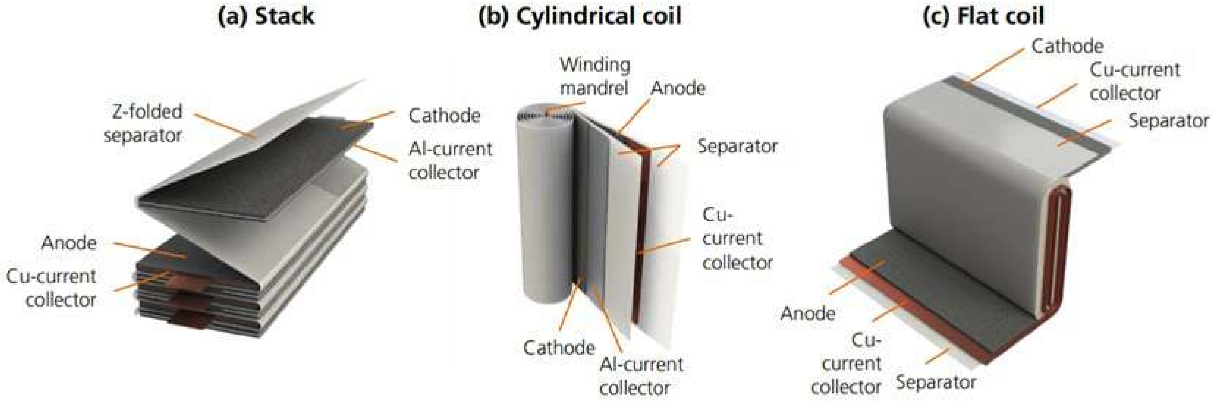
Cell Assembly

The next step is to assemble the electrodes into a cell, which involves placing the anode and cathode into a container and filling it with electrolyte. The cell format can be of three types- cylindrical, pouch and prismatic, based on the packaging of the electrodes and separator sheets. Cell format goes on to have implications for overall battery design, thermal management and battery management system (BMS).

Cell Stacking and Winding

This involves integration of the electrodes together with a separator and current collectors. The cell quality and the electrical properties of the battery depend significantly on the cell stacking process. The exact positioning of the individual sheets is critical. The different methods to create the stacks, such as winding, stacking or z-folding depend on the desired cell format (See Figure 10: Basic techniques of electrode assembly: (a) with pre-cut electrodes in a stacking process, (b) cylindrical coil of continuous electrode on a winding mandrel, (c) flat coil of continuous electrode).

Figure 10: Basic techniques of electrode assembly: (a) with pre-cut electrodes in a stacking process, (b) cylindrical coil of continuous electrode on a winding mandrel, (c) flat coil of continuous electrode



Source: Steffen Link, et al. 2022, Development perspectives for lithium-ion battery cell formats, Fraunhofer Institute for Systems and Innovation Research ISI

Cell Packaging

The completed stacks are inserted into a case and the current collector foils are welded with the cell tabs. It is important to ensure low contact resistance as well as low mechanical and thermal stress during the welding process.

Electrolyte Filling

The cell is sealed on all sides leaving a small opening for electrolyte filling. The sub-processes at this stage include dosing of electrolyte liquid, sealing of the cell and stimulation of electrolyte to enhance spreading within the cell. The electrolyte is filled in a vacuum (filling) with the help of a high-precision dosing needle. By applying a pressure profile to the cell (supply of inert gas and/or generation of a vacuum in alternating operation), the capillary effect in the cell is activated (wetting). The filling apparatus comprises a pressure system, a dosing system and a mounting device.

The cell assembly and electrolyte filling stages require dry rooms with lowest dew points of -40 to -60°C. Presence of moisture inside the cell leads to heavy quality losses (service life) and safety risk (formation of acid). Residual humidity affects the ageing and degradation characteristics of the cell. The design and operation of such a dry room adds to the cost of the battery. Assembled cells are left in a drying oven for hours to days to reduce humidity. Longer drying periods improve durability but increase production cost due to longer oven use.

Cell Formation

Cell formation is a "cell conditioning" step after cell assembly which is crucial for safety. In this step, each cell is connected to a cycler and subjected to a charge-discharge protocol, usually a few cycles under slow C rate to form a solid electrolyte interphase (SEI) layer. The SEI layer is formed on the anode and it helps separate the active material in the cell, especially the anode, from the electrolyte. The SEI layer is a few nanometres thick, allows lithium ions to pass through but is impermeable to the electrolyte. Thus, the SEI layer protects the active materials from electrolyte attack while allowing the electrochemical process to proceed.

The quality of the SEI layer strongly influences the performance and safety of cells. The aim of the formation process is the optimal composition and homogeneity of the passivation layer. The ideal SEI contains an inorganic layer close to the electrode and a porous organic or polymeric layer close to the electrolyte. The layer should be 50 to 200 nm thin and homogeneously distributed on the surface of the anode[32]. The formation protocol is usually proprietary information for cell manufacturers.

End of Line (EoL) Testing

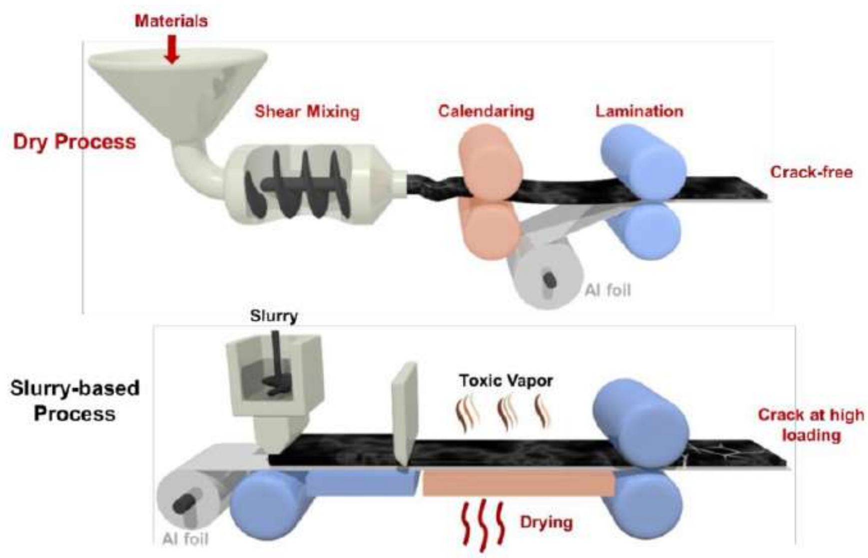
The cell undergoes further quality checks for relevant parameters such as capacity, internal resistance, self-discharge, rate capability, weight and dimension. The EoL testing results allow the sorting of the battery cells by quality in a downstream process called "grading" or "classification."

Recent advances in cell manufacturing technology

Dry coating

The manufacturing process can be shortened with **dry coating** of electrodes, a new technique of electrode fabrication, which utilizes a shortened "powder–film" process instead of the conventional "powder–slurry–film" wet-solvent process. Dry coating technology works without the use of solvents and provides significant savings in energy consumption, processing time and costs since the energy-intensive drying step and solvent recovery become obsolete (See Figure 11: Schematic of dry electrode and slurry-based cathode fabrication procedures and Table 3: Comparison of Wet and Dry Coating)

Figure 11: Schematic of dry electrode and slurry-based cathode fabrication procedures



Source: Yao, et al 2022, A 5V-class Cobalt-free Battery Cathode with High Loading Enabled by Dry Coating, 10.26434/chemrxiv-2022-nssm2

Table 3: Comparison of Wet and Dry Coating

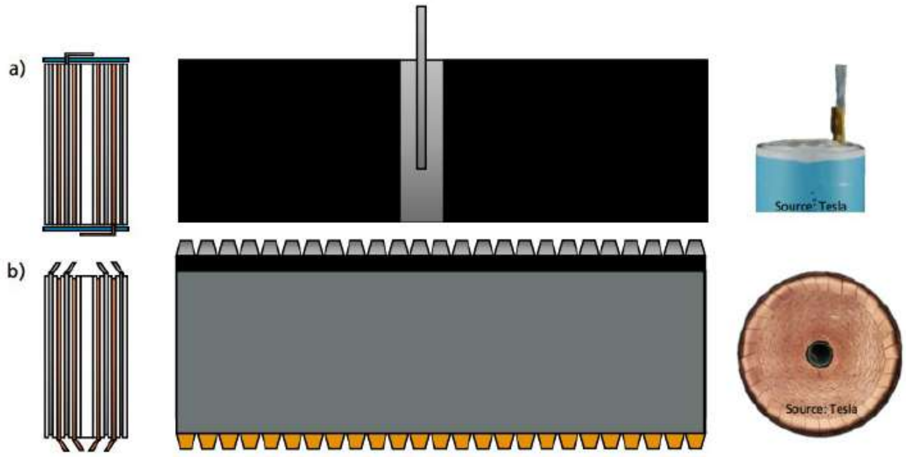
Property / measure	Wet Slurry Coating	Dry Powder Coating
Solvent	Expensive, hazardous and has to be handled in a closed loop recovery system	No need for solvent
Mixing Process	Two step mixing process needed to achieve required level mixing.	Single step dry mixing is sufficient and with lower binder PVDF content
CAPEX	Higher	Lower
OPEX	Higher	Lower
Loading of Solids in the mix	Restricted to 50-60%	Higher solids content per unit area
Uniformity of coating	Higher	Low
Strength of coating adhesion	Moderate	Low
Drying Process	Drying step required before roll – compaction	Direct hot rolling
Microstructure	Moderate	Better microstructure control of particle- particle interface + carbon over-layer
Electrochemical performance	Moderate	Better electrochemical performance and better conductivity & bonding are achieved
Change over between coatings of Anode & Cathode	Requires lot of time for cleaning of equipment	faster
Energy consumption	Higher- due to drying and solvent recovery	lower
Human resource	Higher Man hours	Lesser man hours and supervision

Source: CSE Research

Tabless cell design

Low contact resistance for large format cells can be achieved with tabless design. Tabless design in a cell makes use of the direct connection between continuously uncoated segments of the current collector foils with the cell contacts (See Figure 12: Electrode and jelly-roll design of a) conventional cell and b) tabless cell design). This technique can dramatically increase the contact area between the current collector and cell contacts thereby improving thermal and electrical conductivity.

Figure 12: Electrode and jelly-roll design of a) conventional cell and b) tabless cell design



Source: Steffen Link, et al. 2022, Development perspectives for lithium-ion battery cell formats, Fraunhofer Institute for Systems and Innovation Research ISI

Tabless design has found increased application because of the quest for higher and higher energy dense cells with larger cell formats. Global manufacturers are moving away from the 18650 and 2170 sizes to 4860. This is possible with new assembly techniques that enable more volume-efficient interior cell structures to increase energy density further. This also impacts thermal and electrical interconnection, e.g., through tabless design or, in general, the integral use of cell housing for heat dissipation.

SSB Manufacturing Process

While Sodium Ion batteries can be a drop-in replacement in a LIB manufacturing line, SSB manufacturing would require some redesign. According to Fraunhofer's Solid-State Battery Roadmap 2035+, between 20 per cent and 60 per cent of the state-of-the-art LIB production can be directly transferred to the SSB manufacturing process. Table 4 indicates which process steps are transferable from the manufacturing process of current. The colour code illustrates the transferability of production. Green indicates that the process is the same or can be largely adapted from current LIB production, yellow signifies that the process has overlaps but also has some distinct differences and a process marked orange is fundamentally different.

Table 4: Production steps of different chemistries

Production Steps	Lithium-Ion	Oxide SSB	Sulfide SSB	Polymer SSB	Long-term goal
Anode	**Wet processing** Slurry mixing and coating, drying, calendering	**Extrusion process (Li-foil)** Extrusion, calendering, lamination	**Extrusion process (Li-foil)** Extrusion, calendering, lamination **Wet processing (Si-based anode)** Slurry mixing and coating, drying, calendering	**Extrusion process (Li-foil)** Extrusion, calendering, lamination	In-situ Li anode formation
Cathode composite	**Wet processing** Slurry mixing and coating, drying, calendering	**Wet processing** Slurry mixing and coating, drying, low-temperature sintering	**Wet processing** Slurry mixing and coating, drying, calendering	**Extrusion process** Extrusion, calendering	Dry processes or green solvent-based processes
Separator	**Extrusion process** Dry extrusion process (PP) Wet extrusion process (PE)	**Wet processing** Slurry mixing and coating, high-tem- perature sintering, lamination, low-temperature sintering	**Wet processing** Slurry mixing and coating, drying, calendering	**Extrusion process** Extrusion, calendering	Dry processes or green solvent-based processes
Cell-Assembly	**Cell-Assembly** Stacking, tab wel- ding & packaging, electrolyte filling, formation, degassing and sealing, aging	**Cell-Assembly** Stack pressing, no electrolyte filling and degassing, formation and aging shorter than for LIB	**Cell-Assembly** Stack pressing, no electrolyte filling and degassing, formation and aging shorter than for LIB	**Cell-Assembly** Stack pressing, no electrolyte filling and degassing, formation and aging shorter than for LIB	Completely omit formation and aging

Source: Fraunhofer ISI 2022, Solid-State Battery Roadmap 2035+

Cell technology scale-up from research to manufacturing

For the technology to evolve from a research stage to commercial production requires a Technology Readiness Level (TRL) roadmap. It helps define, assess and track the maturity level of a certain technology and its readiness for full-fledged commercialisation. Table 5 shows a typical TRL levels and their descriptions for battery cell manufacturing.

Table 5: Technology Readiness Level (TRL) stages for cell manufacturing

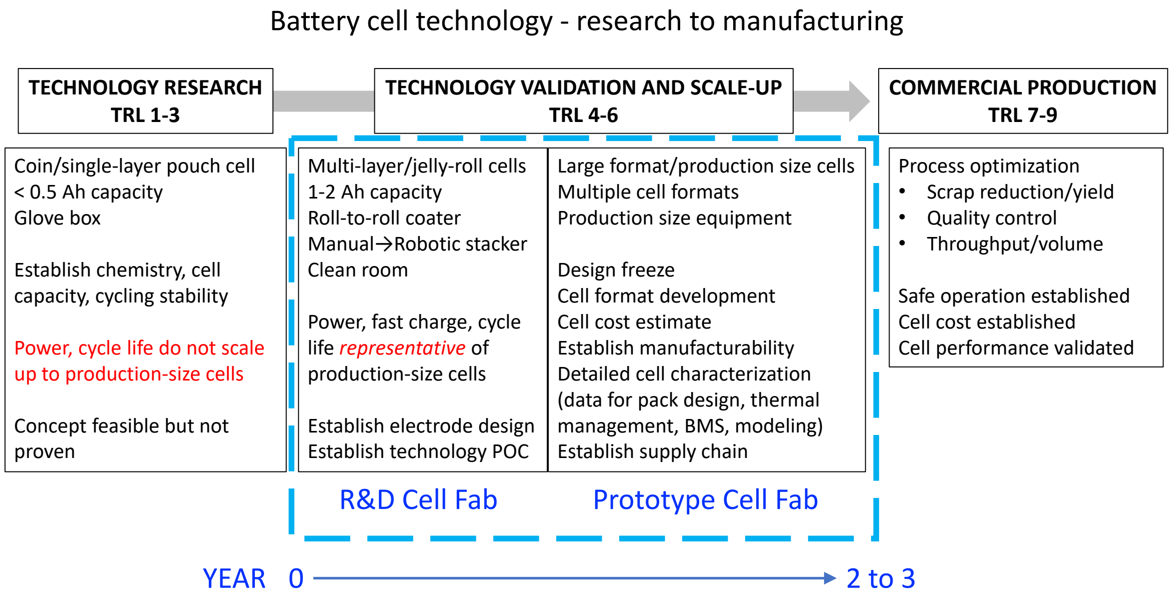
TRL	TRL Activity	TRL Description
TRL 1	Theoretical Concept Development, idea formulation	Define EV applications and scope, basic cell chemistry and design
TRL 2	Determine fundamental component (electrode) properties	Build and test half cells. Establish material electrochemical properties and electrode design/ formulation.
TRL 3	Establish concept feasibility Full cells, small cells: Coin cells, single-layer pouch cells, < 1 Ah	Establish cell electrochemical performance. Performance parameters - Cell Voltage (including open circuit voltage - OCV), cell capacity, cycling stability, first-cycle efficiency. Improve electrode formulation and cell design. Estimate of cell energy density and preliminary cell cost when scaled to a production-size cell
TRL 4	Establish proof of concept Small format, multi-layer pouch cells < 5Ah	Roll-to-roll (or similar high quality) cell fabrication Establish full-cell performance. Performance Parameters – Cycle life (>80% capacity retention in 500 cycles), cell power, fast charge; OCV changes with cycling. Develop physics-based electrochemical cell models as appropriate Build battery state estimators (BSEs)
TRL 5	Establish proof of technology Large-format cell A sample Pilot or prototype scale	Freeze cell design, Bill of Materials (BOM); identify BOM suppliers Performance parameters: Cell cycle life (Typically 1500 cycles at 90% SoH), fast charge and power performance and safety testing Establish charging protocols Identify suppliers for cell components and raw materials Identify and scope manufacturing site Set BMS requirements

TRL	TRL Activity	TRL Description
TRL 6	Establish cell manufacturability – Production size sample Pilot or prototype scale	Full-scale cell performance and safety testing. Verify that cell performance meets vehicle requirements Supplier qualification Cell cost established Safe operation established Start BMS design
TRL 7	Demonstrate full scale cell production capability Production size cells, limited quantity manufacturing scale/ plant	Process capability (quality, throughput defined) Determine process capability and quality Extensive cell testing Preliminary BMS requirements
TRL 8	Full-scale production	Demonstrate continuous operation Optimize production process (quality, yield) Validate process capability, yield, safety, throughput Validate cell performance, safety Complete BMS specifications
TRL 9	Commercialisation Full-Scale operational plant	Demonstrate plant utilization, long-term continuous operation, quality control Supplier and inventory management Customer delivery Assess field data from vehicles and confirm technology robustness

Source: CSE Research

TRL 1-3 is concept development in a laboratory research scale; TRL 4-6 is scale up to prototype, demonstrating proof of concept, design validation, and manufacturability; and TRL 7-9 is full-scale commercial production. Figure 13 shows the steps necessary to take a concept from the research level to full-scale manufacturing. The scale-up step typically involves (a) R&D Cell Fab - fabrication and testing of small capacity multi-layer cells whose performance is representative of (but not the same as) production size cells and then (b) Prototype Cell Fab – where the cells are large format, production size cells whose testing can demonstrate techno-commercial viability of a candidate cell technology for full-scale cell manufacturing and subsequent implementation in EVs. This step takes time (2-3 years) and incurs significant cost. Such a capability will enable scale up of short-term and long-term technologies and other innovation developed at various institutions, and support cell modelling and diagnostics activities. It is a critical requirement in achieving the electric mobility goals in India.

Figure 13. Scale-up of battery cell technology to commercial production



Source: CSE compilation

02

CELL AND BATTERY IMPLEMENTATION IN EVS FOR PERFORMANCE, DURABILITY AND SAFETY

Alongside selecting the right cell chemistry, the battery technology has to address a range of performance parameters related to vehicle range, power, safety, electrochemical stability and durability under real world operations. Cell/pack energy density, power density, cycle life, and thermal stability are important parameters for successful implementation of battery technology and operation of EVs. Cell characterisation data and modelling and diagnostic tools play a critical role in meeting these vehicle requirements.

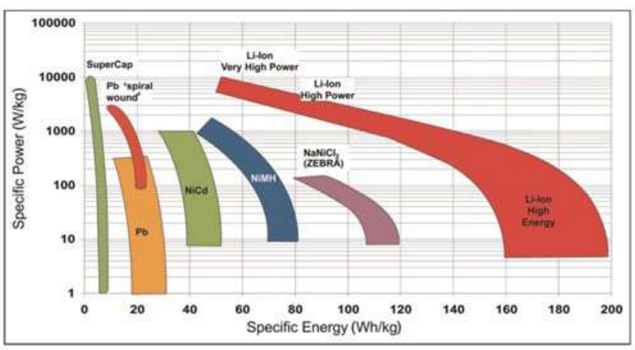
Battery performance – energy and power

Lithium ion batteries typically exhibit a design trade-off between energy density and power density depending on application. With electric vehicles, that becomes a tricky issue as they require both high energy during discharge (high driving range) and high power during charge (fast-charge capability).

In other words, on the one hand, high driving range is desired, requiring high energy and on the other hand, fast-charge capability requires a high power battery. The energy density of batteries for EVs has been rising over the last few years, and now some of the highest performing battery cells can reach energy densities of over 300 Wh/kg, up from around 100-150 Wh/kg a decade ago – meaning that with the same mass, electric cars can now travel twice as far.[33]

Energy density (measured in Wh/kg or Wh/L) and power density (W/kg or W/L) comprise two important performance parameters considered for battery development; the third is cycle life. Energy and power capabilities are strongly governed by the electrode designs, specifically the electrode coating thickness or loading. High energy cells have thicker electrodes (See Figure14: Ragone plot comparison for several rechargeable battery chemistries showing the wide range of performance offered by various Li-ion chemistries) while high power cells have typically thinner electrodes. [34] The cell chemistry - the active materials in the cathode and anode - also plays a role. Higher nickel content inherently increases resistance associated with the cathode. Smaller particle size for the cathode and anode active materials also increases power but at the expense of cycle life.

Figure 14: Ragone plot comparison for several rechargeable battery chemistries showing the wide range of performance offered by various Li-ion chemistries



Source: Heide Budde-Meiwes, et al. 2013, A review of current automotive battery technology and future prospects, Journal of Automobile Engineering

Among different Lithium-ion battery technologies, Nickel Manganese Cobalt (NMC) cathode chemistry offers energy density of up to 220 Wh/kg, while Lithium Iron Phosphate (LFP) chemistry offers energy density of up to 160±10 Wh/kg.

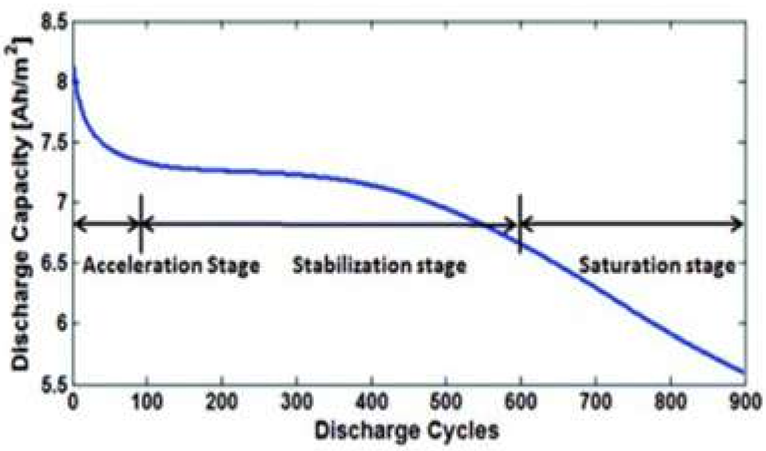
Battery durability

With years of use in a vehicle, the battery ages, and its capacity declines or degrades. The battery reaches its "end-of-life" (EOL) in a vehicle when the battery capacity loss is 20-30% of the initial capacity. Cells degrade due to a combination of cycle and calendar aging, marked by battery cycle life and calendar life.

Cycle life refers to the number of charge-discharge cycles that the battery can undergo without significant performance degradation. Cycle ageing is directly linked with cell use and to the charge and discharge current with respect to its C-Rate, Depth of Discharge (DoD), number of cycles performed and temperature. Charging mode (fast charging or charging at extreme temperatures) and driving style (acceleration, braking) greatly influences cycle aging.

The degradation of battery capacity is not linear and there is the phenomenon of knee point which is the onset of rapid capacity loss. (see Figure 15: Battery aging is divided into three stages: acceleration, stabilisation, and saturation). For well-established NMC-graphite chemistry, the knee point typically occurs at 60 to 70 per cent of initial cell capacity, but varies with cell chemistry - for lithium-metal anode cells this occurs earlier which is a challenge to commercialisation of this technology. Enhanced electrolyte reactions, electrolyte dry-out, break-down of the cathode active material, disintegration of the anode particles, and loss of electrical connectivity within the electrode are some of the phenomena attributed to the rapid capacity loss. The exact mechanism is still not well understood and R&D efforts directed at unravelling this behaviour will be key to the success of new technologies.

Figure. 15: Battery aging is divided into three stages: acceleration, stabilisation, and saturation

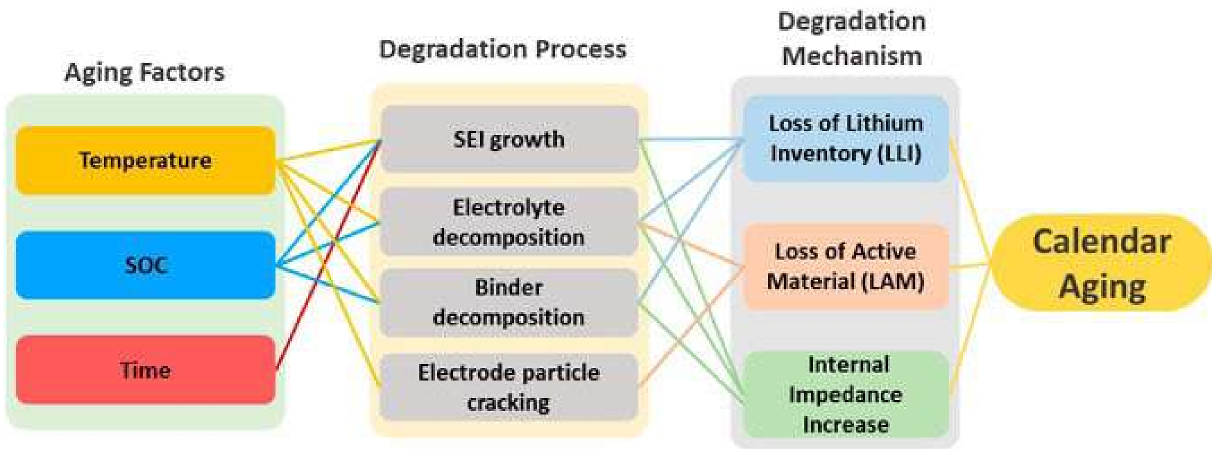


Source: Lin et al. 2013, IOP Publishing

Apart from the above-mentioned performance parameters, manufacturers select cells on the basis of their thermal stability, cost and raw material availability. Cost is an important selection parameter for battery chemistry. Most of the high-performance Lithium-ion battery chemistries like NMC and NCA are not suitable for low-cost applications in Indian two-wheelers and three-wheelers because of the presence of critical minerals like Nickel and Cobalt. Availability of raw material and sustainability of supply chain are increasingly being emphasised by industry, academia and national governments including India.

Calendar life refers to cell aging degradation of the cell independent of charge-discharge, and it is related to the average State of Charge (SoC) during storage, storage time and temperature of storage. In Indian tropical conditions, calendar aging (see Figure 16: Overview of the factors accelerating the overall calendar aging rate) may have a pronounced effect as vehicles are often parked under direct sunlight for long periods.

Figure 16: Overview of the factors accelerating the overall calendar aging rate



Source: Hayder Ali, et al 2023, Assessment of the calendar aging of lithium-ion batteries for a long-term – Space missions, Frontiers in Energy Research

Cycle and calendar aging modify the morphology and integrity of the cell through processes like solid electrolyte interphase (SEI) growth, loss of active material, electrode delamination, and lithium plating. These degradation mechanisms lead to increased cell impedance, which can result in higher cell temperatures. the operational effects include capacity fade and power fade.

Battery safety

Context of fire incidents

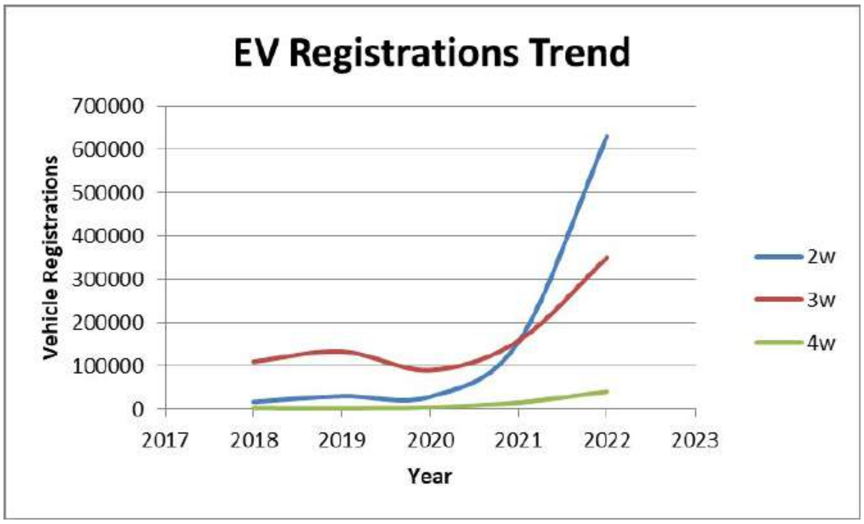
Safety in real world operations is central to the performance matrix of cell technology. Cell development has to focus on thermal stability, operational safety and durability. This requires an efficient Battery Management System (BMS) and Thermal Management System (TMS) to detect and monitor internal health of cells when vehicles are in operation.

It is also increasingly recognised that battery safety management and regulations need to consider the constraints of tropical climate in India. The standards for vehicle testing and engineering that are largely derived from the internal combustion engine regime, need to be adapted to respond to the high ambient temperature conditions in India. This has not been done adequately yet. In addition, the various vehicle segments have their own drive cycles and cooling strategies which need to be considered in the standards.

These concerns have come to the forefront after a spate of fire incidents in 2022, largely affecting low load and small format two wheelers and to a smaller extent light duty. The official investigation into the fire incidents has highlighted several factors that are now held responsible for these incidents. These include quality of cells used, faulty battery pack design, inadequate BMS and weak testing standards.

Driven largely by government subsidy, the low load two wheelers are the fastest growing EV segment today (Figure 17: Registration of two and three wheelers – skewed growth (2017-22). As many as 64 automakers have registered for the FAME 2 subsidy scheme of which 62 are L category[35] manufacturers. A majority of the fire incidents reported in 2022 were in the two wheeler segment and have led to several product recalls. In comparison to the two wheeler segment, there were far fewer thermal events in the larger vehicle categories.

Figure 17: Registration of two and three wheelers – skewed growth (CY 2018-22)



Source: Vahan data, CSE analysis

The expert committee investigating the EV battery fires highlighted several concerns:

» Battery management system (BMS) was found to be seriously deficient across most of the vehicles that caught fire.

» The battery cells used in the electric vehicles did not have a proper venting mechanism, which allows overheated cells to release heat.

- The quality of the cells was also dubious and pointed at several shortcuts taken by electric vehicle makers. Many used an off-the-shelf BMS and the imported cells used were not tested adequately, jeopardizing vehicle and rider safety in the process.
- The investigation brought to light the lack of safety considerations incorporated in indigenous EV battery design due to aggressive product deployment timelines, especially in the L vehicle segment in India.
- It pointed at the lack of an active thermal management system to cool the battery in most cases. Electric scooters have a space constraint within the battery cavity and cost constraints in a competitive market add to the challenges associated with accommodating an active cooling system.
- The fires in the M1 category vehicles (Tata Nexon EV) were attributed to unauthorized maintenance procedures and of M3 vehicle (city bus) to mechanical abrasion of the overhead battery pack with a flyover beam.

Although the expert committee report pointed to lapses by OEMs, what is often missed is safety risks arising all through the battery value chain right from the choice of cell component material in the design phase to quality in the manufacturing phase and abuse during operations. In other words, risk can be associated with various stakeholders in the value chain namely- cell manufacturers, battery pack assemblers, OEMs, charging infrastructure providers and finally even the end-users.

The complexity of risks involved with battery systems makes measuring and understanding battery behaviour and performance a necessary task. And calculating the probability of a thermal incident in a lithium ion battery is not a small ask. When a new technology is onboarded, it takes time to set up adequate practices with compliance to standards. It also requires a systemic platform that tracks and documents battery behaviour and performance.

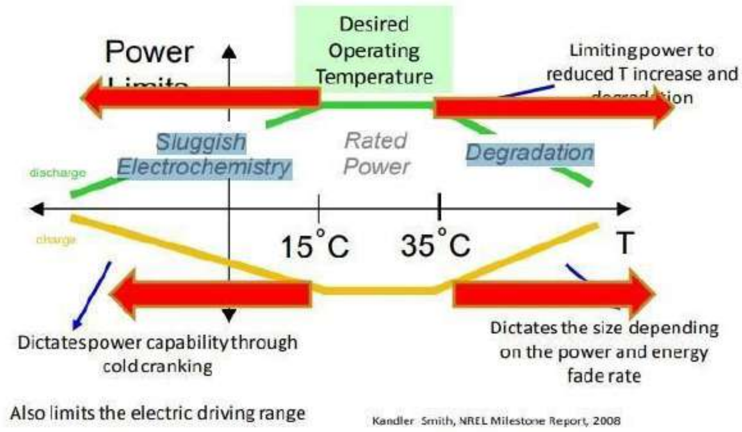
Improving Safety

Even as research is being driven to improve performance of Lithium ion batteries, meeting those milestones with safety parameters is a challenge. Based on expert consultation and literature review several aspects of safety performance have been identified that need to inform the technology pathways.

There are two basic types of battery failure. One occurs at a predictable interval per million and is connected with a design flaw involving the electrode, separator, electrolyte or processes. These defects often involve a recall to correct a discovered flaw. The more difficult cases are random events that do not point at a design flaw. These random events usually creep in at the manufacturing stage and may be handled with statistical quality control. The complete elimination of these manufacturing defects is unavoidable, but instances of their occurrence may be reduced with the adoption of modern manufacturing practices like Six Sigma and Kaizen.

Also, Li-ion batteries that have been exposed to stresses may function normally but they are more sensitive to mechanical and thermal abuse. Therefore, factors such as excessive vibration, elevated temperature and erratic charging behaviour could lead to a safety event. In addition, exceeding the recommended charge current by ultra-fast charging also harms Li-ion batteries. Heat combined with a full charge is said to induce more stress to Li-ion batteries than regular cycling (see Figure 18: Ideal temperature for lithium ion batteries).

Figure 18: Ideal temperature for lithium ion batteries

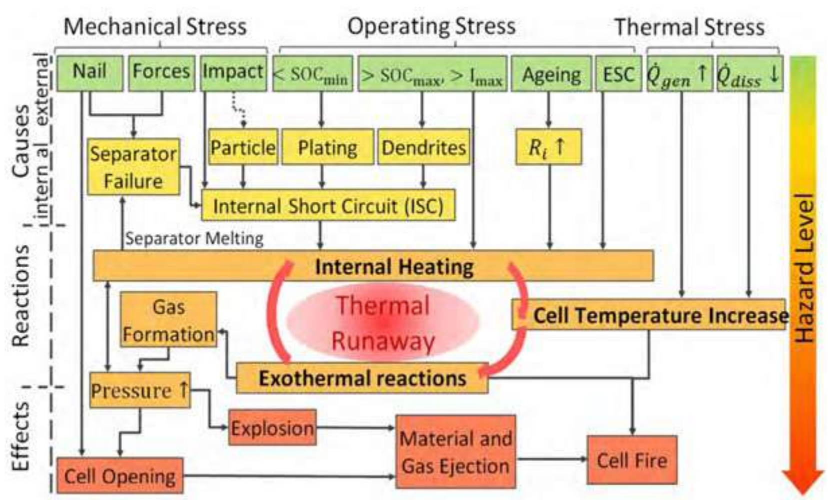


Source: National Renewable Energy Laboratory, US

Inside a battery fire

Battery fires could be caused by multiple failure modes including unforeseen stochastic[36] events. Their causes can be related to key materials (including cathode, anode, electrolyte or separator) as well as cell design and fabrication techniques having significant influence on electrochemical as well as safety performance. The causes could be compromises in mechanical, electrical or thermal tolerance levels that result in internal heating leading to a thermal runaway (see Figure 19: Abuse conditions and failure modes of Li-ion cells).

Figure 19: Abuse conditions and failure modes of Li-ion cells



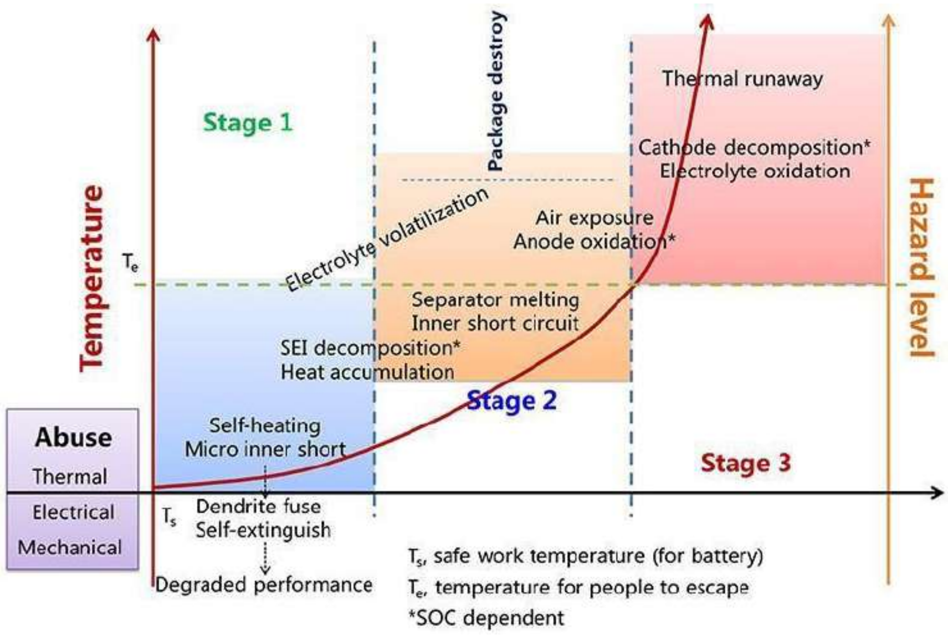
Source: C. Ziebert, et al. 2021, How Calorimetry can help in Battery Research, KIT

A malfunction in an ICE powertrain or an overheated engine leads to a drop in performance or a vehicle breakdown, but a malfunction in an EV can potentially result in a life-threatening fire. More so, in the aftermath of a fire in an EV, the cause of the fire is not easy to identify in comparison to a powertrain malfunction in an ICE vehicle which can be pinpointed accurately.

The most crucial challenge with lithium ion battery systems is that while severity of a battery failure event can be evaluated through testing, the probability of failure can be difficult to determine under the current estimation practices. Thus, the risk assessment and mitigation paradigm of an EV cell & battery requires a significantly different approach because of the considerably higher stakes of the consequences of a mishap.

A thermal runaway process can be mapped in three stages[37] (see Figure 20: Stages of Thermal Runaway) according to the degree of internal short circuit or heat generation speed. The first stage includes self-heating due to micro-shorts caused by preliminary dendrite formation on the anode which may get extinguished if the dendrite[38] gets fused by the heat generated during the short in some cases. If that does not happen, in the next stage, the dendrite grows further, punctures the separator and reaches the cathode. This causes a full internal short circuit, accompanied by further temperature increase. When temperature reaches around 90°C, the solid electrolyte interphase (SEI[39]) on the anode will decompose; as the heat continues to accumulate, the separator melts followed by electrolyte and anode decomposition and side reactions between the electrode materials and electrolytes. All of this contributes to further heat generation. In the last stage, the cathode decomposes, releasing oxygen, which further accelerates a host of exothermic reactions, leading to uncontrollable heating. The rapid rise in temperature and the generation of gases from the reactions lead to cell explosion.

Figure 20: Stages of Thermal Runaway



Source: Xiangkun Wu, et al. 2019, Safety Issues in Lithium Ion Batteries: Materials and Cell Design, Frontiers in Energy Research

Cell safety mechanisms

Lithium ion cells are typically designed to ensure deterrence to thermal events within the cell itself. The first level of safety mechanisms within a cell includes separator fuse, conscious reduction of metal particles within the cell, uniform solid electrolyte interphase (SEI) formation, optimal electrode structure and lithium plating avoidance among others.

Separator fuse: Lithium ion cells have a polyolefin (a type of polymer) separator, which is a permeable membrane with pore sizes ranging from 30 to 100 nm.[14] When the cell experiences a thermal event reaching temperatures of 130 °C, the separator melts, closing the pores, effectively shutting down the cell. Without this provision, heat in the failing cell could rise to the thermal runaway threshold and vent itself along with flames. Some cells have three layers of separators with different melting points for multiple level deterrence. The latest trend is ceramic coated separators that can significantly enhance battery safety by ceasing a potential fire in stage 1. But these separators are very expensive.

The separator should be as thin as possible so as to not add dead volume and still provide sufficient tensile strength to prevent stretching during the winding process and offer stability throughout the life of the battery. The separator's pores have to be uniformly spread to ensure even distribution throughout the separator area and it must be compatible with the electrolyte to allow easy wetting. Dry areas can create hot spots because of poor conductivity and elevated resistance that weaken the integrity of the separator, leading to cell failure. Uneven separators can also trigger cell failure.

Metal particles: Metal particles found in a cell are typically impurities trapped in the cell during the cell manufacturing process. When those microscopic metal impurities come into contact with other parts of the cell, it can lead to an electrical short circuit.

Uniformity of Solid Electrolyte Interphase (SEI): The SEI layer over the electrodes plays a key role in the functioning of the cell and its uniformity is key to stable battery behaviour. Electrolyte manufacturers typically increase the concentration of salt used in the electrolyte to build a stable SEI.

Low Resistance Electrode: Energy storage is a complex process of electrical energy to chemical energy conversion and vice versa, and mass transfer and heat transfer between the positive and negative electrodes in cells. The generation and dissipation of heat in batteries are strongly influenced by the electrode structure, including its thickness, porosity, tortuosity and specific surface area, through changing the cell resistance. For example, a decrease in porosity or increase in electrode thickness increases cell resistance and hence heat generation. The heat generated in the battery accumulates at the positive tab at high discharge rate, the optimized design of current collecting tab can significantly reduce the cell temperature and lead to more uniform heat distribution.

Thicker electrodes designed to improve energy density of the cell can cause more uneven temperature distribution, leading to performance instability and safety risk. When the local temperature reaches the critical value of a thermal runaway, a chain reaction occurs at this point, which further results in a large area of heat accumulation. Hence in order to develop high-performance LIBs with guaranteed safety, better refined electrode structures are required.

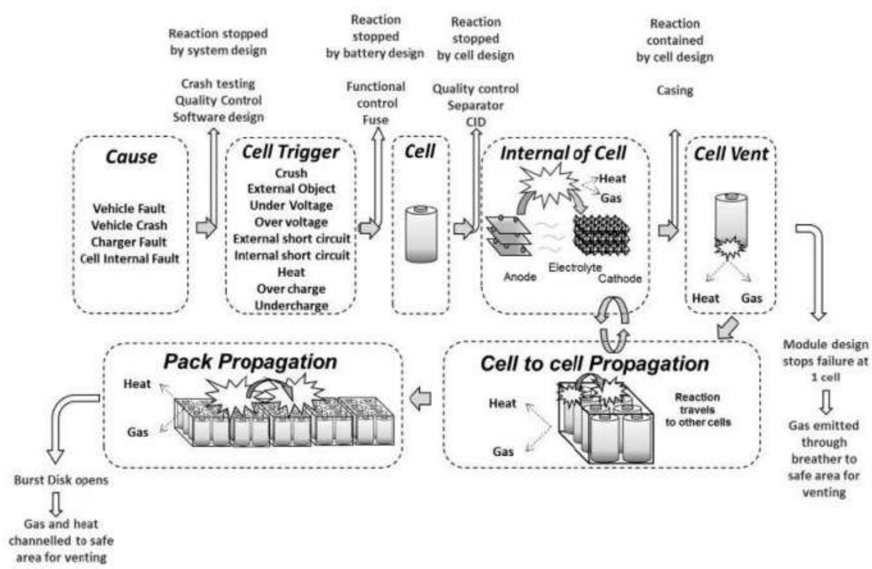
Ideal NE/PE ratio to avoid lithium plating: The ratio of negative to positive electrode capacity (N/P) of a lithium-ion battery is a vital parameter for stabilizing and adjusting cell performance.[17] Low N/P ratio plays a positive effect in design and use of high energy density batteries.

A good cell design should ensure that the charging capacity is fully utilized in the voltage range without Lithium plating. The capacity balancing of the negative electrode (NE) and positive electrode (PE) is crucial for calendar life and safe operation. This can be achieved with good cell design in order to minimize the risk of lithium plating at the surface of NE during charging. Ideally, there has to be slightly excess capacity of NE relative to PE to enable better safety. It should be a cathode-limited cell design, i.e., cathode capacity should be the limiting factor.

The side reaction between metallic lithium and electrolyte makes the metal get deposited on the graphite surface, leading to dendrites and plating. Both initial coulombic efficiency and cycle stability are greatly influenced by the N/P ratio.

Design for Safety: The passive protection components built into the design of a cell that can prevent thermal runaways include a positive thermal coefficient barrier layer, current interruption device (for cylindrical cells), shear thickening electrolyte, thermal fuses, vents, and breakable current collectors/electrodes. These safety mechanisms respond to a critical temperature or current and shut down an entire cell under failure conditions. (see Figure 21: Schematic of Battery Failure Modes with possible containment actions).

Figure 21: Schematic of Battery Failure Modes with possible containment actions



Source: Jurgen Garche, Klaus Brandt 2019, Li-Battery safety, Electrochemical Power Sources: Fundamentals, Systems, and Applications, Elsevier

Battery Management Systems and Prediction tools

Battery characterisation, modelling and diagnostics

Before assembly into vehicles, the cells need to be tested and their performance characterized. The testing and characterization should be performed under Indian road and climatic conditions. The data can be used for building cell diagnostics and cell models. Cell diagnostics techniques for early warning against thermal runaway and battery capacity failure can enhance the safety and save OEMs from the high battery replacement costs. Physics and machine learning based battery models can render optimum battery performance and accurate prediction of battery life; pack models incorporating thermal behaviour are needed for mitigating thermal runaway and better thermal management. The diagnostics and models may also be deployed on board by incorporating into the battery BMS.

In the case of batteries, pure physics based modeling can be a challenge because of the unavailability of real world data leading to several unknown variables. The new paradigm in modelling is called hybrid modelling, which is a combination of physics based modelling and machine learning. Some experiments are conducted and then combined with simplified physics based models to arrive at quick models that can be as close as possible to the real world. Deploying such models to understand battery behaviour is expected to be the future of all kinds of predictive analysis.

Electrochemical Impedance Spectroscopy (EIS) is another non-destructive modelling technique. Impedance increase is generally indicative of cell degradation. Characterising impedance, therefore, is integral in defining battery operational boundaries, estimating performance and tracking SOH and SOF. EIS can be used at various points throughout a battery's lifetime as a diagnostic or prognostic tool: for quality assurance; for state estimation including for monitoring of internal temperature; and for characterization for second-life applications.

Beyond battery state predictions, a key area of development is the model of thermal runaway in a cell which may help understand the potential triggers and likelihood of thermal runaway, providing a way forward to improving resilience in cell design that can reduce the severity of the outcome. There are multiple algorithms available for predicting battery behaviour and performance. But they have different models with varying degrees of accuracy. Typically, for EV batteries, there isn't a single standard algorithm available across the industry.

Simulation prediction capability is required to understand the propagation across the module or the pack. This allows for prediction and early warning to the passengers and allows for safer design of battery packs.

A thermal runaway can be predicted using two approaches: (a) By understanding the phenomenon happening inside the cell, as to how and where the thermal runaway was initiated, and once it is initiated how it propagates within the cell before the cell goes into thermal runaway, and (b) By understanding the effects of a thermal runaway on cells beyond Cell 0 that leads to the whole pack catching fire and exploding.

There is a case for on-board cell diagnostics that can be done for swappable batteries. The diagnostics can be run before a new pack is inserted into the vehicle providing information on the health of the battery and the likelihood of degradation. In the particular case of Battery as a Service model it is important to track incremental aging.

Battery Management System (BMS)

The battery management system (BMS) controls battery charge and discharge functions, manages optimum operating conditions, governs safety limits, runs the battery charge and health algorithms, monitors battery parameters, and communicates with other associated devices. BMS enables cell balancing to ensure all cells are cycling at the same state of charge. An effective BMS can protect the battery from damage, ensure safety, predict battery life, and maintain the battery operation in order to keep efficiency high.

The BMS architecture is designed, developed and calibrated for each particular type of battery system.

One of the issues with Indian two and three wheeler OEMs is the use of off-the-shelf, non-customized BMS without any safety simulations that can lead to safety issues. A majority of system failures point at either the absence of a BMS or inaccurate BMS algorithms or malfunctioning/limited functionality in BMS control.

State of Charge (SoC) and state of health (SoH) estimation is a key function of the BMS as it provides a window into the short-term and long-term state of the battery. SoC is a critical parameter that indicates the battery's remaining available charge capacity and thus provides the estimated remaining range of an EV. Accurate SoC measurement is also important to prevent overcharge and over discharge of the battery.

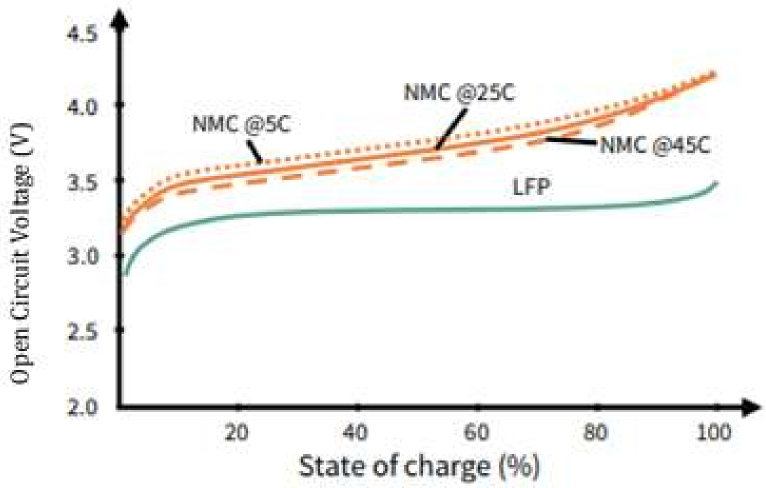
SoH is an indicator of capacity loss or cell ageing. It is defined as the ratio of the maximum capacity that the battery can currently charge to its initial rated capacity. It is attributed to multiple factors such as power fade, SEI growth along with capacity loss. The degree of degradation and its variations between cells is dependent on the operating conditions, schedules, and factors such as charge-discharge behaviour. The ability to accurately predict SoH is key to improve battery cycle efficiency and quantify battery age for feasibility of secondary usage.

SoC and SoH cannot be measured directly, as they do not have a direct physical equivalent. They can be estimated utilizing measurable parameters like voltage, current, temperature, C rate and impedance.

The BMS should incorporate a sufficient number of sensors (temperature, voltage, humidity, isolation, vent gas concentration) to capture changes that may indicate the onset of thermal runaway.

Estimating the SoC in an LFP battery is harder than in an NMC battery because of its flat voltage characteristics. This means that a very small variation in voltage measured by the BMS represents a large variation in SOC in the case of LFP, relative to NMC. Although these flat characteristics enable better voltage measurement for non-destructive purposes, voltage measurement in LFP batteries can become difficult to implement with low-precision Voltmeters. The SoC estimation, therefore, cannot be based solely on voltage measurements and it requires a combination of methods such as coulomb counting or physics based modeling. There is a need to deploy fairly sophisticated tools and customization according to the cell chemistry and material proportions. (see Figure 22: Open Circuit Voltage vs SoC curve of NMC and LFP cell).

Figure 22: Open Circuit Voltage vs SoC curve of NMC and LFP cell



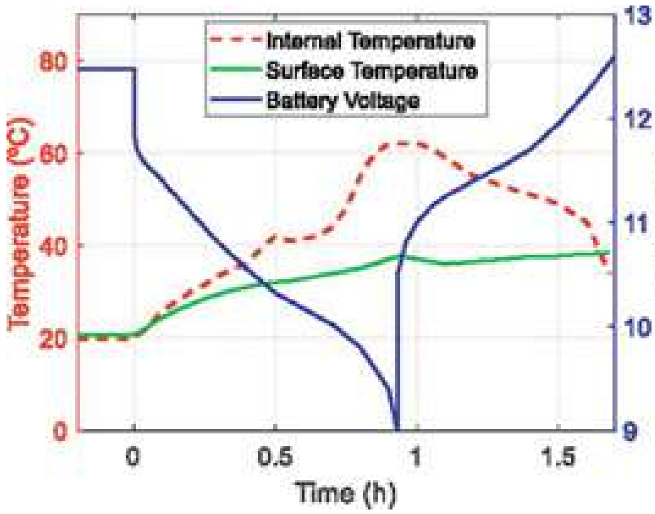
Source: Mahmoud Ismail, et al. 2022, Understanding and overcoming the challenges of building high voltage automotive battery management systems, Infineon Technologies AG

Detecting a thermal runaway: Thermal runaway in a battery is initiated within a single cell, which is the most basic unit of the battery. Surface-mounted temperature sensors, such as thermistors or thermocouples, are a common method to measure the temperatures within a battery pack. Although these sensors are assumed to indicate temperatures close to the (average) internal cell temperature, they suffer from heat transfer delay due to the thermal mass and thermal conductivity of batteries, and consequently, transmit incomplete and delayed information. Particularly, in certain operating scenarios, such as fast charging, high ambient temperatures or demanding load conditions, the internal temperature may significantly differ from the surface temperature (see Figure 23: Internal and superficial temperature during fast charging and discharging). Moreover, since a cell is not a homogenous system, there will be hotspots in the cell that may go up to 80-90 °C even if the measured cell temperature is 60 °C. These hotspots are enough for self-ignition to get initiated[40].

The resulting internal temperature differences, especially in larger format LIBs, may remain undetected and affect performance, aging, and safety of the LIB in an adverse way.

Therefore, several temperature estimation methods have been developed to overcome the limitation of surface temperature measurements and indicate the internal temperature of LIBs. These methods usually utilize a certain impedance feature of the EIS to determine the LIB's temperature, whereby the nature of the determined temperature varies from method to method. These methods may range from electrode-specific temperatures, internal/core temperature to average/integral, and internal temperature distribution.[22]

Figure 23: Internal and superficial temperature during fast charging and discharging



Source: Lalinde, I., Berrueta, A., José Valera, J., Arza, J., Sanchis, P., & Ursúa, A. (2022). Perspective Chapter: Thermal Runaway in Lithium-Ion Batteries. IntechOpen. doi: 10.5772/intechopen.106539

BMS should implement early anomaly detection and monitor as many cells/groups of cells as possible to anticipate a thermal runaway well before it occurs. To perform accurate estimation, the BMS needs a certain level of sophistication beyond just OCV (Open Circuit Voltage) measurements as the OCV may be decoupled with the anode and cathode voltages. Even the electrode voltages are often not accurate representations of SoC. While the anode voltage may be completely delinked from the SoC, the cathode voltage is usually a linear function of the SoC. A combination of methods incorporating Coulomb counting, EIS, Kalman filter estimation models, Physics based simulation and Machine learning tools need to be deployed.

Examples of anomalies which the BMS should detect are:

- Excessive self-discharge or drop in block voltage during rest periods
- Long taper current charging times
- Noisy voltage profiles during charge and discharge
- Excessive cell heating near the end of charging
- Charge capacity being higher than discharge capacity, beyond typical losses
- Change in efficiency of charge/discharge over a short period of time

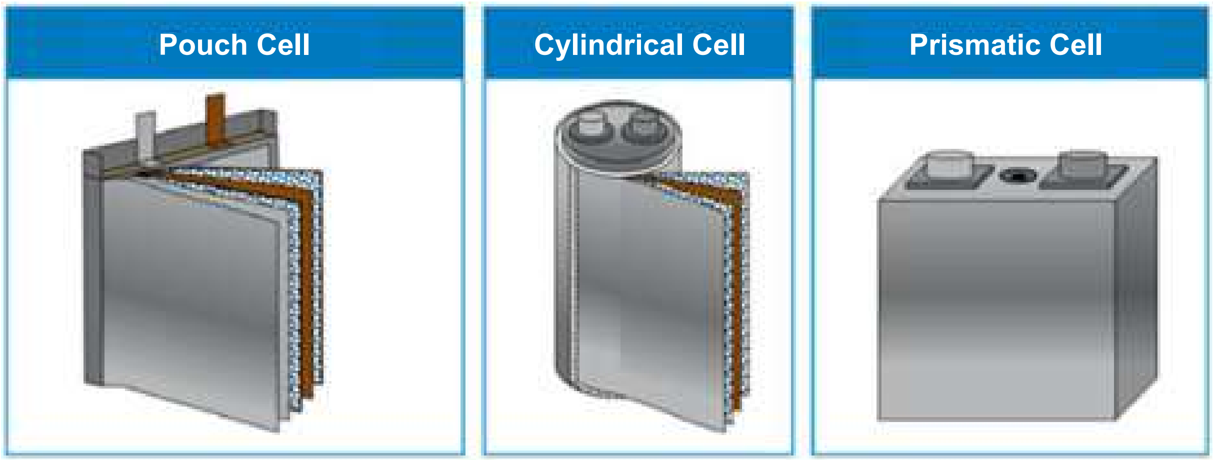
Battery Thermal Management System (BTMS)

The battery thermal management system (BTMS) is responsible for controlling the operating conditions of the battery in a high ambient temperature environment. It is also responsible for dissipating the heat generated within the battery. When a thermal situation occurs in a single cell, managing the propagation to neighbouring cells requires cooling and/or thermal insulation.

The pack design of the battery, which includes cell format (see Fig 24: Cell Formats), arrangement and distance of cells and their thermal isolation, has a large influence on the thermal conductivity, thermal radiation, and convection and therefore on propagation of a thermal situation within the module and the battery pack. Increasing packing density of cells, for instance, can expand the energy density of a pack. This means that there is less space available between the cells for cooling which can be challenging during regular operation and can be a disadvantage in removing heat to avoid a thermal runaway.

OEMs pay close attention to the cell format being used (see Figure 24: Cell formats). Cylindrical cells have some distinct advantages with respect to thermal management. The cylinder as a shape is able to retain much higher pressure in the event of gas generation at high operating temperatures. With cylindrical and prismatic cells, vents can be positioned so that the gases are directed appropriately and expelled through the vents. Pouch cells, however, can rupture anywhere on its surface, without directional control of the vent gases. In addition, the cylindrical format cells provide intrinsic pathways for cooling fluid, be it air or liquid. In comparison, pouch format calls are susceptible to deformation since they are enclosed in a flexible aluminium-coated plastic film. However, pouch cells offer an advantage with cooling. Since they have a larger surface area for conductive heat transfer, they are used in large format applications like buses along with intervening layers of compression pads (with dielectric foam).

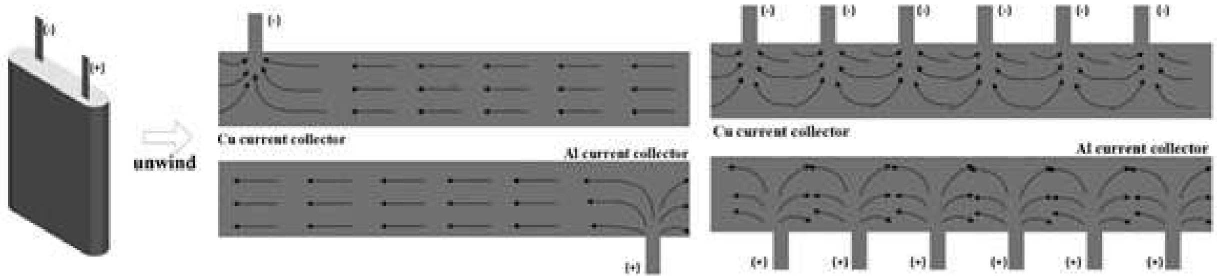
Figure 24: Cell formats



Source: PEM, RWTH Aachen University

Design factors such as the location, number and size of tabs[41] also play an important role in temperature distribution (See Figure 25: Electron transport path in the current collectors of (a) cell with a single pair of tabs; (b) cell with multiple pairs of tabs).

Figure 25: Electron transport path in the current collectors of (a) cell with a single pair of tabs; (b) cell with multiple pairs of tabs. A single pair causes queuing of electrons and higher ohmic resistance. Multiple tabs lead to shortened electron transport length and more uniform heat distribution.

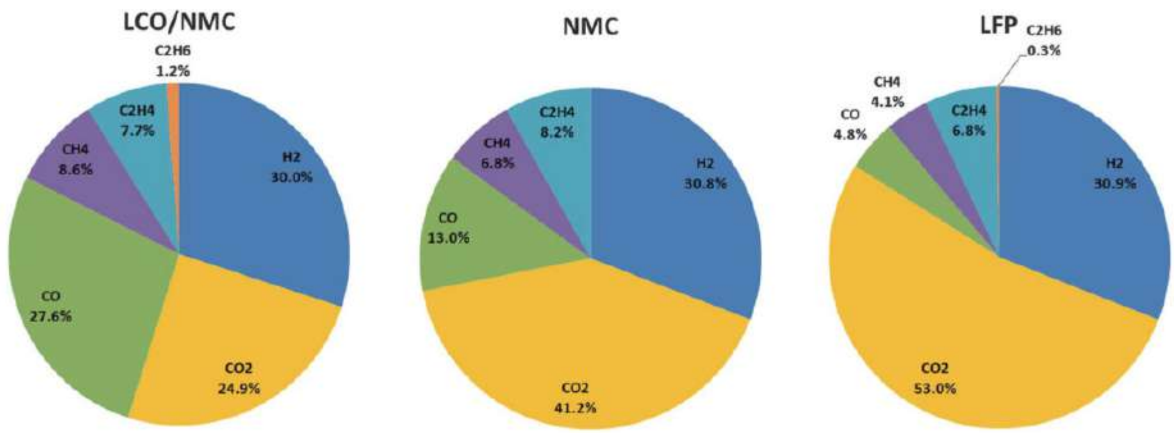


Source: Wei Zhao, et al 2014, Effect of tab design on large-format Li-ion cell performance, Journal of Power Sources, Elsevier

In addition to cell-to-cell heat transfer, the effect of heating through burning gases and liquids outside of the cell in case of a thermal runaway needs to be considered when designing a battery. The failure of transfer may be caused by mechanical effects (pressure or flying parts) or electrical in case of connected systems/batteries (overvoltage, short circuit, etc).

Detecting thermal runaway at the point of origin (cell 0) can help prevent cascading chain reactions. Carbon dioxide gas sensors and opacity detectors are among the proxy methods which can identify the initiation of thermal runaway (See Figure 26 Effect of cathode chemistry on gases released during thermal runaway).

Figure 26: Effect of cathode chemistry on gases released during thermal runaway

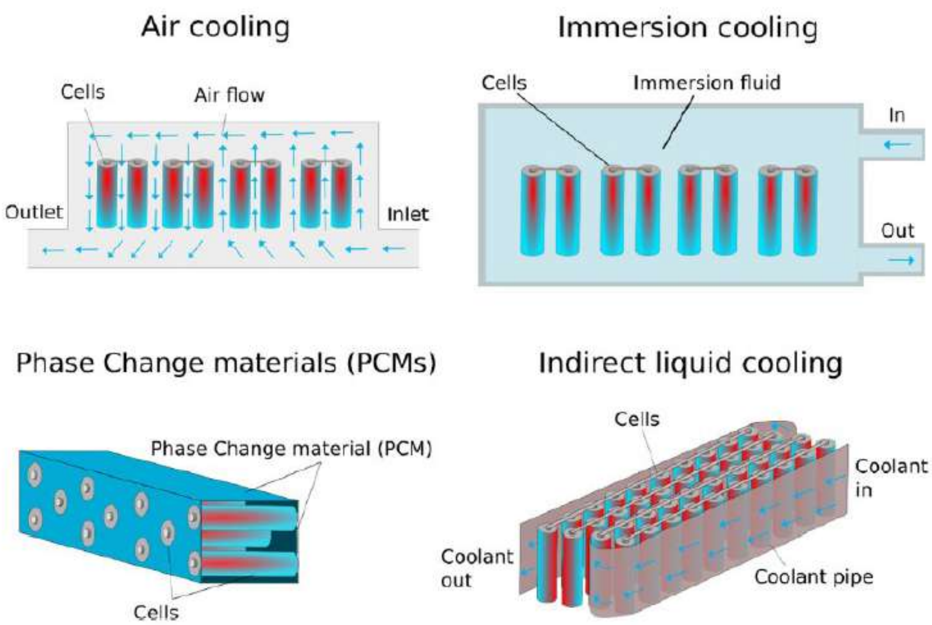


Source: Andrey W. Golubkov et al 2013, Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivine-type cathodes, RSC Advances

Battery packs are insulated from external contaminants by hermetically encapsulating the cells/packs in a solid case, which serves as a mechanical safeguard and provides protection upon mechanical impact. The conflicting objectives of mechanical insulation of cells and need of ventilation for heat dissipation presents a pack design challenge.

The devices providing safety features induce additional weight, volume, and cost to the LIBs and may offset some benefits from the high voltage and high energy density chemistries, which tend to have lower stability.

Figure 27: Different Thermal Management Systems



Source: Charlotte Roe, et al. 2021, Immersion cooling for lithium-ion batteries – A review, Journal of Power Sources, Elsevier

Types of external BTMS include air cooling, indirect liquid cooling, direct liquid immersion cooling and phase change materials (see Figure 27: Different Thermal Management Systems).

OEMs prefer air cooled systems depending on the size of the battery, due to low cost, simple design, low weight, easy maintenance, and no leakage issues compared with other cooling systems. These systems can be divided into two main categories: active air cooling (forced convection) and passive air cooling (natural convection).

While the e-two wheeler market in India uses passive air cooling due to price constraints, their systems proved to be insufficient for more aggressive operations. Air has lower heat capacity as well as lower thermal conductivity compared with other mediums (e.g. liquids and phase change materials) reducing cooling capabilities and causing poor temperature uniformity in the battery pack.

Given the limitations of air cooling systems, liquid cooling offers an alternative route for large scale EV BTMSs. Liquid cooling encompasses both indirect liquid cooling and immersion cooling. Indirect cooling is one of the most widely used EV BTMS due to its ability to maintain uniform pack temperature distribution, favourable specific heat capacity, and robust thermal control. Commonly used coolants include mixtures of water and ethylene glycol. The coolant flows along channels of pipes or cooling plates, carrying the rejected heat out of the battery pack. Based on the cooling channels' position relative to the batteries, indirect cooling systems can be divided into bottom cooling and side cooling solutions.

Recommendations for thermal management of the battery include:

- Engineering the battery pack for better heat dissipation during charging and discharging at various C rates
- Use temperature data from cell characterization for building models to aid with robust pack design and thermal management
- Adapting the electrolyte systems to enhance the life and safety of the battery systems
  - » Electrolytes with wider electrochemical potential window (5V) are required form safety point of view, when high voltage electrodes (eg: Ni rich NMC) are used.
  - » Adding electrolyte retardant and overcharge additives
- Developing new electrolyte systems
  - » Non-flammable electrolytes include aqueous lithium-ion batteries, ceramic solid electrolytes, polymer electrolytes, ionic liquids, and heavily fluorinated systems
  - » Liquid electrolytes are being engineered to limit dendrite growth from electrodes
  - » Solid-state electrolytes can offer a solution to reduce or eliminate dendrite growth in the anode

Building safety standards

Taking cognizance of the gap in the regulatory framework with the assembly of light electric vehicle batteries, the government set up an expert committee to build safety standards for battery, BMS, and related components in electric vehicles. Standards and regulations would need to drive the terms of technology development.

As noted earlier, thermal runaway is caused by internal or structural defects in the battery that provide the seed for nucleating the failure mode and this is often caused by minor manufacturing defects that get amplified when the battery is charged and discharged several times. These defects may be managed through quality control practices during the manufacturing stage.

Adherence to the standards will require outstanding manufacturing practices and quality control procedures to reduce risk of thermally unsafe events. Numerous companies in the light EV segment are start-ups with short product to market timeframes. Many are dependent on imported componentry that builds vulnerability because of their inability to characterize deployed systems. The safety systems will improve with time as the scale of operations and locally produced content increases, and the regulatory system matures.

The Automotive Research Association of India (ARAI), which is one of the prime testing and certification agencies notified by the Government of India under Rule 126 of Central Motor Vehicle Rules (CMVR), 1989, has promulgated standards for testing and evaluation of Electric Vehicles and Hybrid Electric Vehicles. There are seven EV Standards for this purpose classified as Automotive Industry Standards, namely AIS-038, AIS-039, AIS-040, AIS-041, AIS 048, AIS-049 & AIS-156.

Until 2020, India had the AIS 048 safety certification meant mainly for lead-acid batteries. In early 2021, the AIS 156 was released with specific requirements for L category electric vehicle certification and AIS 038 (Rev 2) for M and N category electric vehicle certification.

The AIS utilizes UNECE (UN Economic Commission for Europe) standards and UNGTR (UN Global Technical Regulations) standards as a base to develop regulations in India[42] and has adapted them to Indian environmental conditions. AIS 156 and AIS 038 are written in line with UN regulations UN R136 and UN R100 Rev3.

While the inadequacy of the current standards and test protocols requires a deeper investigation to assess the gaps in addressing the critical safety parameters and interface with the climatic conditions in India, a broad-based comparison shows the current missing links in relation to the global standards. (See Table 6: Comparison of Global Regulations and standards with Indian regulations). Also, the key elements of the individual tests which are incorporated in AIS 156 have been highlighted. (Table 7: Key testing procedures in AIS 156).

Post the fire incidents in the summer of 2022, amendments to AIS 156 and AIS 038 (Rev 2) were notified. The amendments have been made applicable from December 1, 2022, and some clauses of these AIS standards became effective from March 31, 2023.

Table 6: Comparison of Global Regulations and standards with Indian regulations

Regulation	ECE R100 Rev 3	AIS 038	UN ECE R 136	AIS 156	GB/T 31467.2-2015
Issuing country	EU	India	EU	India	China
Vehicle Category	M,N		L		
Vibration test	✓	✓	✓	✓	✓
Thermal shock and cycling test	✓	✓	✓	✓	✓

Regulation	ECE R100 Rev 3	AIS 038	UN ECE R 136	AIS 156	GB/T 31467.2-2015
Mechanical drop			✓	✓	
Mechanical shock	✓	✓	✓	✓	✓
Mechanical integrity	✓	✓			✓
Fire resistance	✓	✓	✓	✓	✓
External short circuit protection	✓	✓	✓	✓	✓
Overcharge protection	✓	✓	✓	✓	✓
Over-discharge protection	✓	✓	✓	✓	✓
Over-temperature protection	✓	✓	✓	✓	
Over-current protection	✓	✓	✓	✓	
Thermal Propagation Test		✓			
Withstand voltage test			✓	✓	
Water resistance test			✓	✓	
Seawater immersion					✓
Salt mist					✓
High altitude (Low atmospheric pressure)					✓
Technical Requirements for Traction Battery (Amendments)		✓		✓ Thermal Propagation test included	

Source: CSE Research

Table 7: Key testing procedures in AIS 156

TEST	DESCRIPTION
Vibration	Between 7 and 200 Hz
Thermal Shock	Temperature cycles between -40 and 65 C
Mechanical Shock	Acceleration/ deceleration pulses up to at least 20 g
External Short circuit	External short-circuit resistance < 5 mΩ until 1 h after temperature has stabilized
Overcharge	Charge with 1/3 C rate until tested device automatically interrupts charging or 200% SoC
Overdischarge	Discharge with 1/3 C rate until tested device automatically interrupts or until 25% of nominal voltage level
Over temperature	Charge and discharge cycling at temperatures up to specified maximum operating temperature

Source: CSE Research

Additional safety requirements have now been published as part of amendments to EV standards related to battery cells, battery management system, on-board charger, design of battery pack and thermal propagation due to internal cell short circuit leading to fire. The standards now mandate adequate spacing of individual cells in a battery pack, temperature sensors which can send out audio-visual warnings to prevent thermal incidents and smarter battery management systems (BMS) and chargers.

AIS mandates that each cell complies with IS16893 Part 2 which refers to reliability and abuse testing and Part 3 which refers to safety requirements.[43] It is worth noting that although IS 16893 Part 2 and Part 3 have similar test items, the results are reported based on a different set of parameters. Part 2 needs to assess the reliability of the cells and collect the basic data of reliability and abuse behaviour. The test report needs to record the current, voltage and temperature data and describe the test results of the cells. Part 3 specifies the pass and fail conditions for each of the tests. For example, the cell cannot catch fire and explode during the test, if not, the test will fail.

Important cell level tests include overcharge test, short circuit test, vibration and shock test, crush test and forced discharge.

For the battery management system, AIS mandates a microcontroller based system, which is a step further than a simple BMS with just sensing and protection without the scope of using algorithms. It requires BMS to have EMC (Electromagnetic Compatibility) protection to prevent sporadic blips and resets due to external interference. It also mandates a minimum of four thermal sensors in the battery pack.

At the battery level, the pack needs to be rated for IPX7 water resistance.[44] It requires a mandatory safety fuse and circuit breaker along with a pressure release vent. The additions also mandate a thermal propagation test to simulate thermal runaways.

Further work is required to develop a satisfactory test for thermal propagation within a battery pack that may arise from internal short-circuiting in a cell. Revisions to the AIS 156 standards have proposed different methods such as heating or overcharging a cell to take it to thermal runaway stage – all of which have implications on the design of the pack and related costs. While these methods will not be able to mimic the actual mechanisms of an internal short within the cell, it is certainly much better than the nail penetration test that it has replaced.

While the above mentioned design changes typically reflect Type Approval[45] tests, to ensure Conformity of Production (CoP)[46] process changes have also been issued. Cell traceability and cell cycling are two major changes that have been introduced. To carry out cell cycling, manufacturers are keen on devising accelerated cycle life testing to reduce production time.

Challenges with meeting standards and future research: The challenge posed with meeting the lithium-ion battery standards specifications revolves around simulation of a potential thermal runaway in a single cell within a pack. In this context, the UL-9540 offers methods to create a thermal runaway in a single cell to study its propagation.

Special kinds of packs have to be developed particularly to conduct these tests and they are not the ones that are being manufactured on the assembly line. The tests, when conducted on specifically designed packs, provide insights about the design of new packs that do not allow thermal propagation from one part of the pack to another.

This method of assessing the impact of thermal runaway within a pack and the trajectory of its propagation or how it can be prevented is covered under the standard. What is not clear is the process to create the runaway condition in a cell within a pack, which is representative of an event that may actually happen in real life.

Currently two methods are stated in the standards to initiate runaway in a cell. One is to heat up the cell and second is to overcharge the cell, and neither accurately represents an internal cell short. Both are conducted through external interference. As per the tests specified in the addendum to AIS 156, a pack has to be built with a cell that has an attached resistor that can be used to heat it from the outside.

There is a need to conduct research on the mechanism to initiate and propagate a thermal runaway condition in a cell within a pack. To understand the method of inducing a fire, India could take a leaf out of global practices.

US-based Sandia Labs introduces shards of nickel and other particles inside the cell to simulate manufacturing defects to intentionally create an internal short. The Japanese, however, have a modified nail penetration test. The GB/T 38031 standard in China requires that vehicle passengers be warned at least five minutes before a fire from a thermal event extends beyond the battery pack, or battery venting gas enters the cabin.

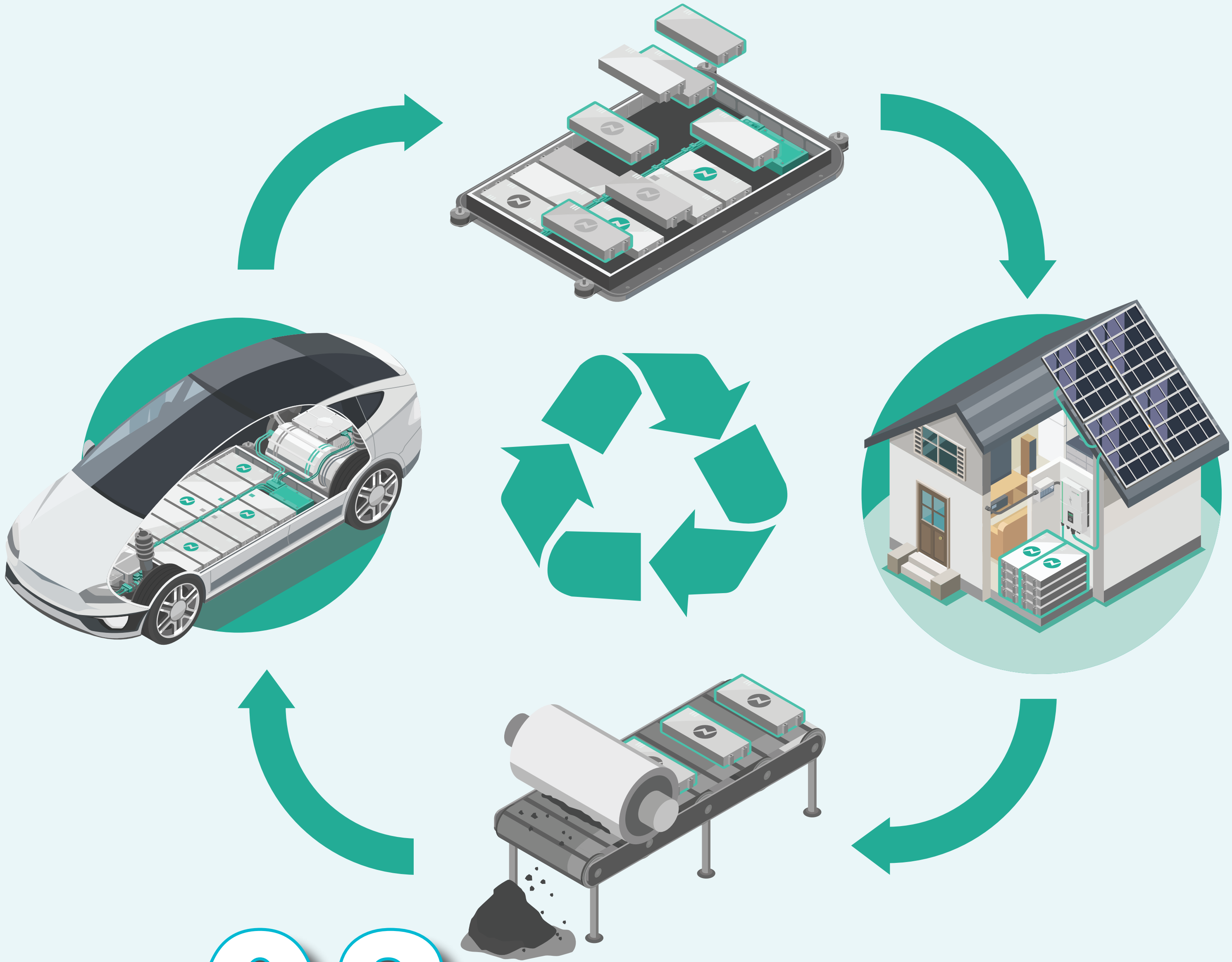
Battery Bank

All kinds of prediction tools will require data collected on the battery's operations throughout its life. A battery bank will have to be developed as a government driven program for different types of cells and batteries to study life-cycle performance, cell degradation and thermal runaway. The data available on the effect of tropical conditions on these parameters is usually scant.

Clearly, more research needs to be carried out on the effect of temperature induced aging on safety. Also, Accelerating Rate Calorimetry (ARC) techniques that provide data on the total energy yield from a cell during thermal runaway can be used on pack drive cycle or ambient condition to study the potential for thermal runaways.

Life-cycle testing of Li-ion batteries is costly and time-consuming, so a publicly available battery dataset could be a valuable resource for comparison and further analysis. A national database could be created by a scientific laboratory on the lines of the FreedomCAR program of the US. It will be imperative for the transparency to be built into the program with a clear understanding with battery suppliers globally on the norms of data sharing. Only the findings from the data would be stored in the repository, which will help augment the safety landscape of EV batteries in India.

This overall assessment shows that battery technology development and cell development need to address improvement needed in battery safety that will have to be achieved along with other performance parameters including durability and longevity in real world operations. The immediate challenge will be to refine strategies for liquid electrolytes in most lithium-ion batteries that are flammable under extreme conditions. This will contribute towards improving safety. Clearly, a research funding agenda needs to take shape quickly in India to support technology development.



03

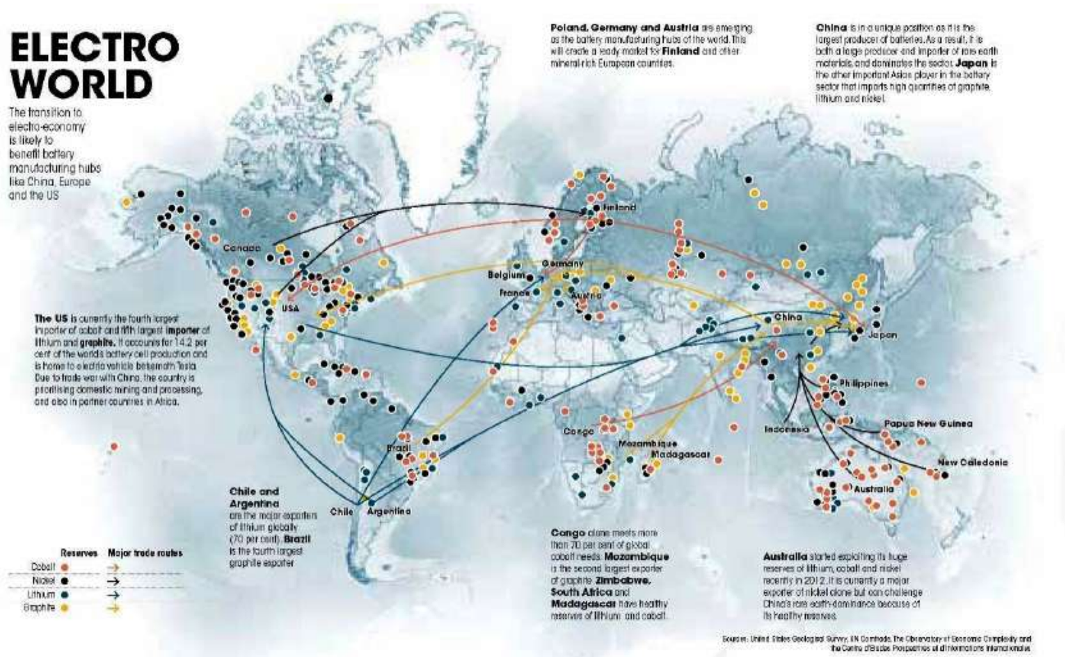
BATTERY CIRCULAR ECONOMY AND RESOURCE SCARCITY

Raw material availability

Raw materials comprise over 60 per cent value of a lithium ion cell, but the availability of these materials is limited and restricted to only a few geographies across the globe. Concerns regarding access to raw materials have even pushed global automakers to sign futuristic contracts with miners to enable materials supply chain security.

EV battery materials are sourced from some of the most politically unstable economies in the world, a fact that brings to light the intensity of supply chain risk and the need for alternatives to be instated. Among battery metals, lithium is sourced from South America and Australia, while Nickel is sourced from Indonesia and Russia and Cobalt from the Democratic Republic of Congo in Africa (See Map 1: Global Battery Metals Supply Map).

Map 1: Global Battery Metals Supply Map



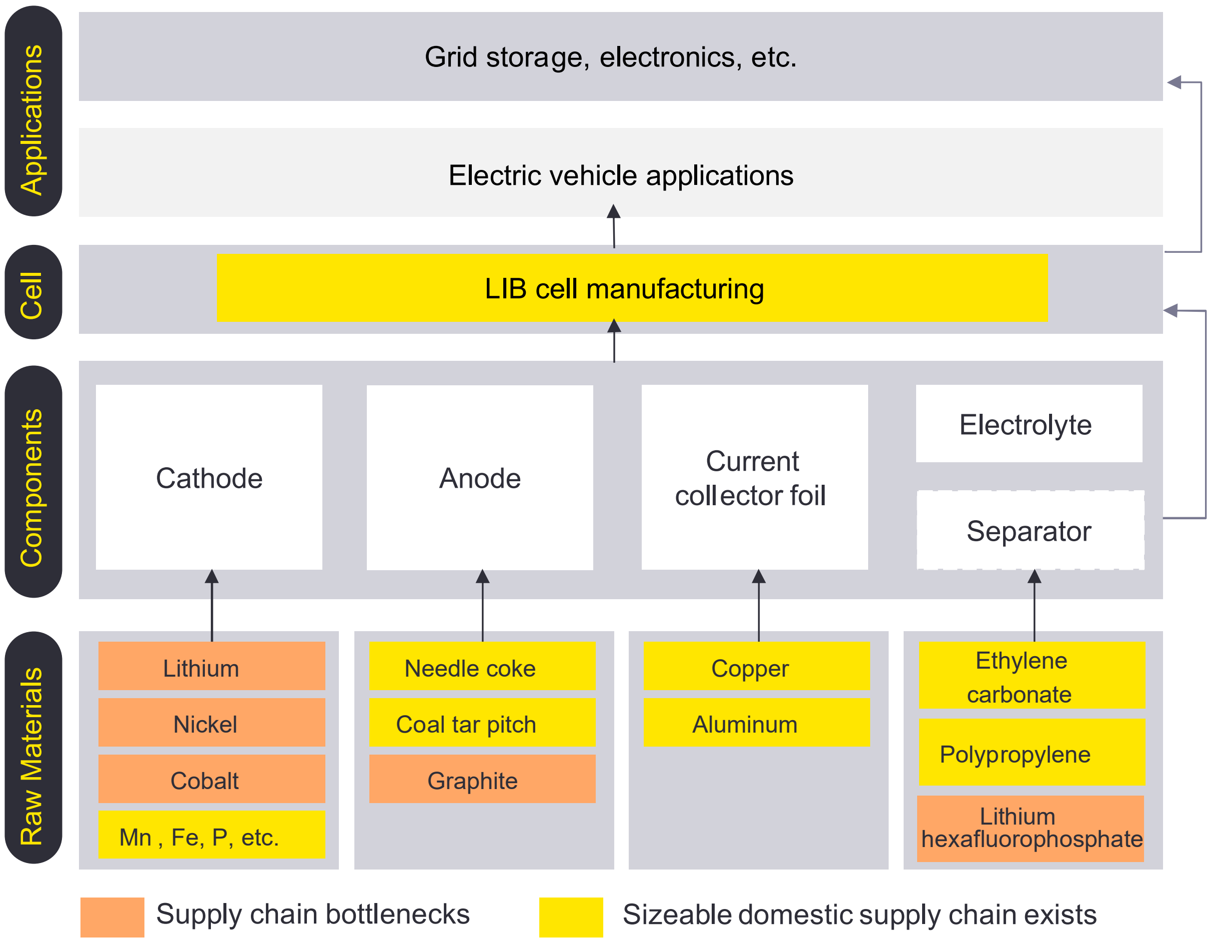
Source: CSE

India has very limited known reserves of lithium and there is not enough cobalt, nickel and graphite to hedge against uncertainties in the battery supply chain. Nor does it have the refining capacity to produce battery grade materials to manufacture them. India will therefore be dependent on other nations in the absence of a robust policy and manufacturing eco-system and remain vulnerable to volatility in prices. Building a new mine and refining the ore into battery-grade materials typically takes five to 10 years. The EV battery supply chain risks appear much more pronounced since 2022 after the Russian invasion of Ukraine tightened the supply of nickel, a key ingredient in the making of EV battery cathodes. The conflict in Ukraine has had economic consequences on battery component prices and has consequently had an impact on the price of electric vehicles. This caused a potential delay in price parity that is important for EV adoption. Globally, the price pressure on critical battery raw materials could expand and battery input costs will likely increase by over USD 7,000 for several popular vehicle models, according to global information services and consultancy firm S&P Global.

The uncertainty in the battery metals market is not new. With battery metals, as with other metals in the mining industry, availability and price form a cyclical phenomenon. Large gaps in supply and demand can push up prices. Even before the Ukraine crisis started, battery metals experienced a fair amount of volatility in the last few years driven by global electric vehicle demand. Prices of EV battery cathode metals nickel, cobalt and lithium prices increased by 37 per cent[27], 41 per cent[28] and 487 per cent[29], between February 2021 and February 2022. (See Figure 28: Key components and materials for manufacturing LIBs)

India's National Programme on Advanced Chemistry Cell (ACC) Battery Storage and the PLI scheme that aims to build an annual manufacturing capacity of 50 GWh of ACC is expected to increase local value addition. The local manufacturing is expected to ensure a minimum 60 per cent domestic value addition at the project level within five years. This scheme is expected to achieve import substitution of around Rs. 20,000 crore every year. This will create enormous demand for critical minerals.

Figure 28: Key components and materials for manufacturing LIBs



Source: Niti Aayog 2023[47]

Minimizing or substituting material

Supply uncertainties are leading to more innovation to improve battery chemistries to substitute or minimise the use of materials that face the problem of unstable supply chains and higher costs. This is leading to a shift towards chemistries that require lower cobalt and nickel content, or that are even free from cobalt and nickel requirements, such as lithium iron phosphate (LFP) batteries. Cobalt and nickel are critical to the battery supply chain because of the risk of supply disruption owing to its sourcing from disparate locations. Focus is on alternative technologies with minerals of low supply risks and shift to more advanced battery chemistries with lower and zero-cobalt.

The WRI study shows that as a result of constant effort to reduce use of cobalt in cathode its share in different li-ion chemistries has reduced -- LCO (60 percent), NMC (6–20 percent), and NCA (9 percent). At the same time LFP, LMO, and LTO-LMO cells do not contain any cobalt.

Additionally, using Sodium-ion batteries as a substitute to Lithium-ion batteries is a very effective means of bypassing the critical minerals rush and yet building a stable battery manufacturing and supply ecosystem in the country. This is because Sodium is more abundant than Lithium, has a simpler extraction process and more importantly, it is available in India.

While lithium is also abundant, the pace of extraction/refinement is slow. The uncertainty in mine supply affects its price. According to World of Statistics data, the price of lithium hydroxide had risen to $78,032 per metric ton (t) in 2022 from $6,800 in 2019. Meanwhile, the price of sodium hydroxide, a common sodium-ion battery precursor, was below $800 per metric ton in 2022. While lithium must be extracted from rocks or brine, battery-grade sodium hydroxide is readily produced during the electrolytic conversion of common salt into chlorine. Given India's peninsular geography and long coastline of nearly 7500 km[48], India has easy access to common salt (NaCl) which is an integral component of seawater and can be recovered by simple evaporation.

India is now part of the coveted critical minerals club, the MSP headed by the United States. MSP is a strategic grouping of 13 member states including Australia, Canada, Finland, France, Germany, Japan, the Republic of Korea, Sweden, the United Kingdom, US, the European Union, Italy and now India. It aims to catalyse public and private investment in critical mineral supply chains globally. India is already a member of the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, which supports the advancement of good mining governance.

India's inclusion in the club is vital for India to fulfil its ambition of shifting towards sustainable mobility through large, reliable fleets of electric public and private transport. Securing the supply chain of critical minerals will also provide the country with the necessary push towards a concerted indigenous electronics and semiconductor manufacturing.

The Government of India has also recently amended the Mines and Minerals (Development & Regulation) Act of 1957, allowing private players to mine lithium and other five critical minerals, enabling a much needed public-private partnership in the ecosystem.

Private players will bring more capital and foster use of new and emerging technologies for exploration and mining processes. These minerals are in high demand as countries move towards green transition and e-mobility. Lithium is one of the most sought-after minerals today across the world, due to its strategic use case in production of batteries needed for electric vehicles.

Material recovery through recycling

The United States Inflation Reduction Act, 2022 allows recycled battery materials (for example, lithium, cobalt and nickel) to qualify for significant tax credits available through the domestic materials clause, even if those materials were not originally mined in the US or in countries with which the US has free-trade agreements.

The European Union has also instituted its end-of-life vehicles directive that mandates automotive original equipment manufacturers (OEM) to take back vehicle owners' end-of-life batteries. The EU's 'Fit for 55' package has further promoted OEM interest in recycling by requiring the publication of battery carbon footprints, as well as by setting collection and recycling targets, including minimum recycled content requirements, for newly built batteries.

In the US, regulatory initiatives in California (Lithium-ion Car Battery Recycling Advisory Group) and Texas (EV Battery Reuse and Recycling Advisory Group) have recently provided recommendations that are expected to influence regulatory measures further towards battery recycling.

Even though the EV market is in its nascent stage, early intervention for promoting circularity can provide immense benefits. The EV market in India grew from less than 1 per cent in 2020-21 to almost 4.7 per cent[49] of new vehicle registrations in calendar year 2022, and 6.38 per cent of new vehicle registrations in calendar year 2023, pushed by incentivisation programs by the Government of India. CSE's assessment shows that the cumulative recyclable material from spent EV batteries in India will be around 2,45,554 tonnes[50] in 2037 (in a 15 year timeframe). This quantity of recyclable material can be utilised by Indian OEMs or exported to other countries to enrich India's Balance of Trade.

India, therefore, needs to actively push for recycling as an alternative source of battery raw materials. In addition, access to battery material for manufacturing can trigger deep localisation in the supply chain and lead to fresh investments in the indigenous supply chain.

Spent lithium ion batteries contain a significant amount of valuable metals, some with an even higher grade than the metal grade in natural ores. They usually contain by weight 5–20[51] per cent cobalt (Co), 5–10 per cent nickel (Ni), 5–7 per cent lithium (Li), 5–10 per cent other metals (copper (Cu), aluminum (Al), iron (Fe), etc.), 15 per cent organic compounds, and 7 per cent plastic, although their compositions differ depending on the cell chemistry. This offers the potential to support the country's battery supply chain and contribute to energy security benefits if it becomes feedstock for new batteries.

At a global scale an estimate by International Council on Clean Transportation (ICCT) shows that an efficient recycling of end-of-life vehicle batteries and prolonged usage in second-life applications can reduce the combined annual demand in new lithium, cobalt, nickel, and manganese mining by 3 per cent in 2030, 11 per cent in 2040, and 28 per cent in 2050. When accounting for second-life use of batteries after the electric vehicle has reached the end of its life, recycling can reduce the need for new material mining by 20 per cent in 2040 and 40 per cent in 2050. Even with recycling, the cumulative use of lithium and nickel could reach 25 per cent of known global reserves by 2050, and 30 per cent for cobalt. This is approximately a 25 per cent reduction in the cumulative use of materials as a percentage of known global reserves in 2050 compared to a no-recycling case. Regulations and capacity are needed to recover approximately 90 per cent of the critical battery materials. Even though recycling is still very low volume, the concentration of the materials in battery packs is often 10 times greater than that of the original ores and that makes it desirable.

Battery manufacturers usually consider the end of life for an EV battery to be when the battery capacity drops to 80 per cent of the rated capacity. However, batteries can still deliver usable power below 80 per cent charge capacity, although they will produce shorter run-times. For a reuse case, however, it is essential to determine the residual value of the battery using accurate SOH prediction tools.

After refurbishment and second life use, the battery can move into end of life management to extract valuable metals contained in them. Almost 95 per cent of EV battery materials can be recovered and fed as feedstock in new batteries. According to one estimate, 4000 tonnes[32] of spent lithium ion batteries contain 1100 tonnes of metals as well as more than 200 tonnes of toxic electrolyte.

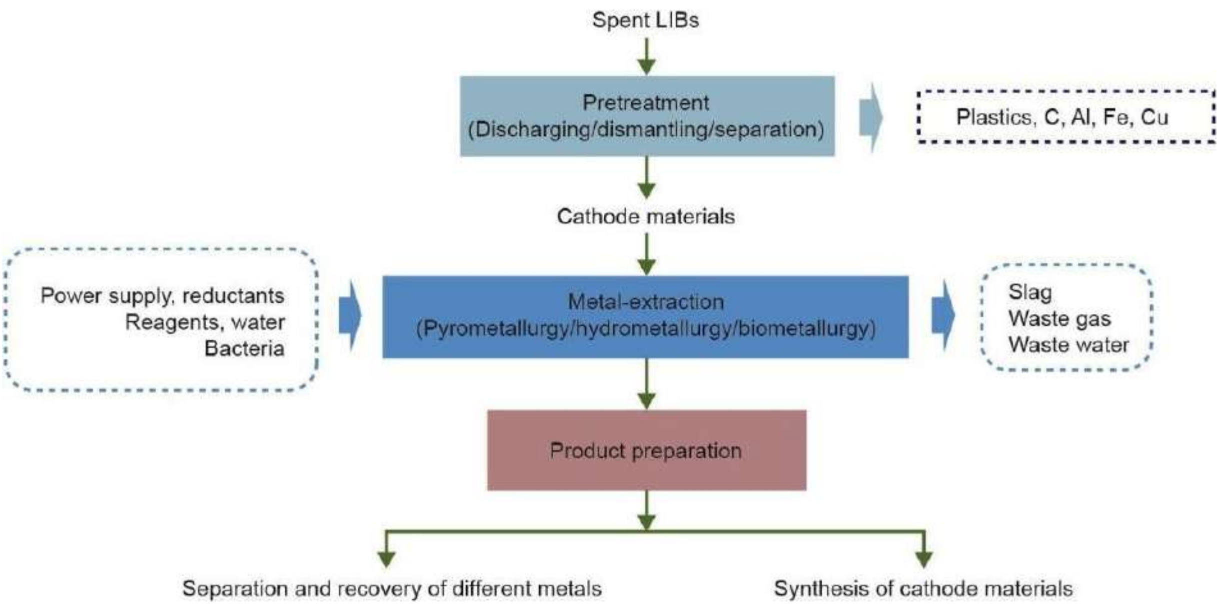
As EV adoption moves forward, vehicle and battery manufacturers have the opportunity to frame strategies and define budgets for battery reuse, remanufacturing and recycling.

Within a cell, the recyclability of each of the components varies. In comparison, the lead acid battery is simpler to dismantle. It is self-contained in one unit, not assembled into modules and packs, and it needs no disassembly prior to recycling.

Mechanics of recycling

Typically, lithium-ion battery recycling includes disassembly, mechanical or thermal pre-treatment, separation, and metal extraction (see Figure 29: LIB Recycling Process). The recycling efficiency is determined by the collection rate of end-of-life batteries and the recycling efficiency.[33]

Figure 29: LIB Recycling Process



Source: Science Direct

The anode typically consists of copper foil covered by a fine layer of carbon while the cathode contains metals like nickel, manganese, cobalt, iron, aluminium and lithium depending on the cell chemistry. To gain access to these metals dissembling battery packs involves three steps. First, the batteries are discharged with a common salt solution, dismantled by removing the cells from the packs. The cathode, anode, and separator are collected and dried in an oven for 24 hours at 60 °C. The obtained cathode and anode are further separated for the metal extraction process. Several methods are used for separating the metals and binders such as solvent dissolution method , thermal treatment method , and mechanical method.

Design of efficient battery recycling

The presence of a diverse set of cell chemistries, cell formats, module and pack designs in the market, at the same time complicates the recycling process.

The complex nature of lithium ion batteries points at the need for recycling friendly design of batteries. It is believed that about 80 per cent of a product's environmental impact is determined in the design stage. During this stage, the choice of materials, construction and appearance are all finalized. Batteries should be easy to remove from products and easily disassembled into smaller parts. However, designing for circularity does not stop with products – it also involves designing business models that maximize the value of the raw materials used. This is how circular product flows can be aligned with conserving high-quality material contained in those products.

Battery packs are typically secured with screws, welded and have materials glued together. The battery modules are often stuck together with adhesives. In practice, this does not make separation of hard-fused materials viable, thus making recycling the contents for the manufacture of new products much more complicated and expensive.

The solution to these challenges could be standardisation. Screw connections and conjunctions between modules for instance could be standardised in order to facilitate an automated disassembly of the cells. Materials could also be designed for easier end of life management. For example, water-based or alcohol soluble binder for electrode materials can reduce expensive, potentially toxic solvents during recycling. This would enable simple separation of the current collector from the active material without significant use of ancillary chemicals.

If cell design and chemistry were to be standardised, automotive cells will grow in volume share as more and more electric vehicles get sold and this will enable easier recycling streams of grade purity and value.

However, manufacturers have little economic incentive to modify existing protocols to incorporate recycling-friendly designs. But they could offer long term resource utilisation and environment benefits.

According to the Metal Recycling Association of India (MRAI), the recycling industry consumes less resources than mining, in terms of land, power-consumed and logistics costs. It also has a much smaller carbon footprint, and less harmful by-products.

When metal is mined from ore, only 4-5 per cent[52] of it is useful metal while the rest has to be discarded. In comparison, recycling and extraction requires less energy. Recycling uses 1/20th of the energy required for the same amount of metal as mining from ore.

Recommendations to improve battery pack design are provided in the annexure (Refer to Annexure 3).

Cost of Recycling

Lithium ion battery recycling is a capital intensive process. The difference between capital expenditure required to set up a traditional lead acid battery recycling plant and a lithium-ion one is in the order of over 50 times. A lithium-ion battery recycling unit with an annual capacity of 18000 metric tonnes (MT) requires an investment of INR 220-370 crores while a similar capacity lead acid plant costs Rs 4 crore. At the unit level, while lead acid battery recycling costs Rs 7/kg, lithium ion recycling costs between Rs 100-150/kg.[53]

The high energy consumption (in the region of about 1000 kWh) in a lithium battery recycling facility captures a substantial percentage of the cost of setting it up. Apart from access to capital, the most evident reason for the slow emergence of the EV battery recycling industry is the lack of scale in waste generation. EV sales are still picking up and there are not as many batteries to recycle, pointing at an opportunity to import spent batteries for recycling.

Clearly, the lithium-ion battery recycling industry requires policy support with implementation tools and access to capital.

In this respect, the EV battery ecosystem could take lessons from the lead acid battery resale market to become viable. One of the biggest challenges to be addressed is collection of batteries. Once the supply-demand dynamics are worked out, the economics can change depending on the contract. Options that can be explored include i) recycler/refurbisher could get material for free or pay for it; ii) they could get into a tolling contract in which the automaker pays the recycler by the metric ton of batteries or material that they process and return.

It is necessary to implement such contracts in conjunction with open battery passports to make EOL management a smoother process.

Ideally, recycling-friendly batteries should be safe to handle and transport, simple to dismantle, cost-effective to manufacture and minimally harmful to the environment.

To make that possible, the easiest way would be to provide the recycler with information on the content and design of the batteries. Most battery packs contain no information about the chemistry of the anode, cathode or electrolyte, meaning that cells from different packs will throw up challenges at the processing level. The producer therefore needs to mandatorily provide a label with information about battery materials contained in those batteries to enable easier recycling.

Residual Value of Batteries

For reuse cases, a thorough analysis is needed on devising an accurate methodology for determining the residual value of an EV battery. The residual value is the price at which the battery goes for resale and depends entirely on the depreciation mechanism attributed to it. According to a 2017 report by Moody's Analytics, electric vehicles depreciate more or less the same as conventional vehicles in the first couple of years, and increase depreciation value in years three and four.[54] The residual value of a vehicle (which includes the battery) is estimated by automakers and finance providers to write lease contracts, decide on insurance premium as well as vehicle loan products. At the institutional level, the residual value of the EV battery defines the basis on which they sign contracts with manufacturers to take charge of EOL batteries.

For safe handling of lithium ion batteries: Lithium ion batteries are relatively less detrimental to the environment when compared to older batteries based on lead-acid or nickel-cadmium chemistries. The primary danger they pose is related to the high voltage electric charge that they can potentially contain. Regulation therefore needs to differentiate between high and low voltage batteries. The high voltage batteries used in vehicles and stationary and industrial energy storage applications are remarkably different from the lower voltage batteries used in consumer electronic devices. The difference in material content, manufacturing quality and safety hazards between the two needs to be defined better in order to regulate them differently. Regulations pertaining to labour skilling and specialization must be introduced.

Regulatory framework

The Ministry of Environment, Forest and Climate Change (MoEFCC) has released the Battery Waste Management Rules 2022 (BWMR 2022) which is a step ahead over its predecessor, the 2001 rules which was focused on lead acid batteries.

The new directives are wider in scope, especially keeping in view the advent of Lithium-ion batteries. It is technology agnostic and is directed at stakeholders involved in manufacture, import, sale, purchase and end-use of batteries and its components. It is based on the concept of 'polluters pay' principle placing the battery manufacturer in the middle of the battery recycling eco-system with Extended Producer Responsibility (EPR).

The producers (including importers) of batteries are responsible for collection and recycling/refurbishment of waste batteries and use of recovered materials from waste into new batteries. However, the BWMR 2022 does not have any scope for either incentivising recycling capacity in the country or streamlining collection of batteries, even though EV policies at the state level mention government intent to encourage battery recycling activities.

The EPR registration system is managed online on a centralised portal controlled by the central and state pollution control boards. The registration process is expected to capture granular information regarding quantity, weight of batteries along with dry weight of battery materials. The BWMR 2022 also suggests a deposit refund system or buy-back option for the producer to meet their EPR obligations. The producer is also expected to include 5 per cent of recovered material in the total dry weight of a battery by 2027-28, expanding to 20 per cent by 2030-31. The EPR certificate enables transactions and can be used by the recyclers/refurbishers to purchase waste batteries from producers.

The Rules list out limits and labelling requirements for batteries. Labels have to indicate limits on the use of heavy metals — cadmium, mercury and lead — and also have a picture of a crossed-out bin to indicate that the batteries cannot be binned and have to be handed out to a registered battery collector. (See Table 8: Environmental hazards of LIBs).

Table 8: Environmental hazards of LIBs

Component	Materials	Hazardous
Cathode	$LiNiO_2$, $LiMn_2O_4$, $LiCoO_2$, $LiFePO_4$, $LiNi_xCo_yMn_{1-x-y}O_2$	Heavy metals such as Ni and Co pose a threat to the environment and to human health
Electrolyte	$LiClO_4$, $LiPF_6$, $LiBF_4$, DMSO, PC, and DEC	Corrosive, produces hazardous gas such as HF, chlorine (Cl_2), carbon dioxide (CO_2), and carbon monoxide (CO) when burned
Binder	Polyvinylidene fluoride (PVDF), polytetrafluoroethylene (PTFE)	Produces Hydrogen Fluoride when heated

Source: Science Direct

However, the labelling requirements do not address issues with lithium-ion batteries. Information about lithium chemistries used in the battery on the label could enable more efficient and easier recycling processes. Different battery materials require different kinds of treatment at the recycling stage. Lack of information about chemistries would require the recycler to deploy additional resources to investigate the materials present in the spent battery feedstock before they can be processed.

Roadmap for standards & regulations for recycling

The roadmap for battery recycling will require a more integrated approach to regulation development. While waste management rules have provided for battery inspection, battery collection, battery disassembly, and also end producer responsibility, additional measures are needed to make this more robust.

Global assessments as those carried out by ICCT show that standards and regulations on battery durability, safety, and information accessibility are needed to optimize reuse and recycling processes. Information about the technical characteristics, state of health, and operation history of batteries is critical for optimizing reuse and recycling processes and ensuring safety.

Towards this the regulations must require that battery manufacturers disclose and track information on batteries, like the battery passport initiative in the EU. Battery traceability and battery information will be critical to this strategy to define tracking and indicate who is responsible for collecting the battery. China has a traceability management platform to track electric vehicle batteries throughout their lifetime. However, this traceability covers only during the vehicle's lifetime and does not cover the upstream process of battery material mining, extraction and manufacture. U.S. Department of Energy is supporting a pilot project to track electric vehicle batteries' life cycle.

Also, as manufacturers are continuously innovating their battery technologies there is a wide variety of battery configurations in design, shape, size, mass, or chemistry. It is necessary that the information on batteries is made available to optimize reuse practices. Standardize state-of-health metrics to inform decisions on second-life applications.

Mandatory battery durability requirements can incentivize the production of long-lasting batteries and thereby support second-life usage. Finally, defining safety standards for reuse and recycling can also be crucial for reducing risks.

So is introducing mandatory recovery rates and recycled content targets to ensure efficient recycling of all key battery materials.

The European Union adopted the new Batteries Regulation in July 2023 that specifically addresses sustainability and end-of-life requirements for electric vehicle batteries throughout their whole lifecycle.

India Opportunity

Much of the batteries in the early EVs are finding their way into second life applications now. Very few companies around the world have the expertise to recycle all the battery chemicals available in the world. In 2020, there was already over 40 GWh[55] of battery material that could be sourced and put through the extraction process. If India were to take on the challenge of recovering metals from battery volumes of that magnitude, the country has the potential of becoming the leading recycled battery metal supplier of the world. This will not only change the battery narrative from being a China focused one, it can have a positive impact on India's sustainability rank as well.

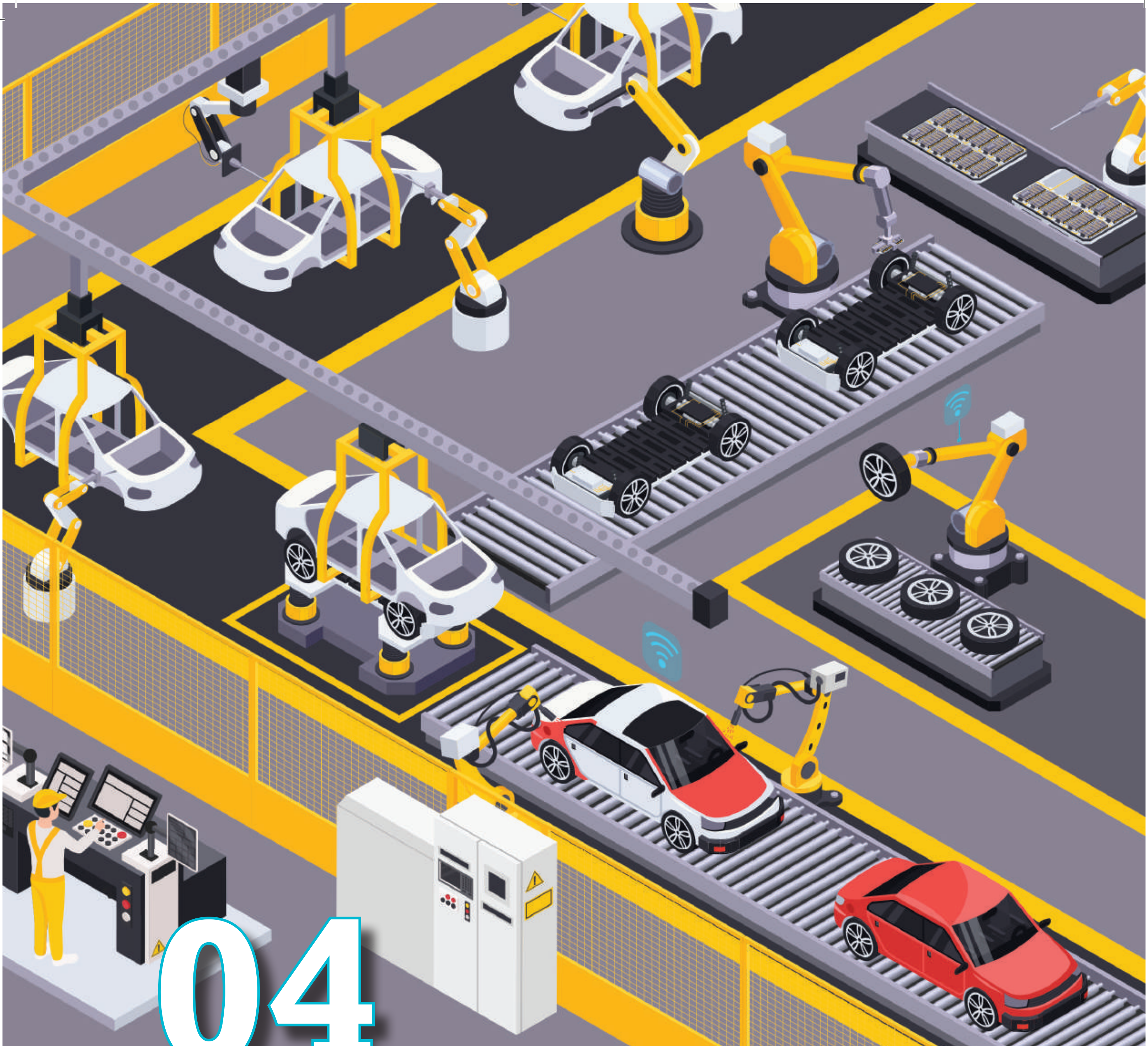
For India to make an entry as a serious player in the battery materials market, it is important to create a roadmap that includes a robust set of Battery Waste Management Rules, benchmarked practice of collection, segregation, testing for second use potential, disassembly and recycling.

Collection of lithium ion batteries pose a massive challenge in India. Since EV batteries are yet to arrive at the end of their design specified life, most lithium ion batteries in the used battery market are part of e-waste that comprises mobile phones and laptops – assets that are either passed down to relatives or traded. As a result, the quantum of lithium ion batteries reaching recyclers through the formal sector is very low, thus affecting economic viability of recycling operations.

Recycling processes are typically managed by kabadiwalas (scrap dealers) in an informal sector. This involves backyard smelters that do not comply with pollution and environmental norms and therefore offer better value against used lead acid batteries. Lithium ion batteries, however, cannot be treated using the same methods and require machinery and equipment that makes the whole set up a lot more capital intensive. Going forward, India's EV battery management and recycling strategy could incorporate the informal economy and its actors to build formal or semi-formal clusters. Safety during recycling is to be considered seriously since the end of life batteries may still retain 70 per cent of their initial capacity and may pose a significant thermal hazard.

The battery collection eco-system could receive a boost if battery producers have a mandated waste management budget to create a collection eco-system for lithium ion batteries. The budget could be linked with the compliance mechanism to provide momentum to the process. Currently, some manufacturers allocate a budget for managing end of life batteries. But, it is a voluntary decision and budgets differ from manufacturer to manufacturer. It is therefore imperative that the policy defines a budget range for producers to follow for allocation and implementation.

Another issue that plagues lithium ion batteries is their complexity. Compared with lead acid batteries, lithium ion batteries are much more complicated which affects recyclability.



04

RECOMMENDATIONS AND THE WAY FORWARD

With the rapid transition to sustainable modes of transport and the need to realize India's global clean energy commitments, electrification of road transport is a necessity for decarbonizing the sector. The Government of India has launched several incentive schemes to promote electrification in the country. However, these incentive schemes are time bound and industry need to gear up for long term goals which need to be self-sustainable. Therefore, there is a clear need to create strong R&D ecosystem and develop indigenous technologies in the areas of battery storage, electric propulsion, new materials, processes and promoting advanced manufacturing capabilities for sustainable economic viability with requirement of new manufacturing equipment/ machinery, electronic systems and networks.

As discussed in the Tropical EV battery R&D Roadmap, focus on battery technology, examining the entire ecosystem from cell component materials to commercial cell manufacturing is imperative for India. The critical pathway outlined by the roadmap identify vital thrust areas that need to evolve for successful implementation of battery technology for Indian EVs. India needs a battery that can operate at its optimum, and is safe and durable, in tropical climatic conditions and with the unique vehicle segments in India. These requirements can be fulfilled only with a deep scientific program that works at the cell level.

Battery cell technology selection and development

The focus can be divided into two categories based on the TRL:

1. Short-to-medium term (high TRL) where the goal is to enable quick vehicle electrification especially in the low-cost and low-load two- and three-wheeler segments, with subsequent extension to four wheelers. The battery chemistry may involve on the cathode side, NMC at varying nickel and cobalt contents, LFP, and its variant LMFP (contains manganese); candidates on the anode side include LTO, graphite, silicon-based anodes, and supercapacitors. The lab-scale studies can be completed in a short time frame since these technologies are well understood. The scale-up studies as described above are still required to provide data for manufacturing although this can also be achieved quickly. Thus, indigenous battery cells of high quality and low cost can be achieved and can be available to OEMs so that our EVs are on par with those in global markets.
2. Long-term (low TRL) technologies that are promising but not yet matured to large-scale production. The candidates are sodium ion batteries (SIB) and solid-state batteries (SSB). Metal-air batteries, especially zinc-air and aluminium-air batteries, also need to be evaluated from India context. Other promising technologies may emerge, given the extensive studies and innovations in India and globally in cell technology development. Such development may be further refined to specifically cater to Indian conditions. Promising results from lab scale may qualify the candidate technology for the scale-up phase.

Additional development work may also focus on indigenous manufacturing of cell raw materials such as cathode and anode active materials, current collectors, electrolyte, etc. Opportunities exist, for example with CAM, for tailoring the material for superior thermal performance and stability. CAM with reduced cobalt content is another opportunity. It will also be useful to explore metallurgical processing of lithium to produce CAM precursors in the event we gain access to lithium from mines.

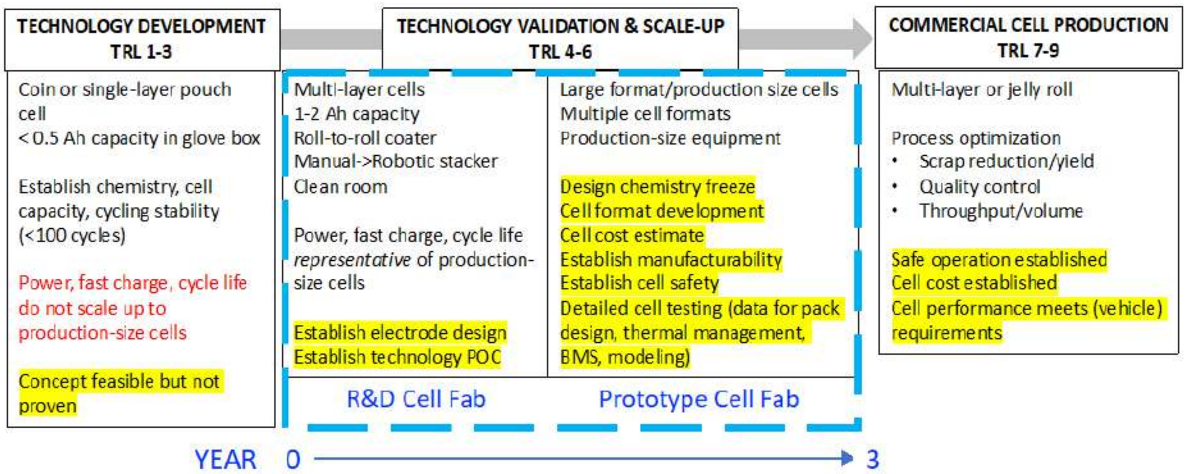
Other focus areas may include high-voltage cathodes and non-flammable electrolytes.

Battery cell technology scale up to manufacturing

Battery cell R&D and prototype fabrication and testing

The steps necessary to take a cell technology concept from a research lab (TRL 1-3) to full-scale manufacturing (TRL 7-9) (See Figure 30: Battery cell technology – research to manufacturing) R&D and Prototype cell fabrication and testing facilities (TRL 4-6) are identified as critical pieces in this evolution.

Figure 30: Battery cell technology – research to manufacturing



Source: CSE compilation

The first scale up step will involve an R&D Cell Fab facility which fabricates multi-layer pouch cells with small capacity with its own cell testing facility. The test data from such a cell is representative of (not the same as) production-size cells and establishes technology proof-of-concept (POC). The process steps will be similar to those in a cell manufacturing plant with slurry mixing units, roll-to-roll coaters, and automated cell assembly but at a smaller scale. Each centre will also include cell testing and characterization capabilities. Successful results would establish technology proof of concept and electrode design, ready for the next scale up phase. Several such facilities are needed, located at key R&D centres in India. After successful POC, the next step is evaluation with full capacity cell builds in a prototype facility.

The second scale up step involves a Prototype Cell Fab centre, which is a larger facility that mimics a commercial manufacturing process but at a lower throughput; it should have the capability to build production size cells at multiple formats (cylindrical, prismatic, pouch). An extensive testing lab with multiple cyclers/thermal chambers as well as analytical and safety labs may be co-located. The purpose of such a centre is to demonstrate techno-commercial viability of a candidate cell technology for full-scale cell manufacturing and subsequent implementation in EVs. The data and knowledge derived will enable cell manufacturers to rapidly translate a cell technology into full-scale production. This is envisioned as a centre that is accessible to various R&D activities across India with streamlined operation and administration (including scheduling).

Cell manufacturing support

Most of the manufacturing equipment is imported and need to shift to domestic development. There should be a target-oriented dialog between battery manufacturers, production researchers and the machine & plant engineering industry for low-cost indigenization of critical equipment. Expertise can be drawn from the pharma and textile industry. Indigenous cell manufacturing should target frugal innovation to simplify processes, increase throughput and lower costs. Other focus areas may include development of dry coating technology, advanced welding techniques, special integrated machines for punching and stacking, and building of low-cost clean and dry rooms.

The manufacturing process can be shortened with dry coating of electrodes, a new technique of electrode fabrication, which utilizes a shortened "powder–film" process instead of the conventional "powder–slurry–film" wet-solvent process.

Supplier development

Beyond raw material sourcing challenges, the electric vehicle cell and battery industry in India also faces a component manufacturing vacuum. Manufacturers typically import all components – current collector foils, separators, cathode and anode active materials as well as casings. There is an urgent need to develop an EV battery supply base in the country which is tailored for India specific requirements wherein high energy density (requirements of western countries) can be sacrificed for robust temperature tolerance, lower cost, high cycle life and fast charging requirements. Vertical consolidation spanning tier1, tier2 and tier3 suppliers will lead to cell-to-pack-to-vehicle integration. This will enable specific interventions from the ground up regarding engineering decisions like energy-power density trade-offs and thermal management systems.

Implementation of battery technology in EVs

Cell modelling and diagnostics

For all candidate cells, the R&D and Prototype Fabrication Centres described above generate a wealth of test data which can be used to establish physics-based cell models and cell failure diagnosis. Physics-based and machine learning based battery models can render optimum battery performance and accurate prediction of battery life; pack models incorporating thermal behaviour are needed for mitigating thermal runaway. Models can rapidly screen multiple pack design and battery operation scenarios, saving the OEMs significant time and cost. Cell diagnostics techniques can be developed for early warning against thermal runaway and battery capacity failure which can enhance the safety and save OEMs high battery replacement costs. The diagnostics and models may also be deployed on board by incorporating into the battery BMS. There is a case for on-board cell diagnostics that can be done for swappable batteries. The diagnostics can be run before a new pack is inserted into the vehicle providing information on the health of the battery and the likelihood of degradation.

Safety and durability

As mentioned above, test data and pack thermal models can be used to select technology options such as pack potting materials or cooling system, to mitigate thermal runaway. A Safety Lab will be part of the Prototype Cell Fabrication and Test Centre with specialized equipment for studying thermal runaway. It will include an Accelerated Rate Calorimeter (ARC) which can characterize the battery cell as it undergoes thermal runaway and a Differential Scanning Calorimeter (DSC) to characterize cell component materials. The ARC will be fitted with various sensors to measure voltage, temperature, pressure, smoke, gas, etc. during thermal runaway to identify early warning systems in the event of fire. These studies can help select cell chemistries and electrolytes that reduce thermal runaway risks. The wealth of data available will also be used to identify cell degradation mechanisms and hence build physics-based cell degradation models. These models can be used to predict cell life and set warranty costs. Safety and durability prediction tools are critically needed by the OEMs to meet important customer needs.

Battery Management System

The BMS relies on the battery voltage data and Coulomb count and keeps track of battery state of charge (SOC), and state of health (SOH). Cells with LFP exhibit a flat voltage profile, making it challenging to estimate SOC from voltage data. Along with a flat OCV curve, LFP and Sodium batteries also show remarkable hysteresis properties which need to be accounted for. Advanced techniques incorporating EIS, Differential Capacity Analysis, Kalman filters, physics-based models and machine learning tools need to be developed and deployed under the BMS.

Battery Thermal Management System

Battery cooling strategies vary with application (two to four wheelers), cell chemistry, and cell type. They include air cooling, indirect liquid cooling, direct liquid immersion cooling, tab cooling and phase change materials. The areas to be considered may include (a) engineering the battery pack for better heat dissipation during charging and discharging at various rates and (b) use temperature data from cell characterization for building models to aid with robust pack design and thermal management.

Building safety standards

Taking cognizance of the gap in the regulatory framework with the assembly of light electric vehicle batteries, the government set up an expert committee to build safety standards for battery, BMS, and related components in electric vehicles. Standards and regulations would need to drive the terms of technology development. For example, adherence to standards will require outstanding manufacturing practices and quality control, reducing thermal runaway incidents.

AIS 156 and AIS 038 (Rev 2) are the two main standards pertinent to EV battery safety. The current standards and test protocols requires a deeper investigation to assess the gaps in addressing the critical safety parameters and interface with the climatic conditions. Lack of testing and understanding on the quality of imported cells create safety issues. Standards also currently do not address issues arising from customer abuse, unauthorised rework and second life qualification.

» Initiatives such as the update of legacy standards, development of new standards, adoption of standardized testing protocols, and standardization of data collection are needed. Validation of new standards also need to be taken up.

» Testing facilities which replicate real-world conditions have to be expanded and made easily accessible to the research community. There is a need for establishing a comprehensive test facility as per the BIS/IEC standards for battery performance and safety testing.

Circular Economy

Battery raw material security

Raw materials comprise over 60 per cent of the cost of a lithium ion cell, and India has very limited known reserves of lithium and there is not enough cobalt, nickel and graphite to hedge against uncertainties in the battery supply chain driven by global politico-economic changes. It is imperative that India builds a concrete plan to address uncertainties in battery material sourcing with an alternative plan to offset potential tightening of the supply chain. More innovation is needed to improve battery chemistries to substitute or minimise the use of materials that face the problem of unstable supply chains and higher costs. This would call for focus on LFP, LMFP, LMO and LTO-LMO cells as well as a major shift towards sodium-ion chemistry.

International partnership initiatives are also essential for access to raw materials. India is now part of the coveted critical minerals club, MSP (Mineral Security Partnership) consisting of 13 members, headed by the United States. More international and private-public partnerships will need to be fostered.

Battery reuse

End of life for an EV battery is when the battery capacity drops to 80 per cent of the rated capacity. However, batteries can still deliver usable power below 80 per cent charge capacity, although they will produce shorter run-times. For a reuse case, however, it is essential to determine the residual value of the battery using accurate State of Health

(SOH) prediction tools. Efforts to develop reuse applications such as stationary storage, grid balancing, and backup power are required.

Battery recycling

Even though the EV market in India is in its nascent stage, early action towards battery recycling can partially offset the material scarcity and cost and reduce waste. Within a cell, the recyclability of each of the components varies. Recycling is a challenging process and recycling-friendly battery design would need innovation but can yield benefits critical for India ecosystem. One of the biggest challenges to be addressed with circular economy of EV batteries is collection of the batteries.

Creation of Centres of Excellence (CoEs) for Battery Research Program

Considering the nature of projects that may emerge which are interdisciplinary in nature, there is a need to develop consortium approach wherein expertise from different fields may be pooled in to address the identified scientific problem. Therefore, it is proposed that the centres of excellence may be created in the identified thematic areas. A suggested Centre of Excellence is shown in Figure 31. Here, each theme may become a consortium with lead and other participating agencies with defined objectives/goals and deliverables. The projects may advance through various stages of scale up, after demonstrated success at each stage.

Structure of the CoEs

a. The Program may envisage a direct collaboration between successful manufacturing enterprises with national laboratories. Specific provision will be made for large participation by SMEs and Start-ups in the R&D consortia.

b. The plan work may cover technology development, validation, field trials, small volume production of key materials & subsystems, with an emphasis on developing the ability to manufacture suitable EV Components in India.

c. The CoEs may house capabilities such as advanced test facilities and limited production facilities,

d. Government may provide risk sharing investments in R&D whereas industry may provide funding support in kind. Industry is expected to engage in research activities, along with researchers, academics and technology specialists from component companies.

e. A large number of patents are likely to be generated in such joint research which can translate into products.

Measurable results expected from CoE include:

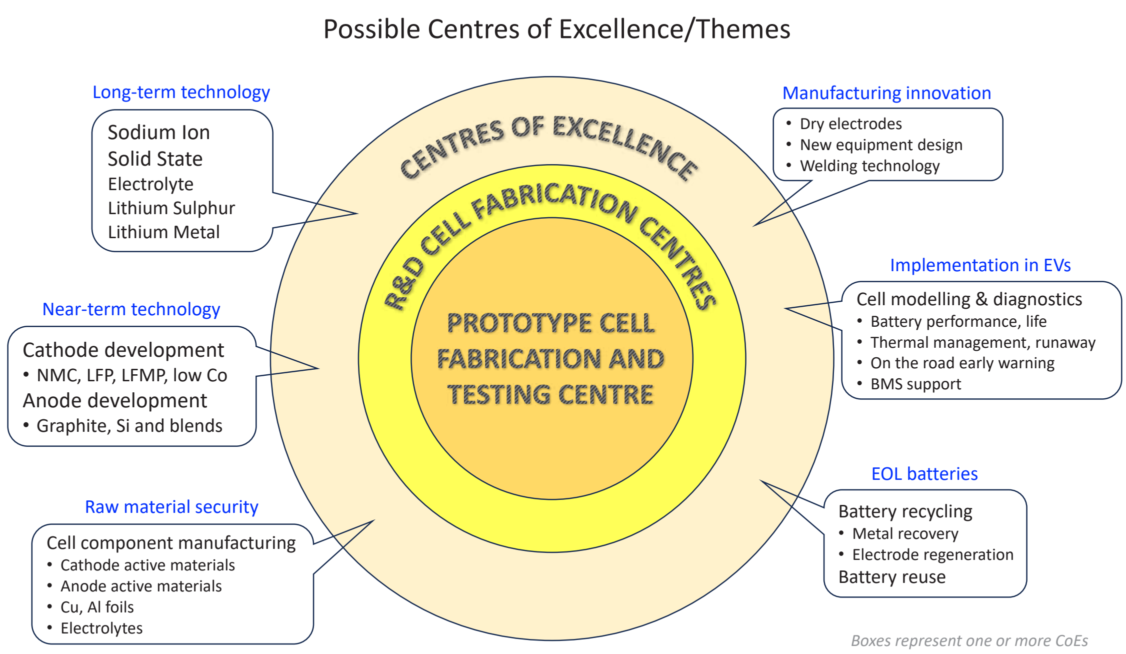
a. Skill development: A large pool of expert human resources will be developed in the country in the new and advanced technologies.

b. Development of components and systems: A wide variety of new EV components/ subsystems/ systems & platform technologies are expected to be developed under the CoEs. They will be utilized by the participating companies in the program. They may also be licensed to third parties.

c. Incubation of component companies: Several industries capable of producing material and machinery to support the electric vehicle component industry is expected to evolve.

d. The measurable indicator of outcome in the technology development projects is expressed as the target Technology Readiness Levels (TRL) targeted under each project.

Figure 31: Possible Centres of Excellence/Themes



GLOSSARY

2W = Two-wheeler vehicles

3W = Three-wheeler vehicles

AAM = Anode Active Material

Accelerated Rate Calorimetry = Analytical technique used to study the thermal behaviour of substances, particularly their reaction kinetics and heat release rates

AIS = Automotive Industry Standards, formulated by ARAI (Automotive Research Association of India)

Allotropes = Allotropes are different structural forms of the same element and can exhibit quite different physical properties and chemical behaviours

Anode = Negative electrode of a battery cell at which oxidation reaction occurs

Anolyte = The portion of an electrolyte near an anode

Arrhenius equation = mathematical formula that describes the temperature dependence of chemical reaction rates

Battery = A battery is a device for turning chemical energy into electrical energy, consisting of a number of primary or secondary cells arranged in series or parallel

Battery Management System = Electronic control circuits that monitor and regulate the charging and discharging of batteries

BWMR = Battery Waste Management Rules

Calendar ageing = Degradation of a cell's capacity and performance over time independently of the number of charge and discharge cycles a cell undergoes and is primarily related to the passage of time

Calendar life = The number of years that the battery can be in service before its degradation/ replacement

CAM = Cathode Active Material

Capacity fade = Gradual loss of a battery's ability to store and deliver electrical energy over time

Cathode = Positive electrode of a cell at which reduction reaction occurs

Catholyte = The portion of an electrolyte near the cathode

Cell = The smallest independent current generating unit of a battery pack

CMVR = Central Motor Vehicles Rules, formulated by Ministry of Road Transport & Highways

Coulombic efficiency = Measure that quantifies the ratio of the amount of electrical charge that can be recovered during discharge (usable capacity) compared to the amount of electrical charge that was originally input during charging

Critical Materials = Critical materials are the resources needed to produce numerous key technologies for the energy transition, including wind turbines, solar panels, batteries for EVs and electrolysers

Current collector = A cell component which collects and efficiently conducts the flow of electrical current between the active electrode material (anode or cathode) and the external circuit

Cycle ageing = Gradual loss of a cell's capacity and performance over time as it undergoes charge and discharge cycles

Cycle life = The number of charge-discharge sequences that the battery can go through before degradation

Delithiation = Reverse intercalation or movement of lithium ions back to the cathode from anode

Dendrite = Dendrites are metallic microstructures that form on the negative electrode during the charging process

Dry room = A dehumidified cell manufacturing facility

EIS = Analytical technique used to study the electrochemical processes that occur at the interface of an electrode and an electrolyte solution

Electrochemical activity = Internal workings of the battery based on its electrical and chemical properties

Electrode = An overarching term used to refer to both anode and cathode

Electrolyte = The solid/liquid medium that enables charge and ion transfer between anode and cathode

Electrolyte wettability = It means the ability of liquid electrolytes to spread out on solid electrode surface

Energy density = The amount of energy stored per unit mass (gravimetric energy density, Wh/kg) or volume (volumetric energy density, Wh/L) of a battery

EoL = End of Life

EPR = Extended Producer Responsibility (EPR) as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle

EV = Electric Vehicles

Exothermic reaction = Chemical reaction in which energy is released in the form of heat

GSI = Geological Survey of India

HDVs = Heavy-duty vehicles

ICE vehicles = Internal Combustion Engine vehicles

Intercalation = The movement of positively charged cathodic ions into layers of anode material

Internal short circuit = Physical contact between the electrodes internally within a cell

Jahn Teller problem = The Jahn–Teller effect, sometimes also known as Jahn–Teller distortion, describes the geometrical distortion of molecules and ions that is associated with certain electron configurations

Knee point = It is the onset of rapid capacity loss in a battery

LCO = Lithium Cobalt Oxide

LFP = Lithium Iron Phosphate

LIB = Lithium Ion Battery

Lithiation = Intercalation process of lithium ions into the anode

Lithium plating = Deposition of metallic lithium on the anode

LMFP = Lithium Manganese Iron Phosphate

LMO = Lithium Manganese Oxide

LTO = Lithium Titanium Oxide

Melting point = The temperature at which a substance starts to change phase from solid to liquid

MoEFCC = The Ministry of Environment, Forest and Climate Change

MRAI = Metal Recycling Association of India

MRL = Manufacturing Readiness Level

NCA = Nickel Cobalt Aluminium Oxide

NMC = Nickel Manganese Cobalt

OCV = Open circuit voltage across the terminals of a cell

OEM = An original equipment manufacturer is generally perceived as a company that produces non-aftermarket parts and equipment that may be marketed by another manufacturer

PLI = Production Linked Incentive

Power density = The amount of power delivered per unit mass of the battery, usually measured in W/kg

Powertrain = Assembly of components responsible for movement of a vehicle

Ragone plot = A commonly used graph of power density versus energy density showing the inverse relationship between the two

SEI = The solid-electrolyte interphase (SEI) is a passivating layer formed on the electrode/electrolyte interface, which, under ideal conditions, is stable during cycling, permits fast lithium transport and, at the same time, is an electronic insulator

SIB = Sodium Ion Battery

SoC = State of charge, represents the current amount of electrical charge stored in a battery or energy storage system, relative to its maximum capacity

SoH = State of Health, represents the ratio of the actual or current capacity of a battery to its original rated capacity when it was new

Specific capacity = The total energy carried by an EV battery

SSB = Solid State Battery

STIP = Science, Technology and Innovation Policy

Thermal runaway = It is the process of rapid heat generation in a battery because of uncontrolled electrochemical activity, leading to battery fire

Thermal stability = The ability of a cell to continue safe operations at elevated temperatures

TRL = Technology Readiness Level (an index defined to measure the manufacturability and marketability of a new technology)

Tropical climate = Climatic conditions prevalent in the tropics like high temperature and humidity

UNECE = UN Economic Commission for Europe

LIST OF AUTHORS AND CONTRIBUTORS

R&D Roadmap Coordinator: Mr. Suresh Babu Muttana, Scientist E, DST

ADVISORY COMMITTEE	
1. Prof. B G Fernandes, Indian Institute of Technology (IIT), Bombay	Chairman
2. Dr. Anita Gupta, Head, Climate, Energy and Sustainable Technology (CEST) Division, Department of Science & Technology (DST), GoI	Co-chair
3. Prof. Siddhartha Mukhopadhyay, IIT Kharagpur 4. Mr. Sajid Mubashir (former) Scientist G, Department of Science & Technology, GoI 5. Dr. Raghunathan, Professor of Practice, IIT Madras; Former Technical Fellow-General Motors - Battery Cell Technology 6. Mr. Suuhas Tenddulkar, Program Director, Environmental Resource Foundation (ERF) 7. Ms. Veena Koodli, Technical Expert EV charging, Robert Bosch, Bangalore 8. Dr. Z V Lakaparampil (former) Sr. Director, C-DAC, Trivandrum 9. Dr. Kiran Deshmukh, Executive Director, Sona COMSTAR 10. Prof. Vijay Mohanan Pillai, IISER, Tirupati 11. Dr. A Ramesha, Director, CECRI, Karaikudi	Technical Advisors
12. Mr. Suresh Babu Muttana, Scientist E, DST	Member Secretary

Contributors of R&D Roadmap

TROPICAL EV BATTERY	
Authors	Ms. Moushumi Mohanty; Ms. Anumita Roy Chowdhury; Ms. Mrinal Tripathi; Mr. Rohit Garg; Ms. Anannya Das; Centre for Science and Environment (CSE) Dr Raghunathan K, Indian Institute of Technology, Madras, Convener, Sub-Committee on EV Battery Mr. Sajid Mubashir, Department of Science and Technology, GoI Mr. Suresh Babu Muttana, Department of Science and Technology, GoI
Contributors	Dr Prabhakar Patil, Ola Electric Dr. Rajendrakumar Sharma, SPEL Technologies Pvt. Ltd. Mr. Swapnil Jain, Ather Energy Dr Shreyas Seethapathy, Ather Energy Dr. Akshay Singhal, Log9 Materials Dr. Vineet Dravid, Oorja Energy Mr Feroz Khan, Hero MotoCorp Ltd. Mr Manjunath Vittala Rao, Underwriters Laboratories Mr. A. J. Prasad, HBL Power Systems Ltd. Dr. Rahul Walawalkar, IESA Dr Ajinkya Kamat, IESA Dr. Manne Venkateswarlu, IESA Dr. Shashank Sripad, Battery Aero, California, US Mr. Rajat Verma, Lohum Cleantech Dr. Satish Chandra B. Ogale, IISER, Pune Prof. Siddhartha Mukhopadhyay, IIT, Kharagpur Dr Tata Narasingha Rao, ARCI, Hyderabad Dr Abhik Banerjee, Research Institute for Sustainable Energy (RISE) Dr Prasada Rao, National University of Singapore Dr Yogesh Kumar Sharma, IIT, Roorkee Dr Sindhuja, CSIR-CECRI Dr. Vijay Mohanan Pillai, IISER, Tirupati Prof. Michael Pecht, University of Maryland Dr Pooja Vadhva, University College London Mr. Sharif Qamar, TERI Dr. Anurag Verma, DST & TERI

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35 Under the Central Motor Vehicle Rules, the L category covers light motor vehicles ranging from two wheelers to three wheelers, for both passenger and goods transport

36 When an event or prediction derives from a random process or random probability distribution, it is described as "stochastic".

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38 Dendrites, whose name comes from the Latin for branches, are projections of lithium metal that can build up on the anode surface and penetrate into the solid electrolyte interface, eventually crossing from one electrode to the other and shorting out the battery cell.

39 The Solid Electrolyte Interphase (SEI) is a layer that forms at the anode surface for all alkali metal ion batteries which utilize liquid electrolytes. The SEI protects the anode by inhibiting the transfer of electrons from the anode to the electrolyte, whilst also allowing metal ions to transfer from the electrolyte to the anode. The ideal SEI is therefore both an ionic conductor and an electrical insulator.

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41 Tabs are metallic connectors between the current collector of the cell and the external load

42 India is a signatory to the 1998 agreement of the World Forum for Harmonization of Vehicle Regulations(WP.29). WP.29 has the mandate to implement worldwide vehicle safety regulations

43 IS16893 covers secondary lithium-ion cells for the propulsion of electric road vehicles: Part 2 includes capacity check, vibration, mechanical shock, crush, high-temperature endurance, temperature cycling, external short-circuit, overcharging and forced discharging) and Part 3 covers safety requirements

44 IPX7 refers to battery being submerged in water for 30 minutes at a depth of 1 meter

45 Type approval certificate is mandatory for any new model, approval for any engineering changes in running models or for compliance to any newly notified requirement

46 Continued compliance to the mandatory requirements (Conformity of Production) is verified by carrying out testing/verification of the randomly selected vehicle/engine and component (as the case may be)

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DEPARTMENT OF
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सत्यमेव जयते

Climate, Energy and Sustainable Technology (CEST) Division
Department of Science & Technology (DST)
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