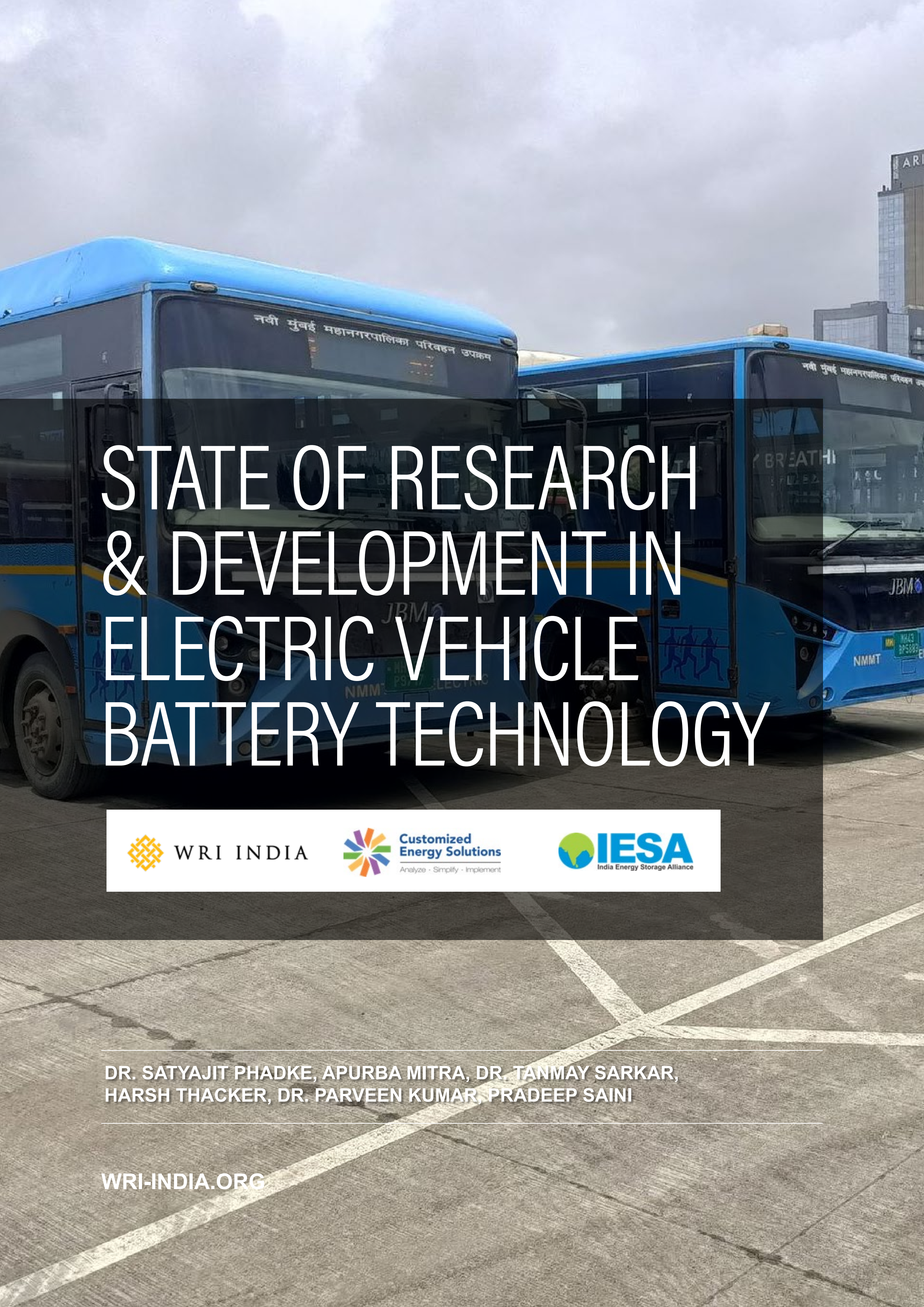

STATE OF RESEARCH & DEVELOPMENT IN ELECTRIC VEHICLE BATTERY TECHNOLOGY

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FOREWORD

The challenges of recent years — whether the COVID crisis, severe air pollution, or the growing impacts of climate change — have reminded us all about the interlinkages between health, environment, and the economy. These interlinkages are also evident in the large-scale shift from internal combustion vehicles powered by fossil fuels to electric vehicles (EVs) powered by clean, low-carbon energy sources.

Accelerating this shift can yield multiple benefits for India: enhanced energy security, cleaner air, and fewer heat-trapping emissions. Recognizing this, the government of India has introduced several measures to incentivize the manufacture and purchase of EVs at the national and sub-national levels. The manufacturing of EV batteries, the most expensive component of an EV, is also being incentivized through schemes such as the Production Linked Incentive (PLI), which aligns with the "Make in India" and "Atmanirbhar Bharat" (Self-reliant India) efforts.

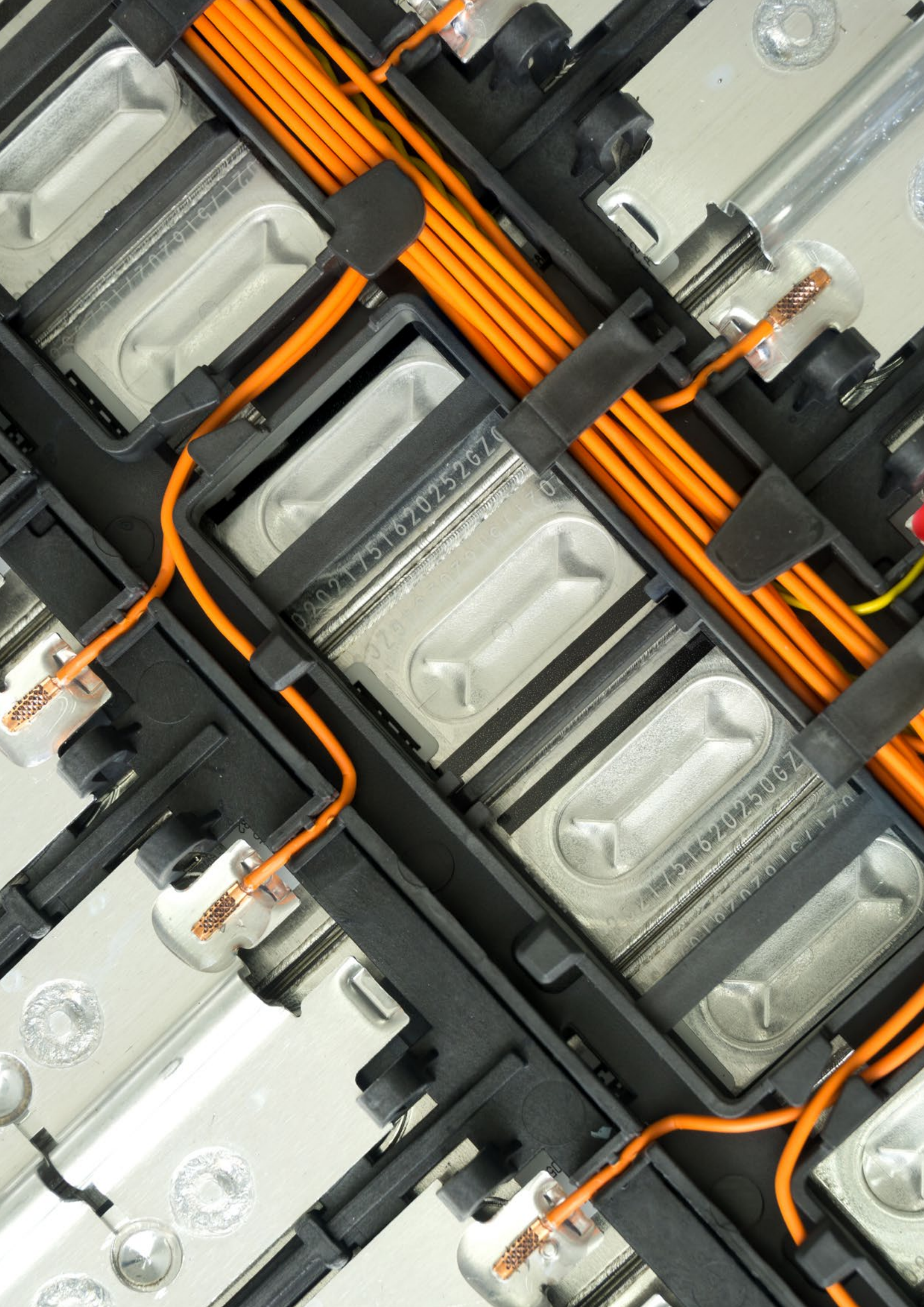
One important obstacle to achieving the EV transition is the disconnect between academia and industry, which can slow EV battery innovation. This report helps to address this gap by providing the latest information on the state of R&D in battery technologies as well as actionable recommendations on how to strengthen industry–academia collaboration.

The authors present key features of successful R&D programs in the United States, Europe, Japan, China, and Australia. Drawing on these experiences, they suggest measures to make India's journey from lab-scale technologies to commercial prototypes faster and more efficient. For example, build a network of technology incubators and Centers of Excellence to advance battery performance, testing, and skill development.

Another potential obstacle is lack of access to the necessary raw materials. Several promising battery technologies are poised to accelerate the adoption of EVs. These include the Li-ion batteries that dominate the market today and new batteries in development, such as Solid-state batteries (SSBs), Li-S, Metal-air, and Na-ion technologies. However, resource availability could be a significant constraint in the future towards. For the raw materials that India lacks, locking in arrangements now to procure ores or concentrates from other countries in the future would be extremely advantageous. Additionally, the early creation of a closed recycling loop, where all materials that go into a battery are re-used at the end of its life, can enhance resource security while creating a sustainable battery life cycle.

India's commitment to increase the manufacture and purchase of EVs by focusing on the crucial battery sector is off to a great start. We hope that this paper serves as a useful guide for relevant policymakers, academics, equipment manufacturers, and auto manufacturers to make informed decisions and foster the technology partnerships that the country needs to fulfil its potential to become a global EV battery powerhouse.

Ani Dasgupta
President and CEO
World Resources Institute



EXECUTIVE SUMMARY

Sustainable storage solutions are crucial to achieving deep decarbonization of the transport sector in the future, and substantial investment is being poured into research and development of battery-based solutions worldwide. Efforts directed at reducing battery cost, increasing energy density, improving durability and lifetime, among other improvements, are being ramped up in a bid to rapidly enhance battery performance and affordability. This report presents a summary of commercially available EV battery technologies, as well as battery research focused on developing alternative technologies, and provides recommendations on how to strengthen industry–academia collaboration in the country.

HIGHLIGHTS

- Today, lithium-ion (Li-ion) batteries have established themselves as the leading storage technology for transportation applications. There are multiple Li-ion technologies with different types of chemistries, each with its distinct performance characteristics, depending on the application requirements and vehicle size.
- Energy storage for electric vehicles (EVs) is a continually evolving set of technologies owing to the introduction of next-generation chemistries (such as lithium-sulfur batteries, solid-state batteries, inorganic liquid electrolytes, high-voltage cathodes, and silicon and lithium metal anodes) and the gradually declining use of older chemistries.
- Stronger collaboration must be established between industry and academia if advanced technologies are to be developed in India. A healthy network of incubation centers and centers of excellence (CoEs) can help bridge the gap between industry and academia and stimulate the creation of a new start-up ecosystem in the field of clean energy technologies.
- Infrastructure for recycling Li-ion batteries must be set up in parallel with the development of Gigafactories and other battery-industry-related efforts, as recycling may become an important source of raw materials in the future.

Introduction

Within the transportation sector, electric mobility transition is a core pillar of deep decarbonization as it has the potential to make renewable power a significant low-cost transportation fuel in the future. Although our electricity grid is currently dominated by fossil fuels, India has ambitious renewable energy plans that could significantly decarbonize the grid in the long term. This could enable EVs to decarbonize the transportation sector substantially in the future, unlike its contribution today, which is moderated by a fossil-fuel-dominated grid. India acknowledges the merits of this transition from internal combustion engine vehicles to EVs and has introduced several national- and state-level policies and incentives to promote it. Electric mobility, apart from addressing climate change concerns, will also help reduce India's oil import bill and enable it to move in the direction of energy independence and self-reliance.

About the Report

This report presents a snapshot of commercially available EV battery technologies today as well as the state of R&D in EV battery technologies. It also provides recommendations on how to strengthen industry–academia collaboration to promote uptake of these technologies.

In this study, we have attempted to cover the breadth of available technological solutions for EV batteries in India. Many promising developments are occurring around the world, with researchers focused on key aspects, such as reducing battery cost, increasing energy density, and improving durability and lifetime. In this paper, we explore battery designs, chemistries, and cell formats and assess their potential in making the transition to EVs economically feasible in a resource-secure way for India. The report focuses on the current commercially available battery technologies as well as on battery research aimed at developing alternative technologies. The study explores the research and development (R&D) landscape for these batteries and investigates how the R&D community can work collaboratively and effectively with industry to address the challenges associated with the manufacture and uptake of battery technologies.

Research Problem

Advanced battery manufacturing in India is in the nascent stage, and the supply chain for the industry has yet to be established—from minerals procurement to battery production. One of the deterrents to accelerated adoption that was identified by auto manufacturers and OEMs in our interactions with them is the uncertainty related to evolving technologies/cell chemistries, which is perceived as a risk to investors, especially in a rapidly advancing technology environment. We wanted to explore this aspect, to be able to understand whether this threat is substantiated and whether the evolution of new technologies does pose a threat to the currently envisaged manufacturing units. One way to address this concern is to strengthen the collaboration between R&D institutions and industry within the country, which is currently weak. Another method is to regularly monitor the promising new developments in R&D, worldwide and within India, in the EV battery space. This report thus presents a summary of commercially available EV battery technologies in India and compares them across several dimensions, while also presenting a snapshot of the state of R&D on these topics and providing recommendations on how to strengthen industry academia collaboration.

Research Method

We conducted extensive literature reviews and consulted experts from academia and industry to identify a comprehensive set of commercially available battery technologies and compare them on different dimensions. We also consulted with experts within the battery R&D community to identify challenges and discuss strategies to enhance industry–academia collaboration. We benefited from the insights shared by technical and strategic experts in one preliminary workshop and thereafter through individual consultations and two expert workshops with several organizations, including battery manufacturers, research organizations, and universities.

Key Conclusions

Several policies and initiatives have been introduced by the Indian government to speed up the adoption of EVs in the country. These efforts span various central ministries, including the Department of Heavy Industries (DHI), NITI Aayog, Ministry of Power (MoP), Ministry of Urban Development (MoUD), Ministry of Road Transportation and Highways (MoRTH), and the Department of Science and Technology (DST). Most notably, the FAME II scheme (DHI), which gives subsidies for EVs, and the Production Linked Incentive scheme (NITI Aayog), which subsidizes the setting up of Li-ion cell-manufacturing Gigafactories, are aimed at fast-tracking the transformation in the transportation sector. Several state governments, including Karnataka, Maharashtra, Telangana, Uttar Pradesh, Kerala, Uttarakhand, and Delhi, have also taken steps to further developments in this space. These state-led initiatives include various activities such as providing funding for setting up of CoEs for R&D, incubation centers for clean energy start-ups, tax exemptions for EVs, promotion of skill development activities, adoption of e-buses for intracity public transportation, and setting up of charging infrastructure. These initiatives are in different stages of planning, and some of them have already been launched. The picture varies from to state to state.

Several existing and next-generation energy storage technologies are suitable for application to EVs in the current context. Li-ion batteries are the leading technology for transportation applications. Li-ion batteries encapsulate multiple chemistries such as nickel manganese cobalt (NMC), lithium iron phosphate (LFP), and lithium titanium oxide (LTO), which are used depending on the application requirements and vehicle size. However, this is a continually evolving landscape due to the introduction of next-generation chemistries and the gradually declining use of older chemistries. In this paper, we have presented a comparative technical evaluation of the performance of the old and new battery chemistries. In the battery development space, the trend has been toward maximizing the energy density of battery packs, which has led to rapid progress in the development of lithium-sulfur (LiS) batteries, solid-state batteries (inorganic and gel/polymer type), inorganic liquid electrolytes, high-voltage cathodes (>4.5 V), and silicon and lithium metal anodes. We have tried to present a balanced view of this complex landscape of technologies, noting the impressive features of the advanced technologies that will be a part of the future while pointing out the challenges to their commercialization and widespread adoption.

In addition to batteries, polymer electrolyte membrane fuel cells (PEMFCs) powered by hydrogen could be a suitable solution for heavy vehicles, including trucks, small boats, and airplanes requiring constant power and very long travel ranges. However, their eventual adoption will largely depend on the cost reductions in the technology and on the availability of hydrogen fuel. Due to the high technological maturity of Li-ion technology for EVs, we have especially focused on its plant design requirements and manufacturing process. Through in-depth consultations with various cell-manufacturing companies in different parts of the world, we have come to the conclusion that the changing chemistries in Li-ion do not pose an immediate threat to existing manufacturing facilities, as at present the cell design and manufacturing processes are largely independent of the chemistries.

Way Forward

Raw materials account for more than 50 percent of the total cost of cells, and a robust supply chain is critical to ensure the cost competitiveness of the end product. With this objective, in this report, we present a detailed analysis of the requirements of eight key raw materials (Li, Mn, Ni, Co, Cu, Al, graphite, and Ti), separators, and electrolytes in metric tons (1 metric ton = 1,000 kg) normalized for 1 gigawatt hour (GWh) of Li-ion cell manufacturing. India has existing reserves of Mn, Ni, Cu, and Al. For these ores, an attempt should be made to produce high-value battery components that local and international cell-manufacturing companies can use. These key raw materials and components are MnSO4, NiSO4, copper foil current collector, and alumi- num foil current collector. In the case of graphite, existing reserves should be evaluated for avail- ability of large-flake graphite content, which is directly applicable as anode material. Synthetic graphite produced from coke is finding increased use as an alternative anode material. Even if the reserves are inadequate, facilities for processing ore and producing a high-value product for Li-ion batteries can be set up locally. India has no reserves of the other raw materials (Co and Li), and for these, adequate arrangements for procuring ores or concentrates from other countries should be made. Localized processing of lithium concentrates is beneficial for the battery industry from a reliability and purity perspective. Purity of lithium raw materials such as Li_2CO_3 and LiOH is crucial for achieving long cycle life.

In addition, it is suggested that infrastructure for recycling Li-ion batteries should be set up in parallel with the development of Gigafactories and other battery-industry-related efforts. Recycled batteries from EVs will become a prominent source of raw materials via “urban mining.” The initial setups could be in the form of pilot plants for recycling small volumes of Li-ion batteries. These can be great tools for skill development and for recycling process optimization. Refurbishment centers could also be established prior to recycling to enable second life use in stationary applications. A strong and mutually beneficial collaboration between industry and academia is needed to develop advanced technologies in India. Currently, the framework for taking lab-scale technologies (Technology Readiness Level, TRL = 1–4) to commercial prototype stage (TRL = 5–7) is fragmented and ineffective. Convergence with MRL (Manufacturing Readiness Levels) is also needed within this framework. As a result, many of the innovations created in universities and research institutes are not able to move to the next stage of the development phase. A healthy network of incubation centers and COEs can help bridge the gap between industry and academia and foster the creation of a new start-up ecosystem in the field of clean energy technologies. The central and state governments have to take various measures and help create an ideal environment so that India can attract next-generation technologies from the global R&D community as well. In many parts of the world, technologies have been developed up to TRL = 5–6, which are ready for pilot plant manufacturing or in some cases for scaled-up manufacturing. Clear objectives regarding performance requirements combined with a robust infrastructure for testing and adequate incentives can pave the way for the fast growth of the indigenous manufacturing industry. We suggest that acquiring technologies for recycling batteries should also be given prominence along with the actual storage technologies. Skill development in the space of Li-ion cell manufacturing will be critical for supporting large-scale manufacturing. In this respect, pilot plants for cell manufacturing can play a crucial role. These can be set up at a miniscule cost compared to a Gigafactory, and they serve multiple purposes: training and skill development in manufacturing, test-beds for optimizing the manufacturing process, and test-beds for testing new chemistries that have shown promise at the lab scale. Such small-scale setups can build a level of confidence in early entrepreneurs and interested industry stakeholders.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SECTION I

INTRODUCTION

Starting with the Faster Adoption and Manufacturing of Hybrid and Electric vehicle (FAME) scheme in 2019, several national and state-level policies and incentives have been introduced to speed up the manufacture and uptake of electric vehicles and battery technologies in India. Notable among them is the Production Linked Incentive (PLI) scheme for "National Programme on Advanced Chemistry Cell (ACC) battery storage" approved this year.

1.1 India's Push toward Electric Mobility

In 2017, the former Indian power minister announced the government's intention to eliminate the sale of petrol or diesel cars by 2030, aiming to reduce the petroleum import bill and running cost of vehicles while simultaneously reducing air pollution and mitigating climate change (NDTV Profit, 2017; NITI Aayog & World Energy Council, 2018). Accompanied by an equally ambitious program on the integration of renewable electricity into the grid, this would truly be a moon-shot mitigation target. However, with several voices suggesting caution, and pointing to technology, manufacturing capability, infrastructure, and finance challenges and implications, a planned national electric vehicle (EV) policy discussion was dropped, and the overall goal was revised to 30 percent of the total road share for EVs by 2030 (Financial Express, 2018; Energy Efficiency Services Limited, n.d.). Meanwhile, the Society of Indian Automobile Manufacturers suggested a target of 40 percent share for EVs by 2030 and 100 percent by 2047 (Society of Indian Automobile Manufacturers, 2017). The NITI Aayog plans to transition three-wheelers to full EVs by 2023 and two-wheelers with an engine capacity of less than 150 cc to full EVs by 2025.

However, several challenges must be addressed before this can happen: India's demand for EVs has been sluggish so far, due to the high initial cost of vehicles, lack of charging and maintenance infrastructure, and consumer perceptions around battery performance. Limited domestic battery-manufacturing capabilities and a nonexistent supply chain are hurdles to building EVs under the Government of India's "Make in India" framework. The fact that the supply of minerals needed for commercially available battery technologies—lithium, cobalt, and nickel–are dominated by a handful of countries is another bump in the road. Until 2020, India did not manufacture lithium-ion (Li-ion) cells, which were imported from China or Taiwan for assembly in India. Assembled battery packs were also being imported. India imported US$1.23 billion worth of Li-ion batteries between 2018 and 2019 (Saurabh, 2019).

To encourage greater adoption of EVs and manufacturing of batteries, central and state governments have taken several steps to promote EVs by launching various schemes and incentives. A timeline of national policy progress on EVs and battery technologies in India is provided in Figure 1.

1.2 Background and Approach

1.2.1 Need for the Study

The targets set in the Paris Agreement—to limit the global average temperature rise to well below 1.5°C above pre-industrial levels—are difficult to achieve with reasonably accessible technologies today, even when very stringent and ambitious abatement strategies are assumed. Hence, rapid technological advancement in the future is considered vital for bringing us closer to the targets. As transportation is one of the toughest sectors in which to achieve deep carbon emission reductions, a thorough understanding of technological solutions is imperative for us to put far-reaching solutions on the table, based on sound judgment and credible research. In particular, the electric mobility transition within the transportation sector is seen as a core pillar of deep decarbonization. Existing long-term strategies globally have typically identified it as a key priority, given that the transition can potentially enable renewable power to become a major low-cost transportation fuel in the future.

Through this study, we attempted to fundamentally improve our understanding of technological solutions for EV batteries through research and discussions with various experts/stakeholders over the duration of the study. Batteries contribute to a large component of overall EV costs, and thus high battery prices have a significant impact on EV manufacturing and sales. Many promising developments are occurring around the world, with researchers engaged in different aspects of battery research such as reducing battery cost, increasing energy density, and improving durability and lifetime. In this paper, we will explore battery designs, chemistries, and cell formats, and assess their potential in making the transit-

Figure 1 | **Timeline of National Policy Progress on Electric Vehicles and Battery Technologies in India**

2017

Guidelines for registration of OEMs (original equipment manufacturers) and vehicle models under FAME India scheme approved DHI

Notification for extension of Phase I up to March 31, 2018 Ministry of Heavy Industry and Public Enterprises & DHI

Notification to modify the scheme to amend electrical range targets for plug-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV) buses and specify new demand incentives for electric buses Ministry of Heavy Industry and Public Enterprises & DHI

Notification to modify the scheme to include L5 category is included in the Retrofitment category under vehicles eligible to obtain demand incentives with demand incentives specified for the newly added category of vehicles Ministry of Heavy Industry and Public Enterprises & DHI

Notification to modify FAME to include low-speed electric three-wheelers (with maximum speed not exceeding 25 km/hour) under vehicles eligible to obtain demand incentives, as well as to specify demand incentives for low-speed three-wheelers Ministry of Heavy Industry and Public Enterprises & DHI

Notification for extension of FAME Phase I up to September 30, 2017 Ministry of Heavy Industry and Public Enterprises & DHI

2012

National Electric Mobility Mission Plan (NEMMP), 2020

2012 2013 2014 2015 2016 2017

2015

Clarification regarding implementation of FAME India scheme Ministry of Heavy Industry and Public Enterprises & DHI

FAME India scheme guidelines issued Ministry of Heavy Industry and Public Enterprises & DHI

FAME India formulated by the Department of Heavy Industry (DHI) Government of India

2018 2019 2020 2021 2022

2018

FAME Phase I extended up to March 31, 2019 or until notification of FAME II, whichever is earlier
Ministry of Heavy Industry and Public Enterprises & Department of Heavy Industries (DHI)

Notification for extension of FAME Phase I up to September 30, 2018
Ministry of Heavy Industry and Public Enterprises & DHI

2019

The Union Cabinet approves the plan to set up a National Mission on Transformative Mobility and Battery Storage
Ministry of Heavy Industry and Public Enterprises & NITI Aayog

The Union Cabinet approves INR 10,000 crore programme under the FAME II scheme to be effective from April 1, 2019
Ministry of Heavy Industry and Public Enterprises & NITI Aayog

2020

MoRTH allows sale and registration of electric vehicles without batteries based on the type approval certificate issued by the test agency

Draft of Battery Waste Management Rules, 2020 from MoEF

The Union Cabinet approves the creation of a Phased Manufacturing Programme (PMP) to be executed between 2019-20 and 2023-24
Ministry of Heavy Industry and Public Enterprises & NITI Aayog

2021

NITI Aayog released handbook to guide EV charging infrastructure in India

Government extends the deadline of Fame II up to March 31, 2024

Government approves Rs 18,100 crore PLI scheme for promoting ACC battery manufacturing

Notes: ACC = Advanced Chemistry Cell; FAME II = Faster Adoption and Manufacturing of Electric Vehicles in India Phase II; MoEF = Ministry of Environment, Forest and Climate Change; MoRTH = Ministry of Road Transport and Highways; PLI = Production-Linked Incentive.
Source: WRI India authors.

ion to EVs economically feasible in a resource-secure way for India. The study will focus on the current commercially available bat- tery technologies as well as on battery research aimed at developing alternative technologies.

Although India does not have a specific transportation- or energy-storage-related target in its Nationally Determined Contribution (NDC) for 2030, considerable effort is underway to ensure that the manufacture and uptake of EVs are promoted in this time frame. Electric mobility, apart from addressing climate change concerns, will also help reduce India's oil import bill and enable it to move in the direction of energy independence and self-reliance. In the Indian context, although experts opine that opportunities exist for vast deployment of battery capacity, this is tempered by the fact that battery manufacturing in India is in the nascent stage, and the supply chain for such an industry has yet to be established—from procuring minerals to producing batteries.

Li-ion batteries are considered the preferred technology for EVs in the near future. Although some auto manufacturers are keenly exploring the viability of manufacturing Li-ion batteries in the country, India is only just setting up the first few Li-ion battery-manufacturing plants in states like Karnataka and Gujarat. The existing EV industry in India is heavily dependent on imports of Li-ion batteries, thus increasing the overall costs. With regard to resource security, given that India is not well endowed with min- erals such as lithium and cobalt, which are used in the commercially available battery technologies today, battery research also needs to focus on developing alternative technologies that require minerals with low supply risks as well as battery recycling techniques that reduce the overall dependence on imports.

Further, one of the significant levers of uncertainty that is usually identified by auto manufacturers and OEMs in our interactions with them is the evolution of technologies/cell chemistries. The risk to investors, especially in a rapidly advancing technology environment, is a major deterrent to accelerated adoption. Manufacturers opine that it is unclear today where companies should focus: on R&D or on manufacturing with the established chemistries. The R&D staff in every organization is limited, making this a significant challenge. With the constant evolution of chemistries, it is difficult for them to estimate future demand accurately, thus increasing the risk perception. Although significant research is being undertaken within the country as well as worldwide on improving battery characteristics, the connection between R&D institutions and the industry within the country is weak, and needs to be strengthened through more efficient dissemination of results and technology partnerships. Our discussions with experts convinced us that there is a need to formulate techniques to monitor the state of health of R&D, both worldwide and within India, in the EV battery space.
In a bid to address this major challenge, the study comprehensively compares and contrasts commercially available EV battery technologies in India on several dimensions, while also presenting a snapshot of the state of R&D on these technologies. Scientists and engineers are working in a variety of capacities to improve the electric car battery on several fronts, including efforts to boost its power, range, safety, and durability.

1.2.2 Research Methodology

The following are the key outcomes that we target through this report:

- Equip OEMs and equipment manufacturers with credible information to build effective EV transition strategies.
- Strengthen collaboration and feedback between the research community and industry.
- Make a positive contribution to the achievement of goals and targets under national electric mobility policies and plans (as they stand currently and develop over time).
- Inform and influence India's long-term climate strategy for this sector given that the electric mobility transition is seen as a core pillar of deep decarbonization in the long term.

We explored several research areas, for which different methods were applied, as shown in Table 1 and Figure 2.

Table 1 | **Research Methods Used in the Study**

AREA OF RESEARCH	RESEARCH METHODS
Commercially available battery technologies and their characteristics	Conducted extensive literature reviews and consultations with experts from academia, manufacturers, and laboratories to identify a comprehensive set of commercially available battery technologies and compare them on different dimensions
Gained preliminary insights from experts during a workshop, and after that gained additional insights through individual consultations as well as two expert workshops	2.1 Has this engagement undergone an environmental and social assessment prior to approval, including consultations with affected stakeholders? 2.2 Does this engagement include a plan for responding to the identified environmental and social risks? 2.3 Does this engagement provide project-specific avenues for affected communities to seek justice if adversely affected?
State of R&D in battery research	Consulted with a number of different organizations, including battery manufacturers, and universities through individual consultations
Ways to strengthen R&D and improve feedback between research and industry	Engaged with technical and strategic experts to share perspectives on important considerations, and also leveraged the India Energy Storage Alliance (IESA) network
Ways to economically and effectively make initial adjustments in a battery-manufacturing process to accommodate future changes in technology/cell chemistries	Studied cases by consulting with national and international laboratories such as the Argonne National Laboratory to assess feasibility, and determine the incremental cost and challenges

Source: WRI India authors.

Figure 2 | **Research Methodology at a Glance**

Literature Review	One-to-One Consultations	Workshops	Government Engagement	Review
Literature review to identify a comprehensive set of commerially available battery technologies and compare them on different dimensions Review of cited publications and articles	Skype calls and in-person interviews with industry experts Extensive consultation with a number of global academic organizations, including national laboratories and universities	Stakeholder meetings throughout the research period Convening of battery manufacturing companies, automobile manufacturing companies, and research institutions	Consultations on battery technologies organized as part of larger conferences such as Accelerating Electric Mobility in India brainstorming workshop with Niti Aayog, pre-MOVE summit and battery technologies workshop with Department of Science and Technology	Internal and external review process Internal reviewers with cross-sectoral expertise in the energy, climate, and transport domains

Source: WRI India authors.
Note: The numbering system followed in this working paper is the Indian numbering system. Typical values that are used are lakhs (1 lakh = 100,000) and crores (1 crore = 10 million).

1.3 Existing Government Directives

In 2021, the Government of India (GoI) approved the National Programme on Advanced Chemistry Cell (NPACC) Battery Storage, which is intended to support domestic manufacturing of 50 gigawatt-hours (GWh) of ACCs. The plan proposes a production-linked subsidy ranging from $27 per kilowatt-hour (kWh) to $56/kWh for manufacturers who set up production units with a capacity of at least 5 GWh. These are essential steps toward realizing the goals of India's National Mission on Transformative Mobility and Battery Storage, which was established in March 2019 (NITI Aayog, 2019). In addition to start-ups, the likes of ISRO, BHEL, Naval Science & Technological Laboratory, and other private sector players have also started developing Li-ion battery technologies indigenously.

Indian players are also developing R&D hubs for Li-ion cells and plants to manufacture anode material for batteries, given that India has deposits of graphite and zinc but no processing units have been set up yet. To ensure a consistent supply of critical minerals to the Indian market, GoI has set up a joint venture of three central public service enterprises called Khanij Bidesh India Ltd. (KABIL) (Ministry of Mines, 2019). Recently, KABIL led a strategic partnership with the state-run mining enterprise of Argentina for the exploration and production of lithium. At the same time, India has signed a preliminary deal with Australia for the supply of critical minerals (lithium and rare earth) needed for a new energy economy. India has forged a partnership with Bolivia that entails Indian investment in the development of Bolivia's lithium deposits and the supply of lithium, lithium carbonate, and cobalt to India (Ministry of External Affairs, 2017). Simultaneously, India plans to float a proposal for global investors to set up 50 GW of battery-manufacturing facilities by 2022 with incentives for eight years until 2030.

Increased driving range of vehicles and enhanced energy density of batteries can contribute significantly to increased EV adoption. Research and development on these aspects of battery technology and the associated setting up of manufacturing infrastructure have been underway, and they will continue to be the focus area in the coming years. As batteries dominate the costs of EVs, the strategy would be to use battery chemistries with optimized cost and performance at Indian temperatures and encourage the manufacture of such battery cells in India, even as we continue to make battery packs (cell to pack). Exploring new battery chemistries is also crucial, as it is the materials used in batteries, such as lithium, man-

ganese, nickel, cobalt, and graphite, that in large part determine their cost. Although it is important to secure mines that produce these materials, India also needs to obtain these battery materials by recycling used batteries.

1.3.1 FAME Scheme

The Department of Heavy Industries (DHI) launched the National Electric Mobility Mission Plan 2020 (NEMMP 2020) in 2013, aiming to achieve national fuel security by promoting hybrid electric vehicles (HEVs) and EVs in the country. Under NEMMP, the government set a sales target of 6–7 million HEVs and EVs from 2020 onward. As part of NEMMP, the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME India) scheme was formulated under the Union Budget for 2015–16. The scheme was introduced to promote early adoption and market creation for hybrid and electric technologies in the country. FAME was implemented in two phases: Phase 1 was set up to encourage sale of all segments (i.e., two-wheeler, three-wheeler auto, four-wheeler passenger vehicle, light commercial vehicles, and buses) of EVs by providing subsidies. The scheme covered hybrid and electric technologies such as Mild Hybrid, Strong Hybrid, Plug-in Hybrid, and Battery Electric Vehicles. Phase I of the FAME India scheme was initially scheduled for a two-year period between April 1, 2015 and March 31, 2017. The scheme was subsequently extended several times until March 31, 2019. Phase II of the scheme was implemented in April 1, 2019 for three years with a total budgetary support of Rs. 10,000 crore.

The DHI under the Ministry of Heavy Industries and Public Enterprises is the implementation agency of the FAME scheme, and the progress of the scheme is overseen by the National Board for Electric Mobility (NBEM) and the Development Council of Auto & Allied Industries (DCAAI). As DHI is the implementation agency, it is responsible for allocating funds after obtaining approval from the Ministry of Finance, planning, review, and execution of the scheme. It is also the nodal agency for addressing problems related to the guidelines and for removing difficulties in the implementation of the scheme.

The government has now extended the deadline of FAME II from March 31, 2022 to March 31, 2024. The following changes have been made to the FAME II Policy (refer Table 2):

Table 2 | **Comparison of the FAME I and FAME II Schemes**

DESCRIPTION	FAME 1	COMMENTS	FAME II	COMMENTS
Date announced	March 13, 2015		March 8, 2019	
Duration	4 Years (2015–19)	Was extended from 2 years to 4 years	3 Years (2019–2022)	
Budget outlay	Rs. 895 Crore	Incentive was based on battery cost and not on capacity	Rs. 10,000 Crore	Three main areas of spending: Demand incentives (86% of funding)—based on battery capacity Charging infrastructure (10%)—one slow charger per bus and one fast charger per 10 buses to be provided Scheme Implementation (4%)—projects sanctioned under FAME 1 to continue
Vehicles covered	All electric vehicles and hybrids	Soft hybrids included	2Ws, 3Ws, 4Ws, Buses, plug-in-hybrids only	2Ws under Rs. 1.5 lakh, 3Ws under Rs. 5 lakh, 4Ws under Rs. 15 lakh, buses under Rs. 2 crores
Subsidy per kWh	N/A, subsidy based on cost		The revised subsidy for 2Ws is Rs. 15,000 per kWh of battery capacity 3Ws, 4Ws: Rs. 10,000 per kWh of battery capacity Buses and trucks: Rs. 20,000/kWh;	Subsidy for e-buses is available only under Gross Cost Contract (GCC) model of procurement; FAME II subsidy is available only for commercial use of e-cars; FAME II excludes lead-acid battery-powered & low-speed 2Ws from subsidy.
Localization	Not specified		Localization mandatory	Society of Manufacture of Electric Vehicles is urging the Project Implementation and Sanctioning Committee to de-link localization from incentives due to high cost
Targets			10 lakh 2Ws, 5 lakh 3Ws, 35,000 4Ws, 20,000 hybrids, 7,090 buses by March 2022	More than 109,044 EVs sold under FAME II (as on August 31, 2020 from DHI Portal)
Scope	Limited to a few metropolitan cities		Pan-India	

Notes: 2Ws = two-wheelers; 3Ws = three-wheelers; 4Ws = four-wheelers; EVs = electric vehicles; FAME = Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles; kWh = kilowatt-hour.
Source: FAME 1 and FAME 2 policy documents retrieved from https://fame2.heavyindustry.gov.in.

- Electric two-wheelers (e-2Ws): Increase in demand incentive to Rs. 15,000/kWh from Rs 10,000/kWh, with a maximum cap at 40 percent of the cost of vehicles.

- Electric three-wheelers (e-3Ws): State-owned Energy Efficiency Services Limited (EESL) will aggregate demand for 300,000 units for multiple user segments. This bulk tendering would lead to economies of scale for OEMs and a consequent reduction in the prices of products. The implementation details will be worked out by EESL.

- E-buses: Cities with a population of over 4 million (Mumbai, Delhi, Bangalore, Hyderabad, Ahmedabad, Chennai, Kolkata, Surat, and Pune) will be targeted. The details related to demand aggregation and implementation will be worked out by EESL.

1.3.2 National Mission on Transformative Mobility and Battery Storage

The Mission will recommend and drive the strategies for transformative mobility and Phased Manufacturing Programmes (PMPs) for EVs, EV components, and batteries by localizing production across the entire EV value chain. The details of the value addition that can be achieved with each phase of localization will be finalized by the Mission with a clear Make in India strategy for the EV components, including batteries. The Mission will coordinate with key stakeholders in ministries/departments and the states to integrate various initiatives to transform mobility in India. The PMPs will be focusing on batteries, including raw materials, electrochemistry, end-of-life treatment, and manufacture of cells, modules, and battery packs for usage in EVs.

Table 3 lists other important initiatives and schemes that the government has introduced to boost the manufacturing and demand of EVs in India. Various ministries have been made responsible for greater efficiency in implementation. For example, the MoRTH focuses on better accounting of vehicles by allotting green licenses and tracking fuel type in cars, while the NITI Aayog, MoP, and MoUD are collaborating to set up charging infrastructure for EVs and ensuring growth in battery production and storage facilities.

1.3.3 Production-Linked Incentive (PLI) Scheme: National Programme on Advanced Chemistry Cell (ACC) Battery Storage

The scheme aims to achieve an annual manufacturing capacity of 50 GWh of ACC and 5 GWh of “niche” ACC with an outlay of Rs. 18,100 crore. The incentive amount will increase as the specific energy density and cycles increase and as the local value addition increases. Each selected ACC battery storage manufacturer would have to commit to setting up an ACC manufacturing facility having a minimum capacity of 5 GWh and to ensure a minimum 60 percent domestic value addition at the project level within five years. The beneficiary firms would have to achieve a domestic value addition of at least 25 percent and make the mandatory investment of Rs. 225 crore/ GWh within two years (at the mother unit level) and raise it to 60 percent domestic value addition within five years, either at the mother unit level in the case of an integrated unit or at the project level in the case of a hub & spoke structure.

The NPACC scheme is expected to achieve the following:

- Facilitate greater demand for EVs

- Stimulate R&D to achieve higher specific energy densities and cycles in ACC

- Achieve import substitution of around Rs. 20,000 crore every year

1.4 State Initiatives

Karnataka was the first state in the country to introduce a policy dedicated to EVs, following which a number of states have introduced their EV policies (Table 4). Most of these states aspire to be manufacturing hubs for EV and EV components, and thus production of batteries, recycling, and storage is incentivized within these policies (such as those of Uttar Pradesh and Maharashtra). Some of the notable battery R&D-relevant initiatives within these policies are highlighted in Table 4.

Table 3 | **Key National Actors and Their Initiatives**

DEPARTMENT/MINISTRY	CURRENT DIRECTIVES
Department of Heavy Industries (DHI) FAME Scheme	Under the FAME II Scheme, demand incentives of Rs 10,000 per kWh are provided for 3Ws and 4Ws. For e-buses, incentives applicable are Rs. 20,000 per kWh and for 2Ws it is Rs. 15,000 per kWh.
NITI Aayog National Mission on Transformative Mobility and Battery Storage	The Phased Manufacturing Programme (PMP) for EVs and EV components will focus on batteries, including raw materials, electrochemistry, end-of-life treatment, and manufacture of cells, modules, and battery packs for usage in electric vehicles.
Ministry of Power (MoP) Sale of electricity for setting up the charging infrastructure	MoP has declared that the charging of batteries of electric vehicles through charging stations does not require any license under the provisions of Electricity Act 2003. Setting up of public charging stations (PCS) shall be a de-licensed activity, and any individual/entity is free to set up PCSs in accordance with performance standards and protocols laid down by MoP and Central Electricity Authority (CEA).
Ministry of Urban Development (MoUD) Building byelaws for setting up the charging infrastructure	Amendments are made in the relevant sections based on the available charging technologies and their evolution, type of vehicle, types of chargers, the number of charging points required for setting up adequate PCSs within local urban areas including the premises of all types of buildings and with the long-term vision of implementing "electric mobility" during the next 30 years.
Ministry of Road Transport & Highways (MoRTH) Green license plates, amendments to Central Motor Vehicles Rules (CMVR), sale of EVs without batteries	To give a distinct identity to electric vehicles (EVs), the government has approved green license plates bearing numbers in white fonts for private e-vehicles and yellow license plates for taxis. A notification to this effect was issued on August 7, 2018. The amendment in the CMVR comes in anticipation of the increasing number of EVs on the market. Space otherwise occupied by the spare tire can be freed up and used to accommodate a larger battery.
Department of Science and Technology (DST) Technology Platform for Electric Mobility (TPEM)	The DST joined hands with the DHI to create a Technology Platform for Electric Mobility (TPEM) that is funded primarily by the DHI and managed by the DST. Under TPEM, centers of excellence (CoEs) and testing facilities will be created along with a push to form Industry Technology Consortia (ITC) led by automotive and component companies.
Ministry of Environment, Forest and Climate Change (MoEF) Draft of Battery Waste Management Rules, 2020	Battery Waste Management (BWM) Rules will replace the Batteries (Management and Handling) Rules, 2001, which provide details for the handling and management of lead-acid batteries only under the Environment (Protection) Act, 1986. BWM Rules will cover all types of batteries and discusses responsibilities of manufacturers and dealers in battery waste management.

Source: WRI India and CES authors.

Table 4 | **State EV Policies**

YEAR	STATE	POLICY	STATUS
2021	Assam	Electric Vehicle Policy of Assam 2021	Approved
2021	Gujarat	Gujarat State Electric Vehicle Policy 2021	Approved
2021	Maharashtra	Maharashtra Electric Vehicle Policy	Approved
2021	Haryana	Haryana Electric Vehicle Policy	Draft
2021	Meghalaya	Meghalaya Electric Vehicle Policy	Approved
2021	Odisha	Odisha Electric Vehicle Policy	Approved
2021	Rajasthan	Rajasthan Electric Vehicle Policy	Draft
2020	Delhi	Delhi Electric Vehicle Policy 2020	Approved
2020	Telangana	Telangana Electric Vehicle and Energy Storage Policy	Approved
2019	Tamil Nadu	Electric Vehicle Policy 2019	Approved
2019	Uttar Pradesh	Uttar Pradesh Electric Vehicle Manufacturing and Mobility Policy 2019	Approved
2019	Kerala	Kerala Electric Vehicle Policy	Approved
2019	Madhya Pradesh	Madhya Pradesh Electric Vehicle Policy 2019	Approved
2019	Uttarakhand	Uttarakhand Electric Vehicle (EV) Manufacturing, EV Usage Promotion and Related Services Infrastructure Policy 2018	Approved
2018	Maharashtra	Maharashtra's Electric Vehicle Policy 2018	Approved
2018	Andhra Pradesh	Electric Mobility Policy 2018–23	Approved
2017	Karnataka	Electric Vehicle and Energy Storage Policy	Approved
2019	Punjab	Punjab Electric Vehicle Policy (PEVP)	Draft
2019	Bihar	Bihar Electric Vehicle Policy	Draft
2019	Himachal Pradesh	Himachal Pradesh Electric Vehicle Policy	Draft

Note: EV = electric vehicle.
Source: WRI India and CES authors.

Table 5 | **Battery-Relevant Initiatives from a Few Selected State EV Policies**

STATE	INITIATIVE
Karnataka	Support for skill development Incentives and concessions to EV battery-manufacturing/assembly enterprises ■ Investment promotion subsidy □ Micro, small, and medium manufacturing enterprises (up to Rs. 50 lakhs) □ Large/mega/ultra/super-mega manufacturers (up to Rs. 20 crores per project) ■ Other incentives include exemption from stamp duty, concessional registration charges, reimbursement of land conversion fee, exemption from electricity duty, subsidy for setting up effluent treatment plants, and interest-free loan on net State Goods and Service Tax (SGST)
Uttar Pradesh	All EV battery-manufacturing or assembly units will be eligible for incentives and concessions under this policy. The Government of Uttar Pradesh has targeted the creation of a capacity of 2,000 MWh for manufacturing/ assembling EV batteries in the state, which would create 10,000 jobs over time. Some key steps include the following: ■ Development of manufacturing zones/parks ■ Battery recycling ecosystem ■ Support for R&D ■ Fiscal incentives for manufacturers Land subsidy (up to 25% of the cost of land), incentive on technology transfer, other incentives such as capital interest subsidy, infrastructure interest subsidy, industry quality subsidy, stamp duty and electricity duty exemption, and SGST reimbursement.
Maharashtra	Packages of incentives will be provided to pioneer units, mega/ultra-mega units, and units manufacturing EVs with the recommendation of a high-powered committee formed for mega/ultra-mega projects. Incentives to micro, small, and medium enterprises (MSMEs) and large units will also be provided. R&D, innovation, and skill development will be promoted. Based on an assessment of feasibility and other details by the high-powered committee, a proposal will be prepared for the establishment of centers of excellence (CoEs) and R&D centers, finishing schools, and other employment-oriented centers. Incentives on extended battery warranty and buyback agreement for the e-2W and e-3W introduced in the revised Maharashtra EV Policy 2021.
Telangana	■ Electronics manufacturing clusters (EMCs) and industrial parks are identified for promotion of EV and battery-manufacturing companies ■ Support for manufacturing via subsidies and incentives available under the Electronics Policy 2016 ■ Government to promote reuse of EV batteries and a recycling ecosystem ■ Incentives to encourage recovery of rare materials via urban mining
Andhra Pradesh	■ Development of industrial parks & clusters ■ Financial support to manufacturing firms including capital subsidy, stamp duty exemption, external infrastructure subsidy, land allocation, power cost reimbursement, 50% concession in water supply tariff, tax incentives, skill development incentives, marketing incentives, and incentives for recycling A research grant of Rs. 500 crores will fund the most innovative solutions in the mobility space. This fund will support the Center for Advanced Automotive Research (research labs working on battery, EV, EV component research, etc.), Center for Advancement of Smart Mobility (incubators, start-ups, prototyping centers, etc., are covered under this), research scholars, and testing and quality labs as needed.

STATE	INITIATIVE
Kerala	Support will be provided to local manufacturers to acquire and develop technology and collaborate globally with technology suppliers. A fund shall be created for technology acquisition for multiple manufacturers in the state. Local R&D will be supported for development of EVs as per Electronics System Design & Manufacturing (ESDM) policy. The state government will establish centers of innovation and excellence for various components of EVs including battery technology, and also for human capacity building and re-skilling.
Tamil Nadu	Incentives via the EV Special Manufacturing Package include reimbursement of State GST (SGST), capital subsidy, electricity tax exemption, stamp duty exemption, subsidy on cost of land, employment incentive, special package for EV battery manufacturing, creation of EV parks and vendor ecosystem, special incentives for the MSME sector, and transition support.
Assam	A nodal agency to act as an aggregator to purchase used EV batteries for second-life application in a stationary application and end-of-life recycling.
Odisha	Policy support to encourage the development of recycling ecosystem for the used EV batteries.

Notes: EV = electric vehicle; MWh = megawatt-hour
Source: WRI India and CES authors.


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SCAN ME

SECTION II

COMMERCIALLY AVAILABLE ADVANCED BATTERY TECHNOLOGIES

This chapter summarizes the development status of various promising storage technologies. Even as efforts focused on enhancing cost-performance characteristics of Li-ion batteries are picking up speed, performance characteristics of alternative battery technologies such as Al-air and lithium-sulfur (LiS) batteries are also continuing to improve via materials, cell design, and system design improvements. PEM fuel cell technology is also expected to witness advancements in terms of energy density via improvements in hydrogen storage technologies.

The global market for battery technologies has been transformed in the last 20 years with the advent of electronics and mobile phones. Newer commercial technologies such as lithium-ion, metal-air, and flow batteries have enabled many modern-day applications such as EVs, grid-scale ESS, and consumer electronics. In this ever-evolving technology landscape, Li-ion chemistries have achieved GWh manufacturing scale after leapfrogging traditional heavyweights like lead-acid and nickel-cadmium batteries.

The impact of ever-changing application requirements and the development of novel high-performance battery chemistries on the evolution of the Li-ion cell-manufacturing landscape has been dramatic. Hence, before discussing the different existing and upcoming chemistries, it is essential to review their technical and performance aspects.

2.1 Introduction to Battery Performance Terminology

The performance characteristics of any battery system are crucial when choosing a battery for an application. In EVs, the compactness of the battery is critical in terms of its volume and weight. A lightweight battery enables a larger battery to be fitted in the vehicle, which can provide an extended driving range, thus substantially reducing the "range anxiety" of the owner. The commonly used performance parameters to compare any two batteries or cells are listed in Figure 3 along with their units of measurement.

The longevity of the battery or cell is measured in terms of its cycle life. It denotes the number of charge-discharge cycles that the battery can perform before its energy storage capacity reduces to 80 percent of its initial nameplate capacity. This is

Figure 3 | **Common Battery Performance Metrics for Comparing Different Storage Technologies**

Energy Density	The energy density measures the compactness of a battery technology. It is the total energy divided by the weight (Wh/kg) or volume (Wh/L) of the battery.
Cycle Life	The cycle life test measures the number of cycles that can be performed before capacity decreases to 80% of the initial capacity (EOL = end-of-life criterion). This parameter measures the overall longevity of the battery.
Round-Trip Efficiency	The energy efficiency is the ratio of the discharge energy to the charge energy and is expressed as a percentage. The total electrical energy that can be drawn from a cell is always smaller than the electrical energy put into the cell.
Self-Discharge	This is the fully recoverable "idling loss" that occurs during times of no usage. Once the cell is recharged, the idling loss is recovered. Self-discharge is strongly dependent on the temperature.
Calendar Life	The calendar life or "shelf life" test for a battery estimates the non-recoverable losses occurring over time. These are independent of the cell usage and cannot be recovered even after the cell is recharged.
Elevated or Low Temp.	The cycle life of a battery is strongly dependent on the ambient temperature (20°C–35°C) during testing. This test determines the effect on the cycle life when we increase or decrease the ambient temperature.
DoD vs. Cycle Life	The depth-of-discharge (DoD) is the fraction of the stored energy in a cell that is used during one charge/discharge cycle. This test measures the impact of reducing the DoD on the improvement of the cycle life.

Notes: In the case of electric vehicles, a high-energy-density battery provides the maximum driving range. Battery performance testing at an elevated temperature (35°C– 45°C) is crucial for high ambient temperature operation in a country like India, where temperatures in summer often exceed 40°C.
EV = electric vehicle; kg = kilogram; L = liter; Wh = watt-hour.
Source: CES authors.

the commonly defined end-of-life (EOL) criterion. For many applications, the EOL criterion may be lower—that is, 70 percent or 60 percent. Cycle life is also important from the application developer's point of view for evaluating the warranties associated with a product. A battery with a longer cycle life will enable the manufacturer to give a longer warranty on the vehicle.

The round-trip efficiency (RTE) is the ratio of the discharge energy to the charge energy and is expressed as a percentage. It is always less than 100 percent, as part of discharge energy gets wasted in the form of heat during usage. If a battery has a low efficiency, it will generate more heat during cycling. The battery pack must be designed accordingly to evacuate the waste heat and maintain a safe operating temperature. Another important aspect of RTE is that it is lower when a higher c-rate is used (it is a measure of the rate at which a battery is discharged relative to its maximum capacity). Thus, to exploit the fast charging option for EVs, the RTE of the battery at a high c-rate plays an important role.

The calendar life test for a battery estimates the non-recoverable losses occurring over time. A high calendar life denotes a long "shelf life" for the battery. The shelf life of any battery depends greatly on the storage temperature and the state of charge (SoC). A longer shelf life is generally obtained at lower temperatures and at 50 percent SoC. Knowledge of the effect of these parameters can help the manufacturer minimize the degradation of the battery during storage prior to sale.

Battery Performance Testing

Performance testing of batteries is critical for determining their suitability for a particular application. It is essential to know that all the above-discussed performance parameters are interdependent. For example, the cycle life has a strong dependence on the depth-of-discharge (DoD), the c-rate for charge and discharge, the ambient and cell temperatures during operation, and, of course, on the cell chemistry. In addition to this, all performance parameters vary with the quality of the cell construction. Defective construction or improper design leads to the generation of local hot spots within the cell, lowering the performance and impacting the battery's overall safety. A change in any one operational parameter affects all the other parameters to some extent.

The cells are thoroughly tested by the battery supplier before they are sold. However, the conditions under which the tests are performed may not be identical to the real-world conditions in which the cells or storage system is designed to operate. Hence, it is critical for the system integrator or the pack developer to independently conduct the battery performance testing under the exact conditions dictated by the final use case. In addition, while giving warranties on a product, it is important to verify all the claims regarding performance by engaging an independent third party. Overall, the testing focuses on ensuring that the cells and the system perform in accordance with expectations when deployed in a real-world application. As a general rule, the performance of a battery pack can never exceed the performance of an individual cell on any of the performance parameters mentioned below. Thus for practical reasons, it is customary to perform cell testing to understand the behavior and longevity of the cells under a predetermined set of conditions that are derived from the expected field conditions. The performance and longevity of Li-ion batteries are highly dependent on the following four parameters:

- **Chemistry of electrodes and electrolyte:** The chemical properties of the electrodes and electrolyte fundamentally govern the cycle life of the cell. Once the chemistry is fixed, the operation parameters—temperature, C-rate, and DoD—primarily affect the cycle life.

- **Temperature:** As the ambient temperature around the cell is increased, the capacity fade rate increases and the cycle life decreases. The comfortable temperature range for Li-ion cells is approximately 20°C–30°C. Continuous operation at temperatures outside this range can significantly lower the cycle life. An approximate rule of thumb is that the cycle life of cells decreases by a factor of 2x for every 10°C increase in ambient temperature. Since the daytime temperatures in most parts of India are above 35°C in summer, the manufacturer needs to evaluate the longevity under conditions that mimic these real-world conditions.

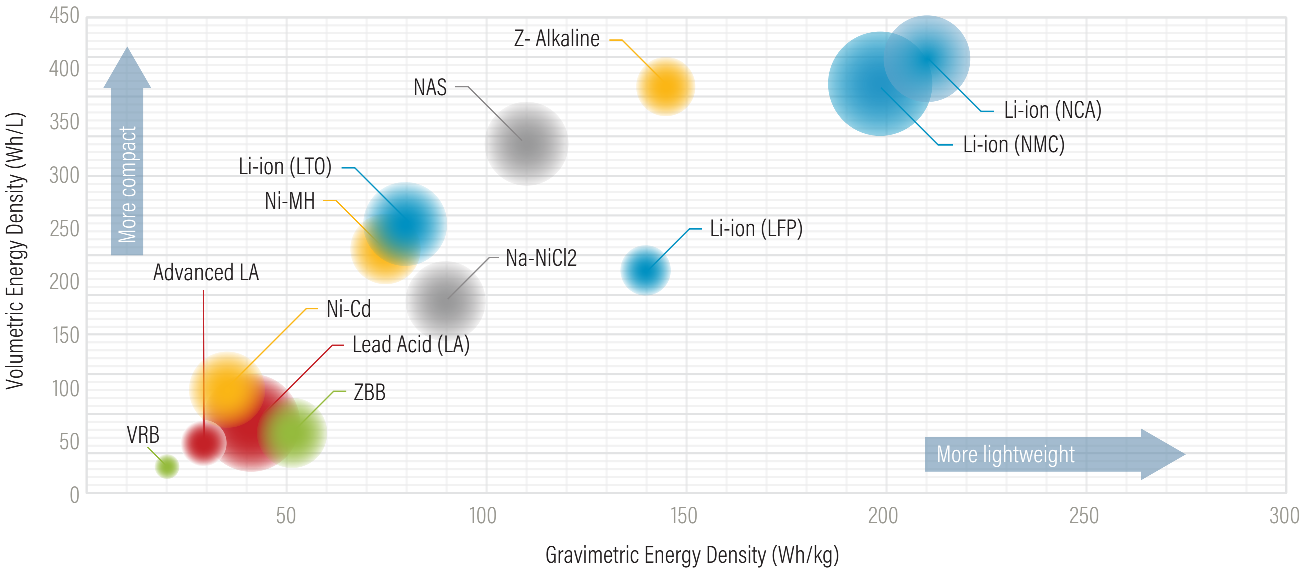
- **C-rate:** At an increased c-rate, a higher current passes through the cell, leading to higher heat generation in the cell due to the internal resistance. A sustained high c-rate mimics conditions of a higher operating temperature, resulting in faster capacity fade. Within Li-ion, the cells are classified as power cells or energy cells based on the specific construction design parameters. If a high c-rate is required for the operation, power cells may be more cost-effective even though their cost is higher (in $/kWh) in comparison with energy cells.

- **DoD:** The DoD has a very significant impact on the capacity fade of Li-ion batteries. A reduction in the DoD can prolong the cycle life. In general, the aging of cells is most pronounced at the extremities of the SoC, that is, when it is closest to being fully charged or fully discharged. A common strategy to prolong the cycle life is to have restricted cycling between 10 percent and 90 percent, or 20 percent and 80 percent, SoC, thus avoiding the extremities of SoC.

2.2 Battery Technologies for EVs

Since the first commercial introduction of Li-ion batteries in 1991, there have been many improvements and variants. In the following section, the performance parameters of different variants are compared along with their suitability for various applications. A high energy density (both volumetric—how much energy a battery contains compared to its volume—and gravimetric—how much energy a battery contains compared to its weight) is critical for transportation applications. Li-ion batteries are the preferred choice as they have high volumetric as well as gravimetric energy density (see Figure 4). Due to ongoing R&D activities, a number of new technologies with higher energy density are also making inroads in the EV sector. These new technologies will also be discussed in the following sections.

Figure 4 | **Cell-Level Energy Density of Current Batteries**



Notes: The size of the bubbles represents the range of energy density for a particular battery technology. Volumetric (Wh/L) and gravimetric (Wh/kg) energy density vary across a wide range in commercially available battery technologies. Higher-energy-density batteries are more suitable for transportation applications due to their compactness.

Kg = kilogram; LFP = lithium iron phosphate battery; NAS = sodium-sulfur; NCA = nickel cobalt aluminum; Ni-Cd = nickel-cadmium; NMC = nickel manganese cobalt; VRB = vanadium redox battery; Wh = watt-hour; ZBB = zinc-bromine battery

Source: CES authors.

2.2.1 Lithium-Ion Battery Technologies: LCO, LMO, LFP, NMC, NCA, LTO

Broadly, all the components of a cell can be classified into two categories: active and inactive. Active components are responsible for storing energy, and they vary between different cell chemistries. On the other hand, inactive components do not store energy but facilitate the flow of current in and out of the cell or are part of the cell packaging. Out of the seven basic cell components, five are always constant irrespective of the type of the battery. The remaining two are active components; namely, the anode and the cathode active material. Since the active materials are the only ones that change between chemistries, it is but natural to use the name of the active material for classifying the variations. It turns out that almost 99 percent of the commercial Li-ion batteries use graphite as the anode, and thus the cathode remains the only unique differentiator. The five large-scale commercialized types are LCO, LMO, LFP, NMC, and NCA. All of these are abbreviations for the name of the cathode material used in the batteries. Table 6 summarizes the characteristics of Li-ion batteries.

- **LCO:** The first lithium chemistry to be introduced was LCO, which stands for lithium cobalt oxide. As the name indicates, this cathode material contains three elements, out of which lithium and cobalt are the key materials, obtained from mining. LCO is good for achieving a high energy density (150 Wh/kg), which is advantageous in electronic devices. However, the limited cycle life (<1,000) restricts its application to electronic devices. Another challenge with LCO is its relatively lower temperature tolerance limit (150°C). This implies that the cells cannot be fast charged or discharged, as this would produce excessive heat internally, leading to safety problems. This is not considered a limitation for electronic devices since a typical cell phone takes 4 h to charge and 24 h to discharge, both of which are classified as very slow cycling. Understandably, LCO batteries have been dominating the electronic device market. Overall, from a safety and longevity point of view, LCO technology is not considered ideal for EV applications.

- **LMO:** Some of the limitations of LCO were overcome with the introduction of LMO, or lithium manganese oxide. Interestingly, manganese oxide was already well known to the battery industry as the cathode material in zinc-alkaline batteries. LMO not only has a high thermal limit of stability (250°C), but it also allows fast cycling (3C and above) with low cell internal resistance. Both qualities make it ideal for high-power applications. These advantages coupled with the low cost of LMO make it an attractive cathode material, in spite of its lower cycle life and energy density. The low cost is primarily due to the inexpensiveness of its main constituent, manganese.

- **NMC:** This cathode material gets its name from its primary constituent elements, lithium nickel manganese cobalt oxide. The variations of NMC such as 111, 311 (or 622), and 811 indicate the relative concentrations of Ni, Mn, and Co. A minor compositional change in the material yields large performance benefits. The cycle life and fast discharge capability are an improvement over LCO without compromising on the energy density. The overall optimum performance of NMC cells on all parameters has ensured that their use is growing steadily for all major battery applications, namely transportation and stationary storage.

- **NCA:** The latest addition to the Li-ion family is NCA, which stands for lithium nickel cobalt aluminum oxide. The key benefit of NCA is its high energy density (250 Wh/kg). A high energy density is a definite advantage (it translates to a longer driving range) for EVs, which is where NCA cells have found their biggest market. NCA technology is less suitable for high-power applications, where fast charging and discharging is required. When used under high c-rates, the cycle life and the RTE of the battery are significantly reduced.

- **LFP:** Other than LMO, LFP is the only other member of the Li-ion family that is unaffected by the price of cobalt. This is because both LMO and LFP do not contain cobalt. LFP stands for lithium iron phosphate (Ferrum is the chemical name of iron). The phosphate has the unique property of a high decomposition temperature (>400°C), giving it a strong safety advantage. The cycle life and high power capability of LFP cells are comparable to those of NMC cells, but their energy density is relatively lower (130 Wh/kg). In spite

Table 6 | **Characteristics of Li-Ion Battery Chemistries at the Cell Level**

PARAMETER	LMO	NMC111	NMC622	NCA	LFP	LTO-LMO
Round-trip efficiency	95%	94%	93%	90%	95%	97%
Available C-rates	C/4–3C	C/4–2C	C/4–2C	C/4–1C	C/4–2C	C/4–10C
Depth of discharge (DoD)	80%	90%	90%	80%	90%	90%
Energy density (Wh/kg)[a]	140–158	220–240	240–260	240–270	130–143	75–84
Energy density (Wh/L)[a]	350–358	600–650	650–670	650–680	270–282	175–186
Power density (W/kg)	30–60	40–60	40–60	40–60	25–45	600–800
Cycle life	800–1,000	3,000–3,500	3,800–4,000	1,000–1,500	3,800–4,000	8,000–10,000
Safety (thermal stability[b]**)**	High (250°C)	Medium (210°C)	Medium (210°C)	Low (150°C)	High (400°C)	High (250°C)
Battery chemistry[c]	Gr, Li, Mn	Gr, Li, Mn, Ni, Co	Gr, Li, Mn, Ni, Co	Gr, Li, Ni, Co, Al	Gr, Li, Fe	Li, Ti, Mn
Maximum operating temperature (°C)	55	55	55	55	65	65

Notes:
*a.*The given numbers are for the cell-level energy density. The pack-level energy density is 30–40 percent lower due to the weight of battery management system (BMS), interconnects, and thermal management hardware. For certain niche applications, the battery pack energy density can be improved via specialized design of balance of plant (BoP) components.
b. Thermal stability limit indicates the approximate decomposition temperature of the cathode material. A lower temperature is indicative of a higher tendency for thermal runaway under conditions of battery abuse or malfunction.
c. Raw material components of active materials.
LFP = lithium iron phosphate battery; LMO = lithium manganese oxide; LTO = lithium titanium oxide; NCA = nickel cobalt aluminum; NMC = lithium nickel manganese

Source: CES authors.

of the lower energy density, LFP cells have found good traction in the transportation sector, particularly for electric buses, which have a higher tolerance for heavier batteries. Other than this, LFP seems suited for stationary applications, where the battery weight is not a critical parameter.

- **LTO:** This variation of the technology uses a different anode compared to all the previously discussed technologies, which use graphite as the anode. In these cells, the anode is LTO, which stands for lithium titanium oxide. In LTO cells, the cathode may be either LMO, NMC, or LFP. However, as the anode is what differentiates it from the other technologies, this abbreviation is used to denote the technology. The energy density of LTO cells is approximately 30 percent lower in comparison with the other chemistries mentioned above due to its lower voltage (~2.4 V). However, the cycle life of these cells is the highest among all chemistries. Moreover, the cells can be cycled at very high c-rates of 6C–10C without affecting the cycle life or safety and with minimal impact on the RTE. As a result, LTO batteries are ideally suited for EV applications where fast charging is crucial.

In general, the self-discharge of Li-ion batteries is generally in the range of 1–3 percent per month, which is acceptable for applications requiring daily or weekly usage of batteries. Although several variations of Li-ion batteries coexist and serve different markets, new cathode and anode materials are always on the horizon. In the following section, we will discuss some of the next-generation technologies for transportation applications. These technologies are currently under development, and their rate of adoption will depend on the extent of performance/cost improvement they deliver over the existing technologies.

2.2.2 Technologies on the Horizon: Li-S, Si-NMC, Solid-State Batteries, PEM Fuel Cells

In addition to the above-described Li-ion battery technologies, several others are currently under development. The R&D community and industry are working on various aspects of existing battery technologies and also on futuristic battery technologies with the objectives of lowering the cost and improving performance. In this section, four such new technologies along with a current assessment of their state of development, prospects, and challenges are discussed.

In the case of EVs, one of the main thrust areas of global R&D activities is to improve the volumetric (Wh/L) and gravimetric (Wh/kg) energy density. A combination of improvements in these two parameters makes the battery pack compact. A more compact battery means that a larger battery pack can be fitted in the vehicle, which translates to a longer driving range. In the inset in Figure 5, a legend shows the relative size (weight and volume) of a 100 kWh battery pack based on its energy density values. A 100 kWh battery pack with an energy density of 1,000 Wh/kg will weigh only 100 kg. By comparison, if the energy density was only 100 Wh/kg, the battery pack would weigh as much as 1,000 kg. So the energy density of the battery pack or other energy storage device is crucial from a practicality point of view.

Over the last few decades, attempts have been made to increase the energy density of all storage technologies. Initially, the main driving force was for use in electronic devices, but in the last 20 years, a major impetus has been provided by the potential application in EVs. The past evolution and projected improvements in system-level volumetric and gravimetric energy densities in the time period 2005–25 are shown in Figure 5. In Li-ion technologies, it is common to report the cell-level energy density values. From a practical point of view and for fair comparison purposes, in Figure 5 we show the system-level energy densities except for solid-state batteries.

The existing Li-ion chemistries will continue to witness improvements via the introduction of new electrode materials and electrolytes. Alternative chemistries such as Al-air and lithium-sulfur (LiS) batteries will also continue to improve via materials, cell design, and system design improvements. PEM fuel cell technology will also continue to benefit in terms of energy density via improvements in hydrogen storage technologies. Table 7 shows the technological development status of various promising storage technologies.

Lithium-Sulfur

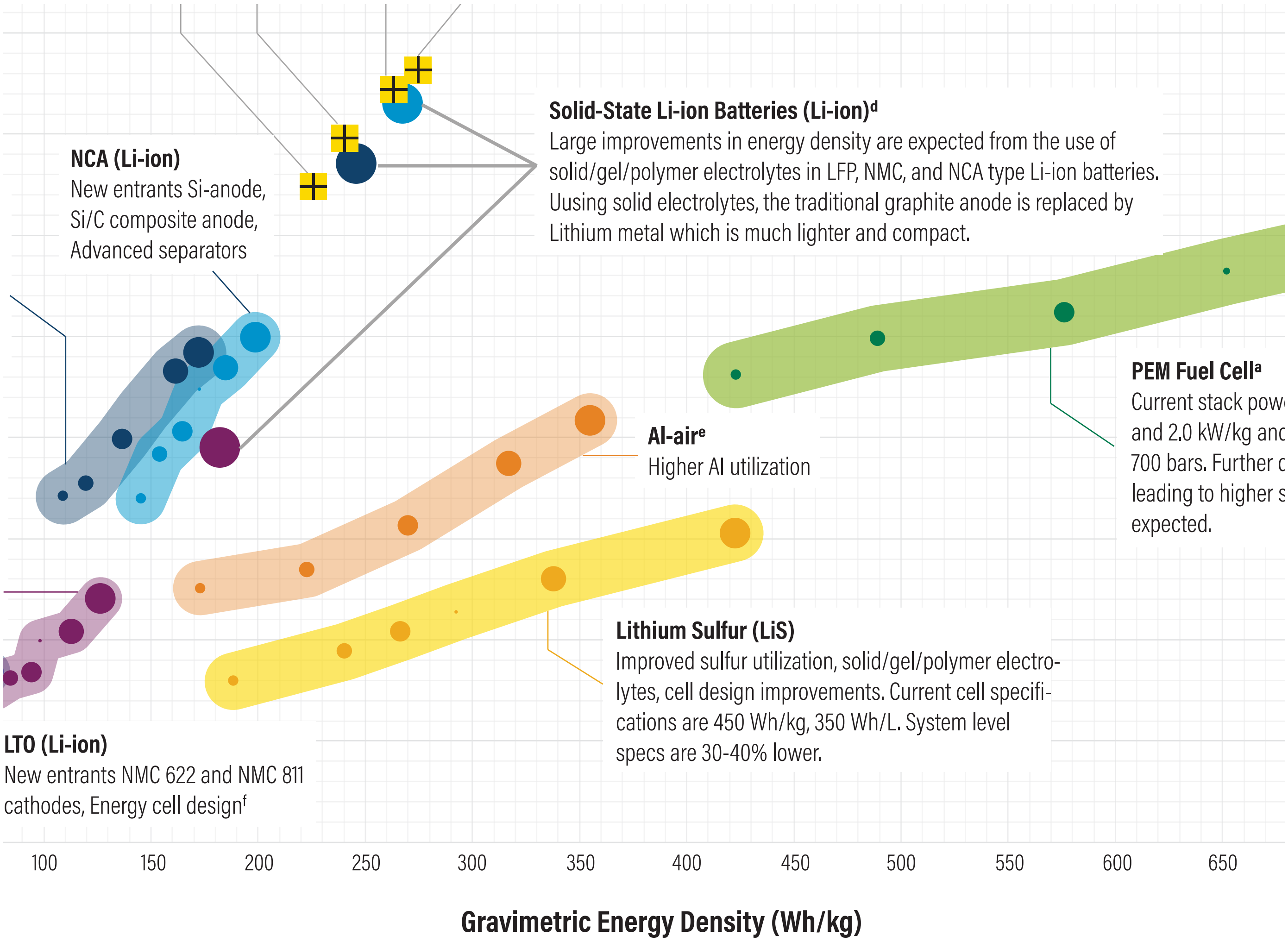
LiS batteries have pure lithium metal as the anode, whereas the cathode is a combination of sulfur, a carbon-based conductive material, and a binder. Both lithium and sulfur are extremely lightweight materials with a high capacity for charge storage. This results in a high achievable energy density (600+ Wh/kg). However, there are challenges that need to be addressed regarding the cycle life and high c-rate capability. Significant global R&D effort (academic and industrial) is dedicated to the development of this battery chemistry.

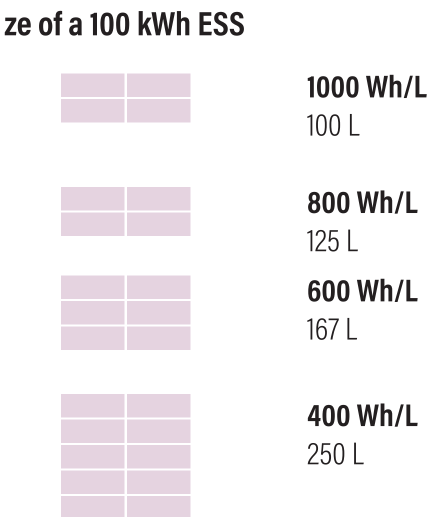
- The theoretical energy density of a Li-S cell is very high—2,500 Wh/kg—when considering the weight of the cathode. The achievable energy density is 25–33 percent of the theoretical value, or approximately 600+ Wh/kg from a practical perspective. This value is more than two times higher than that of current Li-ion batteries.

- From a cost and availability point of view, sulfur has good terrestrial availability, and in many places it can be obtained without mining and in its pure, unreacted form. Further, large amounts of sulfur are also generated from oil refining during the process of desulfurization.

Current state-of-the-art Li-S batteries exhibit a very high energy density (at the cell level) of 450 Wh/kg. However, the cycle life is still limited

Figure 5 | **Comparison of System-Level Energy Density of Technologies for EVs**





Notes:
a. PEM Fuel Cell system includes tank + stack + boost converter. Values calculated for system designed for car with 500 km range and tanks storing 5 kg hydrogen at 700 bars.
b. In Li-ion batteries, the system-level energy density is approximately 40 percent lower than the cell-level energy density due to the weight of the battery management system (BMS), thermal management, electrical connectors, and other components.
c. LCP = lithium cobalt phosphate, LNP = lithium nickel phosphate.
d. Expected performance in 2025.
e. Al-air system includes weight/volume of stack, electrolyte storage tanks, and pumps. There are no known commercial prototypes of the Li-air battery.
f. Thicker coatings and larger active material particles enhance energy density at the cost of power density.

Evolution of energy density from the year 2005 and projections up to 2025 are shown by increasing bubble sizes. A large increment in the energy density of Li-ion batteries is expected with the entry of solid-state batteries using lithium metal anode and high-voltage cathodes. (Top right) The relationship between the weight and volume of an energy storage system (ESS) and the energy density is shown.
This chart is prepared with available data and predictions as of 2019.

Source: CES authors.

Table 7 | **Technology Development Roadmap for Next-Generation Storage for Transportation Applications**

STORAGE TECHNOLOGY	TECHNOLOGY ROADMAP	
	2020	2025
Solid-state batteries	Thin-film batteries (TFBs) are at lab scale. Polymer/gel electrolyte SSBs are at commercial prototype scale.	Large format TFBs. High-energy density cells (400+ Wh/kg) with gel electrolytes.
Li-S	Pouch cells with high energy density (450+ Wh/kg). Low cycle life (200+ cycles). Small-scale production.	Improvement in cycle life (1,000+ cycles). High power capability with improved cell design (>1C).
Metal-air	Li-air is in lab-scale prototype. Al-air is a fully developed system, but manufacturing is at very small scale.	Li-air will continue to develop further at lab scale. Al-air may be commercialized for EV applications.
Na-ion	Na-ion battery in the advanced prototype stage.	Large-scale production will bring down the cost.
Fuel cell	Technological challenges like new composite membranes and Platinum-free electrocatalysts are being pursued. Production, availability, and the cost of hydrogen are also the limiting factors.	Advanced research on Pt-free electrocatalysts will reduce the cost. Increased manufacturing will lead to large cost reduction. Improvements in hydrogen distribution network. Prominent usage likely to be in heavy vehicles and in aerial transportation.

Source: CES authors.

to a few hundred cycles. Further improvement in cycle life will allow Li-S batteries to give stiff competition to current batteries in portable electronics and transportation applications. Some of the scientific challenges to the development of LiS batteries are the following:

- Dendrite formation is a well-known problem that occurs on the lithium metal anode during charging and especially during fast charging. Ongoing research efforts to overcome this problem include development of suitable anode coatings and electrolyte composition modifications.

- In the initial part of the discharge, the sulfur in the cathode reacts with lithium to form lithium sulfides. Lithium sulfide with high sulfur content is soluble in the electrolyte. Due to dissolution, these chemicals are gradually lost from the cathode are deposited on the anode. This leads to rapid capacity degradation with each cycle, a phenomenon called "polysulfide shuttle." To solve this problem, common approaches involve the use of solid or gel or polymer electrolytes or the use of proprietary additives.

- A chemical product that is formed during late discharge (Li_2S) is electrically insulating. Over time, the precipitation can lead to the formation of an electrically insulating layer, which makes subsequent charge and discharge more difficult. To solve this problem, uniquely architectured conductive and microporous host structures are being developed. Large improvements in cycle life are observed using this approach. However, the additional weight of conductive additives has a negative impact on the energy density.

A few companies, including some large car manufacturers, have already put significant efforts into Li-S manufacturing. For example, according to the specification sheets of a company that has a few pilot plants producing batteries for certain niche applications, the current pouch cells have a nominal cell voltage of 2.1 V and a capacity of 10–35 Ah. Based on the cell weight, the energy density is 400+ Wh/kg. Another variant of this cell is the high-energy-density cell with 500+ Wh/kg capacity for small electric aircraft, UAVs, and high altitude pseudo-satellites (HAPS).

Silicon Anode

The silicon anode is much lighter than the conventionally used graphite anode and the LTO anode. Therefore, the replacement of graphite with silicon in Li-ion cells of any chemistry (LMO, NMC, NCA, LFP) is expected to lead to improvements in energy density. One of the challenges in the silicon anode is the severe limitations in cycle life due to the large expansion and contraction during charge and discharge, although nanoparticles and nanowires give less volume expansion. Consequently, several companies have started blending 10–20 percent nanostructured silicon in the anodes along with graphite. With this approach, some improvement in energy density is obtained without affecting the cycle life.

Liquid Inorganic Electrolytes

Liquid inorganic electrolytes are a new alternative to organic solvent electrolytes, which are currently used in all types of commercially available Li-ion batteries and are one of the flammable components of the cell. By comparison, inorganic electrolytes are fundamentally non-flammable as they are composed of only inorganic materials. They are liquid at room temperature and typically offer high conductivity (70–107 $mS.cm^{-1}$). However, one of the challenges associated with the electrolyte is a positive vapor pressure, which makes a tightly sealed cell casing necessary.

Solid-State Batteries

Solid-state batteries refer to a rather large family of batteries in which the solid electrolyte replaces the liquid electrolyte. The solid electrolyte may be either a polymer type, gel type, or solid inorganic type.

Liquid organic electrolytes in the conventional Li-ion battery provide high ionic conductivity and excellent wetting of electrode surfaces. However, they suffer from low ion selectivity and low thermal stabilities, and their operational safety needs to be improved. Organic electrolytes are susceptible to decomposition if overcharging occurs. If high currents arise from accidental short-circuiting in Li-ion cells, the problem of decomposition is exacerbated.

To avoid these problems, researchers are exploring solid electrolytes, which can address many of the safety concerns associated with liquid electrolytes. Solid electrolytes have a wider voltage range of stability, improved high temperature tolerance, and are non-flammable, making them a better choice from the safety point of view. The major challenge so far has been the low conductivity of these electrolytes, which leads to diminished capacity and efficiency at high c-rates. In addition, solid electrolytes can adapt to higher-than-ambient temperatures (60°C–120oC) from a conductivity perspective, which may make them more suitable for Indian conditions.

The general advantages associated with a solid-state battery are as follows:

- The solid electrolyte not only provides Li-ion conduction but also acts as a barrier between the cathode and anode like any other Li-ion battery separator. As a result, a separator is not required.
- Higher tolerance to elevated temperatures of operation. Polymer-type solid-state batteries exhibit the best performance at a cell temperature of 60°C–80°C and thus benefit from high ambient temperatures.
- Due to their low flammability and reduced tendency for dendrite formation, lithium metal can be used as the anode material. It is approximately 10 times lighter than the graphite anode. This weight reduction is expected to improve the cell-level energy density by 30 percent.
- Certain types of solid electrolytes are chemically stable against high-voltage cathodes such as lithium-rich NMC (LMR-NMC), lithium cobalt phosphate (LCP), and lithium nickel phosphate (LNP). High-voltage cathodes dramatically improve the energy density of the cells by improving the voltage of the individual cell (>4.8 V).

Types of Solid Electrolytes. Two types of materials are mainly used as solid electrolytes in Li-ion solid-state batteries: inorganic ceramics and lithium-ion-conductive polymers.

- **Inorganic solid electrolytes:** Inorganic solid electrolytes suitable for use in Li-ion batteries can be either perovskite-based, NASICON-based, garnet-based, or sulfide-based materials. The use of inorganic solid electrolytes is quite well known in other energy storage and conversion systems such as NAS batteries (β-Al_2O_3), solid oxide fuel cells (YSZ, yttria stabilized zirconia), vanadium flow batteries (Nafion), and hydrogen fuel cells (Nafion).

One of the earlier solid-state electrolytes (SSEs) developed was called LIPON, an abbreviation of its chemical composition ($Li_{3.3}PO_{3.8}N_{0.24}$). Although LIPON was effective in preventing lithium dendrite formation, its conductivity was quite low. Two newer SSE materials called LATP ($Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$) and LLZO ($Li_7La_3Zr_2O_{12}$) exhibit much higher conductivity. The newest addition to the list is LGPS ($Li_{10}GeP_2S_{12}$), which exhibits a very high conductivity that is comparable to that of the conventional organic liquid electrolytes. LGPS is highly moisture sensitive, but this is unlikely to be a major challenge as the electrolyte-handling processes in Li-ion manufacturing are already carried out in dry rooms, where the moisture level in the air is very low.

- **Polymer and composite solid electrolytes:** Three polymer electrolytes are mainly used in Li-ion battery applications: dry solid polymer type, gel polymer type, and composite polymer type electrolytes. In general, the gel polymer and composite polumer electrolytes have good conductivity at ambient temperatures. Dry electrolytes have good conductivity in the range of 60°C–80°C.

Thin-Film Batteries (TFBs). TFBs present a complete rethinking of the cell design and fabrication procedure of Li-ion cells. In the case of TFBs, the layers of current collectors, electrodes, and electrolytes are fabricated via vapor deposition techniques. Such techniques are commonly used in microchip manufacturing and offer very precise control over the thickness and uniformity of the layers. In TFBs, the solid electrolyte LIPON has been most explored so far, and the use of higher-conductivity electrolytes such as LGPS can improve performance. The electrode materials for the anode and cathode in TFBs are similar to those used in conventional Li-ion batteries. Currently, TFBs are being used primarily for embedded storage devices on microchips (100–200 µAh per cell). Significant scale-up of the cell size is required to make the technology suitable for EV applications. The vapor deposition rates of manufacturing processes will need to be greatly increased to meet the requirements of high-volume battery manufacturing. Overall, TFBs can lead to a quantum leap in almost all metrics of performance compared to the existing state-of-the-art Li-ion batteries.

Proton-Exchange Membrane Fuel Cells

In a proton-exchange membrane fuel cell (PEMFC), energy is stored in the form of hydrogen fuel in high-pressure tanks. When energy is required, hydrogen reacts with the oxygen absorbed from air in the stack to generate electricity. The only by-product of this reaction is water, and there are no carbon dioxide emissions. Much of the initial PEMFC development work was conducted in the 1970s at NASA. Fuel cells were used in the Apollo and Gemini missions as on-board power supply devices, which operated with hydrogen as the fuel. The exhaust water generated as a by-product from these systems was used as drinking water by the astronauts.

The design of a fuel cell (FC) system is very similar to that of a flow battery. There is a fuel tank, which contains the required hydrogen fuel. The fuel flows to the stack, which is the heart of the system, and electricity is generated in the stack. In the case of PEMFCs, which operate at a relatively low temperature (~100°C), a special catalyst is needed at the electrodes. A good catalyst material is platinum (Pt), which is coated on carbon (C) particles to form the electrodes. The use of platinum is one of the main reasons for the high cost of the PEMFC stack. In the last 10–15 years, a major focus of industrial and academic R&D has been to minimize the quantity of Pt required (or Pt loading in mg/cm^2)—or if possible to eliminate it altogether—without compromising performance.

The other major focus has been on improving the compactness of the stack. Between 2008 and 2019, the power density of the PEMFC stack has doubled, from 0.83 kW/kg to 2.1 kW/kg. The volume has also been halved, with the power density increasing from 1.4 kW/L to 3.1 kW/L. For a mid-sized car, 1 kg of hydrogen provides approximately 100 km of driving range. Current PEMFC cars have a capacity of 5–6 kg of hydrogen, which gives a driving range of 500+ km. Beyond cars and buses, in recent times the applicability of PEMFC to trains and airplanes is being tested. The first train running on FCs, developed by Alstom, is already operational in Germany.

Attempts at powering small aircraft using PEMFCs are underway at Boeing, with the projects notably being in the early development stage.

One of the advantages of using hydrogen as a fuel is its high energy density (Wh/kg). One kg of hydrogen stores about 33 kWh of energy. With the electrical conversion efficiency of a PEMFC being 55 percent, we can generate 21 kWh of electrical energy from one kg of hydrogen. By way of comparison, 1 kg of petrol generates 13 kWh of energy, and the efficiency of an internal combustion engine is only 20 percent. So we can generate only 2.6 kWh of energy from 1 kg of petrol, which is 7× lower than hydrogen and gives the latter a significant weight advantage. However, one of the major challenges for hydrogen is that it takes up a large volume. This is not a major impediment, but there is definitely much room for improvement. The storage pressure that hydrogen tanks are able to hold increased from 150 bars (in 2005) to 700 bars (in 2018). This means that five times more hydrogen can now be stored in the same volume. In spite of these developments, in the current state-of-the-art prototypes, a 114 L tank stores only 5 kg of hydrogen, which means there is much room for improvement. A significant part of the R&D efforts of the academic community is currently dedicated to this aspect of PEMFCs. With regard to compact storage, other approaches under development are metal hydride storage, chemical storage, and cryogenic storage tanks.

One of the challenges concerning the widespread adoption of PEMFCs is the availability and cost of hydrogen. Unlike petrol or diesel, the fuel required for PEMFCs is not readily obtainable by mining. It has to be produced, distributed, and made available when any user needs it. This requirement is fulfilled by electrolyzers. These industrial-scale machines produce H_2 and O_2 via water electrolysis using electric power. Some companies manufacturing such systems are Hydrogenics, ITM Power, Frames, and Proton OnSite. Electrolyzers are available in different sizes ranging from 10 kW to 10 MW, which corresponds to a hydrogen generation capacity of 4.5–4,500 kg per day. The idea of having distributed generation via electrolyzers (preferably linked with renewables like wind or solar) at hydrogen fueling stations is very attractive, as it could potentially lower fuel transportation costs. Some stations of this type are already operational in California, Japan, and some Scandinavian countries.

Supercapacitors

Supercapacitors have the unique capability of high-speed charge and discharge (10C–20C) along with a high cycle life of more than 100,000 cycles. However, their low energy density (5–10 Wh/kg) is one of their main limitations for use in EVs. Currently, R&D on supercapacitors is focused on improving their energy density by using next-generation electrolytes and pseudo-capacitive materials. Some companies are using supercapacitors in EVs specifically to handle acceleration and regenerative braking loads that require several cycles of high-power charge and discharge. This isolates the battery from handling frequent high pulse currents and helps prolong battery life. Also, the battery-supercapacitor hybrid combination is under research for use in EV applications.

2.3. Lithium-Ion Battery Manufacturing

2.3.1 Manufacturing Process

The manufacturing process of Li-ion batteries can be broadly classified into three steps: electrode manufacturing, cell assembly, and module manufacturing.

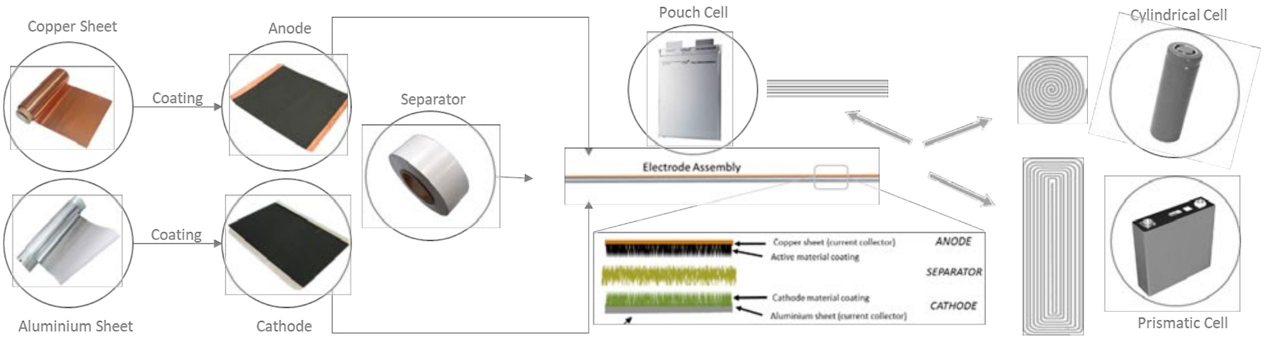
Electrode manufacturing. The process starts when raw materials are received for the electrode manufacturing at the plant.

The cathode powder can be any of the materials mentioned earlier; namely, LCO, LMO, NMC, NCA, or LFP. For the preparation of the cathode, the key materials are the cathode active powder, conductive powder, and the binder. In the first step, these materials are mixed together to form a paste-like formulation called coating ink. A liquid organic solvent (usually NMP) and binder are used to prepare the paste formulation after mixing the powders. The relative weight fraction of the cathode powder, conductive powder, and binder is approximately 90:5:5. The exact ratio is proprietary to the manufacturer and depends on the chemistry. The ink is layered on an aluminum sheet (current collector) in a continuous process (m/min), which then passes through a solvent

evaporation chamber for drying. The calendaring equipment compresses the electrode sheet to produce a dense coating, to comply with thickness tolerances. For the anode preparation, a similar procedure is followed, with a few differences. The current collector is a copper sheet, and the anode active material is graphite. The binder material for the anode is different, and the solvent used is generally water. Similar coating, drying, and calendaring steps are performed to obtain the anode. Specifically, in the case of the LTO anode, the active material is LTO, and the current collector is aluminum. The mixing, coating, and calendaring stages are critical for obtaining reliable performance from the cells. The procedure for making electrodes, folding or stacking the electrodes, and packaging to form the cell are described in Figure 6.

After the electrode preparation, the sheets are slit into the required sizes for making a cell and dried under vacuum to ensure complete removal of moisture from the electrode. This is because the electrolyte (which is added in the next stage) contains moisture-sensitive components. The dried electrodes are taken to the air-locked chamber (or dry room), where a very low humidity is continuously maintained (dew point $< -35°C$).

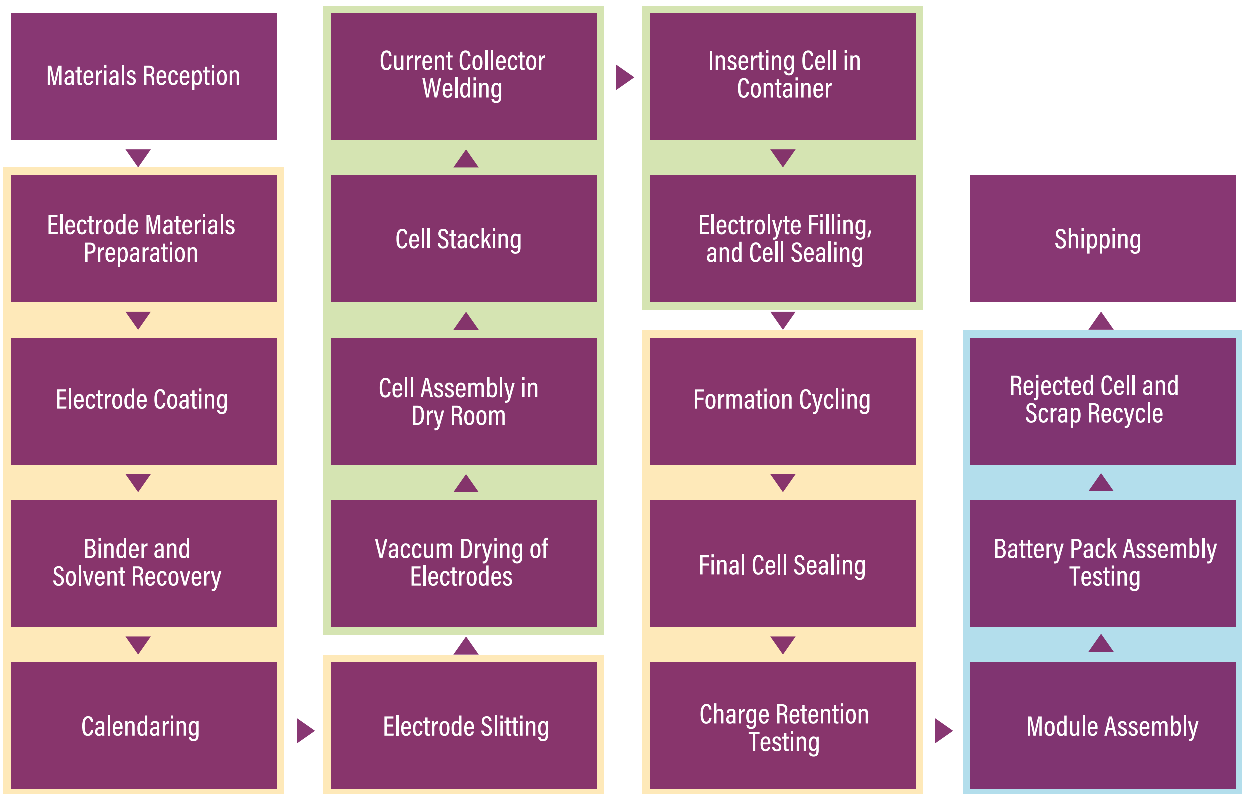
Figure 6 | **Electrode Coating and Cell Fabrication Procedure for Making Pouch, Prismatic, or Cylindrical Cells**



Note: In the case of a lithium titanate oxide (LTO) anode, an aluminum current collector is used instead of a copper current collector.
Source: CES authors.

Cell Assembly and Testing. The sheets of anode and cathode are layered on top of each other with a sheet of separator between them to produce the electrode assembly. The method of packaging this assembly depends on the type of cell format that is to be produced. For cylindrical and prismatic cells, the electrodes are rolled up into a spiral or flat shape as shown in Figure 6. In the case of pouch cells, pre-cut segments of the electrode assembly are stacked on top of each other. The rolling process used in cylindrical cells requires less expensive equipment and can pro-

Figure 7 | **Process Steps for Manufacturing Li-Ion Cells from Electrode Fabrication to Module Assembly**



Source: CES authors.

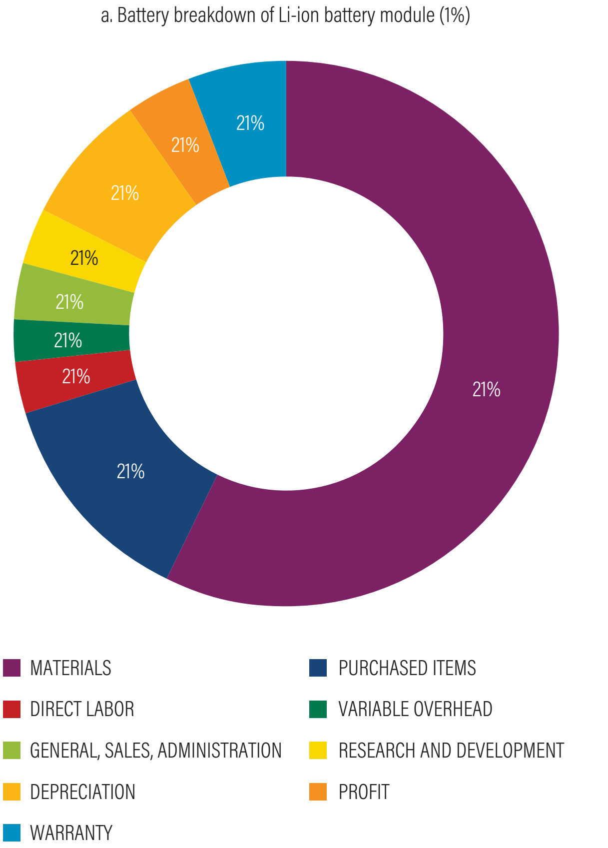
vide a higher throughput rate than pouch cells.

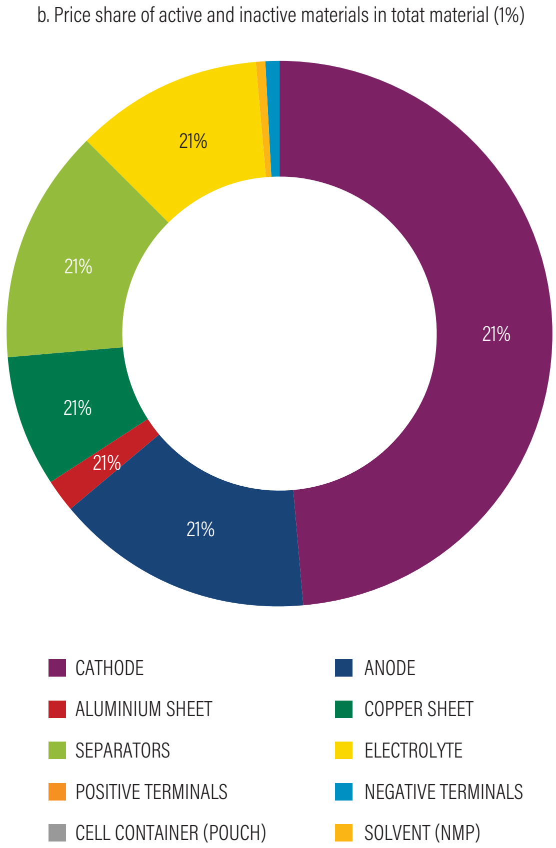
The current collectors are then welded to the end tabs (electrical connectors), and the entire assembly is packaged into the respective container (cylindrical case, prismatic case, or pouch). The cell is filled with electrolyte and hermetically (airtight) sealed. The cell can then be brought out of the dry room for quality control checks.

The first cycle of charge and discharge is called the formation cycle. During the first charge, a protective layer called SEI is formed on the graphite anode. The SEI layer is critical for the safe operation and longevity of the battery. The formation cycle is a controlled slow cycle (C/10 or C/20) and requires the maximum plant area as well as relatively expensive equipment. The cycling performed in this step also reveals the minor differences in the cells' capacity. Based on this, the cells are segregated into subgroups, and only cells from the same group are used to make a battery pack or module. During the formation step, some gas is produced internally in the cell. Since pouch cells do not have a rigid container (unlike prismatic and cylindrical cells), they tend to swell due to this gas. As a result, for pouch cells, another step of gas extraction and final sealing is required.

Module Manufacturing. The cells are electrically connected via a combination of series and parallel connections using nickel tabs. The tabs are welded to the ends of the cell using either spot welding or laser welding. Laser welding offers more precision, whereas spot welding requires less-expensive equipment. Each battery pack consists of multiple cells and is controlled by the battery management system (BMS). The BMS monitors the current passing through each cell and is responsible for preventing overcharge or over-discharge, which could shorten the life of

Figure 8 | **Component-Wise Price Breakdown of Li-Ion Battery Pack and Contribution of Different Active and Inactive Materials in Total Materials to the Total Materials Cost**





Notes: Materials cost contributes more than half of the total system cost. Within the materials cost, the cathode active material is the highest contributor. The above data are shown for the NMC 622 chemistry.
Source: CES authors.

the cells. Additional wiring is required from the BMS to the cells for individual cell monitoring. It may also employ active cell balancing to ensure that all cells are cycling at a similar SoC. Overall, the role of the BMS is crucial in ensuring safe operation and in extracting optimum performance from the battery pack. Since each type of Li-ion chemistry has different current-voltage profiles, it is important to ensure that the BMS is compatible with the chemistry of the Li-ion cell.

2.3.2 Component-Wise Cost Breakdown of Li-Ion Batteries

For most battery components, the raw materials cost of its constituents is by far the biggest contributing factor. Any cost analysis should consider the price variations and geographical availability of the critical elements. For commercial reasons, the constant endeavor in Li-ion batteries has been to reduce cobalt usage in the cathode. The percentage of cobalt in different cathode materials is as follows: LCO (60 percent), NMC (6–20 percent), and NCA (9 percent). Material has the biggest cost component in a Li-ion battery module, about 42–61 percent of the total cost depending on the chemistry. Due to this, the cost of raw materials and the robustness of the underlying supply chain greatly influence the overall cost of the manufactured batteries.

Within the material category, the cathode material accounts for the maximum share—51 percent—of the total raw material cost of a battery. The next biggest cost comes from anode material, which accounts for 16 percent of the total material cost. The cost of the separator also plays an important role in the total battery cost, as its cost almost equals the anode cost. The prices of various raw materials (such as nickel, cobalt, manganese, lithium, aluminum, copper, and graphite) in the international market influences the final battery cost. Figure 9 explains the sensitivity of NMC 111, NMC 622, and NMC 811 prices with respect to the doubling of prices of Li carbonate (hydroxide), Co, Ni, and Mn. It can be seen that doubling the price of a particular material would not greatly affect the cell prices. However, if the prices of most of the mentioned raw materials double simultaneously, the NMC 811 price can rise by over 20 percent.

2.3.3 Design of a Li-Ion Battery Manufacturing Plant Layout (1 GWh)

To understand the impact of next-generation chemistries on the manufacturing facilities, it is important to understand the battery-manufacturing process. The general layout of a Li-ion manufacturing plant is shown in Figure 10. Each box in the figure represents one particular sub-process of the manufacturing process line, and the size of the box is indicative of the floor space requirement for it. The individual process steps are classified into three parts:

- Electrode fabrication (red)
- Cell fabrication and formation cycling (green)
- Battery pack assembly (blue)

The process steps have been described in Section 2.3.1. The floor space requirement (m^2) for each process is listed in the corresponding box. The total plant area is approximately 15,425 m^2, and the total capital cost of the equipment alone is approximately $59 million. Although the manufacturing costs have been calculated for a 5 GWh plant and the floor requirement for that scale of plant is approximately 56,656 m^2, it should be noted that for larger-sized plants, the area requirement and the capital investment cost cannot be calculated by linearly scaling up the numbers for a 1 GWh plant. This can be seen clearly in Figure 11, where the normalized cost (million $/GWh) decreases when the size of the facility is scaled up from 1 GWh to 10 GWh annual production.

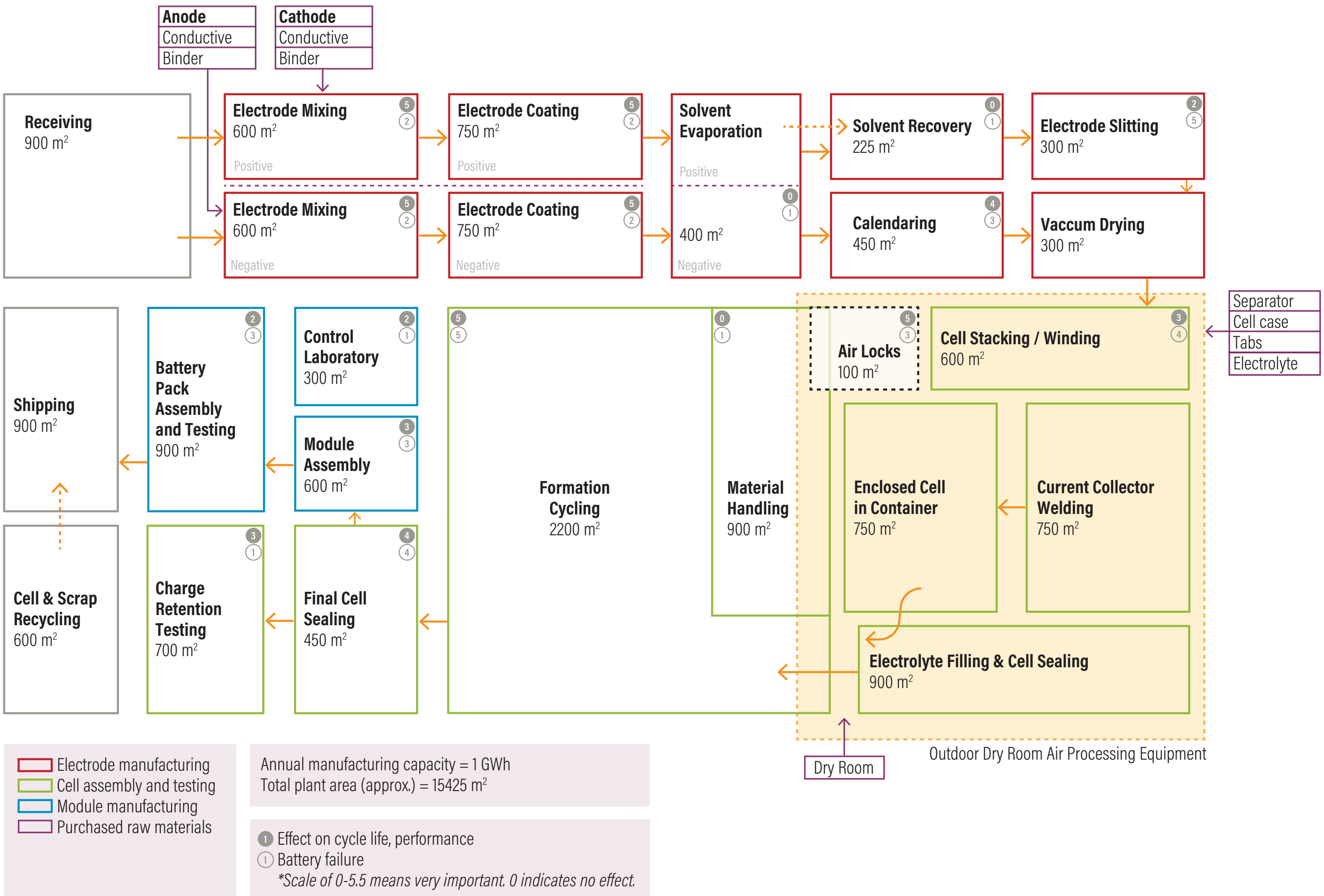
In Figure 10, for each process of the manufacturing line, a rating is assigned for its effects on cycle life/performance (black filled circle) and battery failure (white filled circle). If a process has a rating of 5 on the black filled circle, it means that minor changes in the process parameters will have a large impact on the overall performance and cycle life of the manufactured battery. An example of this is the electrode mixing process, where the active materials are mixed with conductive carbon and the binder. Improper mixing can lead to inhomogeneity in the prepared coating, because of which the current flow will be directed more to the active material-rich areas, creating local hot spots in the cell under

Figure 9 | **Price Sensitivity of Different NMC Chemistries against Price Rise of Different Raw Materials**

- The effect of 4 raw materials (Li_2CO_3, Co, Ni, Mn) on the cell cost ($/kWh) is estimated
- Three different MNC cell chemistries are considered (NMC 111, 622, and 811)
- The effects of increase of DOUBLING of each raw material price on the cell cost is calculated

Source: CES authors.

Figure 10 | **Layout of a 1 GWh Li-Ion Manufacturing Plant**



Source: CES authors.

Figure 11 | **Investment Costs for Setting Up GWh Li-Ion Manufacturing (NMC622)**

Notes: Normalized total investment cost (million $/GWh) decreases as the manufacturing capacity (GWh) of the plant increases.
NMC622 = LiNi0.6Mn0.2Co0.2O2.
Source: U.S. DOE 2013a.

operation. Such local hot spots are detrimental for long cycling and high c-rate capability. Overall, the cell will still function with this defect, but its performance will be lower than expected.

If a process has a rating of 5 on the white filled circle, it means that improper parameters in this step could lead to a drastic battery failure or even major safety issues. An example is the electrolyte filling and sealing step. Improper sealing of the cell will allow moisture from the ambient air to come in contact with the electrolyte and electrodes. Since the electrolyte degrades in the presence of moisture, complete cell failure can occur even prior to initial cycling.

2.4 Considerations for OEMs and Manufacturers to Alleviate Risk Related to Battery Technology Uncertainty

Since the introduction of Li-ion batteries in 1991, they have undergone several changes in chemistry, leading to many variations of the technology. This is an ongoing process; new variations of existing materials are being developed, and in some cases completely new materials are being commercialized. Due to the demands for high-performance electric vehicle and storage devices and the intensive R&D efforts by academic institutions on a global scale, Li-ion battery technologies are constantly being improved.

In this situation, a potential concern is the fate of investments in a particular chemistry if a new variation with significantly better performance is developed. Will the investments fail? The short answer to this question is no, for the reasons described in the following sections.

2.4.1 Effect of Changing Chemistries on Cell-Manufacturing Facilities

At present, a change in chemistry has a very small impact on the capital equipment cost for the cell-manufacturing capacity, for the following reasons:

- Although chemistries may change, the cell format remains the same: the pouch, prismatic, and cylindrical. The entire process starting from electrode manufacturing, cell manufacturing, and module manufacturing is identical. The only variation is in the active material purchased from an external vendor. The active materials are the cathode and anode, which are highlighted in figure 12 in blue and green, respectively. Since only the input materials vary but the processing remains unchanged, the impact of a change in chemistry on the capital equipment cost is minimal.

- Although intensive R&D is underway worldwide on new active materials, only a handful of commercially successful variations exist. Six commercially successful variations have been developed over the last three decades. As a result, if a promising new chemistry is developed, there will be sufficient time for an existing battery plant to adapt itself to the new chemistry. However, it is crucial for the manufacturer to be aware of the new developments and actively scout for new technologies that would give enough time to make the transition to a new chemistry.

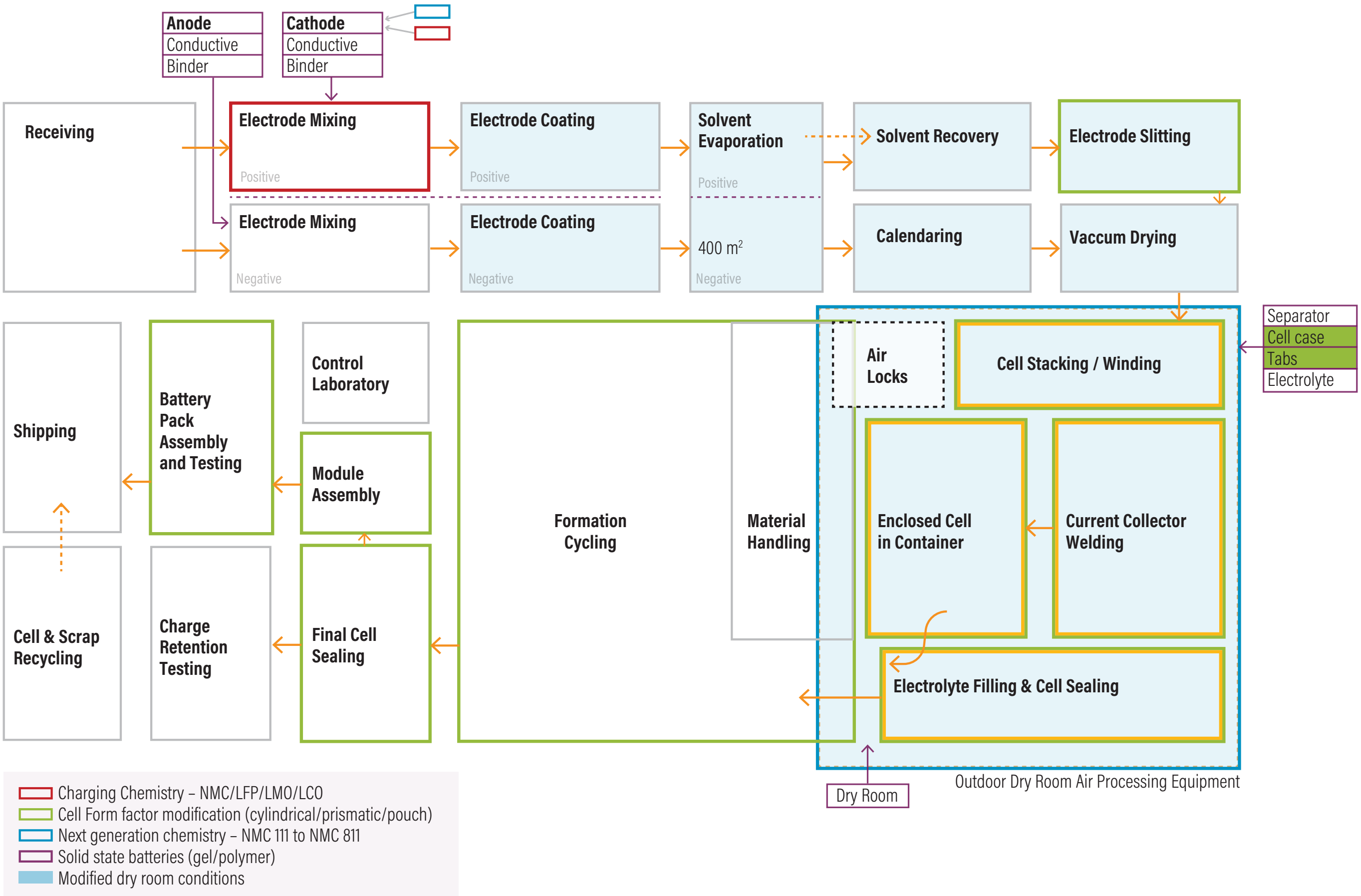
2.4.2 Effect of Changing Form Factors

The smallest working unit in a battery is the layered electrode assembly, which consists of two current collectors and a separator sheet that is sandwiched between a cathode and an anode. This basic arrangement is common to all Li-ion cells irrespective of the chemistry. During cell manufacturing, this electrode assembly is packaged into a cell, and there are multiple ways of doing this. It may be folded over many times to form a pouch or prismatic cell, or it may be rolled up into a cylinder to form a cylindrical cell.

Since at the industrial level the processes of cell assembly are completely automated, changing the form factor requires significant equipment replacement cost in the following stages: cell stacking/winding, current collector welding, electrode crimping, enclosing the cell in a container, and electrolyte filling and cell sealing. When moving from cylindrical to pouch/prismatic cells, the dry room size may also need to be increased to accommodate the larger-sized equipment. In addition, the electrode slitting equipment may also need to be replaced.

In the following section, we have compiled information from the experiences of a number of cell manufacturers regarding Li-ion plant operation and the flexibility to adapt to next-generation chemistries.

Figure 12 | **Plant Modifications Required for Changing the Cell Chemistry or Form Factor, or Transitioning to Solid-State Battery Manufacturing**



Source: CES authors.

Plants Adjusting the Battery-Manufacturing Process to Accommodate Changes in Technology/ Cell Chemistries

The development of battery technology in the areas of battery chemistry, process parameters, and forms factors is a continuous process to extract optimum performance under the cost constraints. The manufacturing cost of a battery also varies based on it's constituent materials and its form factor. To understand this, the CES team had visited Li-ion battery facilities and interacted with various industry experts. The main objectives of the discussions and interactions were to answer the following key questions:

- How adaptable are current manufacturing processes to changing chemistries? How much additional CAPEX would be required?
- How adaptable are current manufacturing processes to changing form factors (cylindrical, pouch, or prismatic)? How much additional capital investment would be required?
- Is it possible to adapt current facilities to fabricate next-generation battery technologies such as Li-S, solid state, or Li-air?
- We received a positive response from the industry experts, and the important points from our discussions are summarized below.

2.5.1 Industry 1

Industry 1 is one of the leading cell manufacturers in China, and the following are the views of one of their team members on investments in cell-manufacturing Gigafactories:

- According to them, switching from LFP to

NMC or vice versa would require less than 5 percent additional investment. However, they do not do it often as there are dedicated lines built in accordance with customer requirements.

- In shifting among different variants of NMC chemistries (111, 532, 424, 622, or 811), the cost incurred is very small as only dry room conditions need to be changed, which translates to a very small investment.
- Changing the form factors would require approximately 60–70 percent of additional capital expenditure. Typically, companies finalize the form factor prior to setting up manufacturing, keeping the application's requirements and the major offtaker in mind.
- Newer technologies such as Li-S and Li-air batteries are on a longer 5–10 year development timeline according to them, and they expect to commercialize them around 2030.
- They have a small pilot plant for cell manufacturing that is used to test process variations, materials variations, and new chemistries.

2.5.2 Industry 2

Industry 2 is a New York State (United States)-based Li-ion battery-manufacturing company. Their plant is not yet operational, although they have sent their batteries, manufactured on smaller lines, to several customers for testing purposes. The plant capacity is 1.2 GWh, and it will become operational by the end of 202. Their generation 1 battery is free of cobalt and nickel, and they currently manufacture prismatic-type

batteries. Their current facility is flexible enough to cater to new chemistries without significant investment. They plan to sell the generation 2 battery by 2021 and the solid-state battery by 2023 using the same manufacturing facility. According to their estimates, changing from the current chemistry to solid-state chemistry will involve 30–40 percent additional capital expenditure as the stacking/winding and cell-packaging process will need to be modified. The coating ink preparation and electrode fabrication processes remain unchanged, although their solid-state chemistry will be commercialized only after 2023.

Cell manufacturers have mentioned that technology shifts will not make their plant redundant overnight, and there is enough flexibility in the process to bring in newer Li chemistries. As the world is talking about a demand of over 1 TWh of lithium-ion batteries by 2025, industries can rest assured that in the over-demand scenario of the future, their plants running on different form factors and chemistries will find a market.

2.6 Battery Safety

The safe operation of ESS is the cumulative result of the synchronized functioning of several engineering subsystems. Several layers of engineered subsystems with many redundancies are incorporated. Their sole objective is to ensure that the cells in the system never approach a temperature where a potential safety risk exists. If the temperature of a Li-ion cell is always maintained below 80°C, then there is no risk of undesirable chemical reactions occurring inside the cell that may lead to a thermal runaway. For obvious reasons, the prescribed upper limit of operation of Li-ion cells is much lower (50°C–600C).

Thermal runaway is a catastrophic event that causes an uncontrolled temperature rise during cell operation and the release of a large amount of heat energy. The cell temperature in such cases can exceed 700°C, making other cells in the proximity susceptible to the same event. The events of thermal runaway can be categorized in three stages. In stage 1, the internal temperature of the battery system can start increasing due to various reasons, including overcharging, exposure to high temperature, and external or internal short circuits. External short circuits occur due to faulty wiring, whereas internal short circuits occur due to cell defects, which include the use of a flawed separator in the cells and lithium dendrite formation due to high current density charging, overcharging conditions, or low temperatures. In the case of cell crush due to vehicle collision, penetration of the battery pack by any metal debris that pierces the separator and the connecting cathode and anode can also lead to internal short circuits resulting in a fire or explosion. The initial overheating of the battery can shift its operation from the normal

to the abnormal state. At stage 2, the overheating or physical penetration can decompose the solid electrolyte interphase (SEI) in the cell, resulting in the release of flammable gases and oxygen. A further increase in temperature due to SEI decomposition can accelerate electrolyte breakdown, melting of the separator, and decomposition of electrode materials, which can result in a further increase in temperature, release of flammable hydrocarbon gases, and oxygen. In stage 3, the released oxygen and heat in stage 2 can initiate combustion of flammable organic electrolytes, leading to a fire or explosion in the battery.

To prevent the battery safety hazard in Li-ion batteries, it is important to develop a method that can precisely detect and monitor the internal health of cells in situ or in operando conditions. An efficient BMS can ensure safe and reliable operation of LIBs. An efficient thermal management system that includes air circulation or liquid cooling, or phase change material can improve battery performance and help avoid temperature abuse. A well-designed multifunctional cell material can significantly reduce the probability of thermal runaway in LIBs. For example, the addition of fumed silica to a carbonate electrolyte can protect LIBs during mechanical impact via the shear thickening effect. A trilayer separator can significantly improve battery safety by reducing the probability of internal short circuits due to formation of hazardous lithium dendrites. A suitable ceramic coating layer on the separator can improve its thermal stability, and the addition of suitable additives to the electrolyte solvent can improve battery safety. The development of non-flammable liquid electrolytes or solid electrolytes can significantly reduce the possibility of fire and explosion in LIBs.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SECTION III

RAW MATERIALS REQUIREMENT FOR LI-ION CELL MANUFACTURING

As the demand for raw materials needed to manufacture batteries grows, the primary challenge lies in the fact that the reserves of these raw materials are highly concentrated in a handful of countries. Thus, building a robust supply chain is critical to ensure continuing availability of inputs as well as price stability of manufactured products. This chapter presents a detailed analysis of the requirements of eight key raw materials in the battery manufacturing process, including availability of reserves and annual production in India and globally.

3. 1 Raw Materials Required for 1 GWh Cell Manufacturing

Estimation of the raw material requirements is essential for cell manufacturing as their supply and pricing significantly impact the overall cost of the cells and battery pack. As can be seen from the data presented in Table 8, more than 1,000 metric tons of raw materials and components are required for manufacturing 1 GWh of cells of any chemistry. Thus, establishing GWh-scale manufacturing facilities will require a strong supply chain mechanism to satisfy the raw material needs of a growing battery industry. In view of this, we have presented in this section a tabulation of the key raw materials required for battery components in cell manufacturing. The requirement is presented separately for the different chemistries. All the numbers presented are in metric tons, and the requirement is normalized for 1 GWh cell manufacturing. These requirements can be compared with global and Indian production, and statistics on raw material reserves are presented in the following two sections.

- The raw materials requirement scales directly with GWh. Therefore, for 10 GWh of manufacturing, the need can be approximated simply by multiplying the given numbers by 10.
- Depending on the cathode chemistry, key elements (one or more) required for producing the active material are nickel (Ni), manganese (Mn), cobalt (Co), aluminum (Al), and iron (Fe). Lithium (Li) is required in all cathode materials irrespective of the chemistry. Depending on the anode chemistry, the materials required are graphite (Gr) or titanium (Ti).

Table 8 | **Raw Material Requirement for 1 GWh Cell Manufacturing of Different Chemistries**

	Gr	Ti	Co	Ni	Mn	Al	Fe	Li	Carbon	Binder	Al C.C.	Cu C.C.	Separator	Electrolyte weight
TYPE OF CELL (Chemistry)	ANODE		CATHODE						OTHER COMPONENTS					
LTO-LMO	-	900	-	-	2130	-	-	250	300	300	820	-	110	1730
LMO	870	-	-	-	1550	-	-	110	170	170	290	710	80	930
LFP	1050	-	-	-	-	-	720	90	160	160	330	820	90	1500
NCA	980	-	120	670	-	10	-	100	120	120	290	710	80	710
NMC 111	980	-	350	350	340	-	-	130	140	140	290	720	80	790
NMC 622	960	-	180	540	160	-	-	110	120	120	290	700	80	730
NMC 811	940	-	90	780	80	-	-	80	110	110	280	690	80	680

Notes: Cell components considered are active materials (cathode and anode), binders, conductive additives, current collectors, separator, and electrolyte.

Raw material requirement (metals, conductive additives, binders, separators, and electrolyte) for cell manufacturing as listed according to the battery type. The numbers shown correspond to cell manufacturing of 1 GWh, and all mentioned numbers are in metric tons.

Additional aluminum is used in making terminals, pouch cell laminate (packing), and components of the thermal management system. Those are not included in this table. Additional copper and steel are required to make components of the battery pack.

Source: CES authors.

- Apart from the active materials, the other components of the electrode are conductive carbon and binder, which are required in all electrode formulations. The carbon and binder requirement generally accounts for 3–6 percent of the total weight of the active material.
- The two remaining components of the cell are the separator and the electrolyte. The electrolyte contains additional lithium in the form of the salt $LiPF_6$. The additional Li requirement for this has been included in the Li metal calculation.

- The positive (cathode) current collectors are made of aluminum; this requirement has been indicated separately. The negative (anode) current collectors are made up of copper, with only one exception—namely LTO-LMO chemistry, where aluminum is used for the negative current collector also.

Cobalt in the cathode. The cobalt requirement varies with the chemistry, as seen in Table 8. LFP, LMO, and LTO-LMO cells do not contain any cobalt. Within the NMC chemistry, the cobalt requirement follows the order 111 > 622 > 811. The cobalt requirement is compensated for by adding an extra quantity of nickel in the Ni-rich chemistries. Between NMC 111 and NMC 811, the cobalt requirement is reduced from 353 metric tons to 87 metric tons for 1 GWh. NCA cells also require less cobalt (122 metric tons for 1 GWh).

Electrolyte and separator requirement. The electrolyte requirement varies greatly depending on the chemistry, from 675 metric tons for NMC 811 to 1,728 metric tons for LTO-LMO cells for 1 GWh. The separator requirement is quite similar for all chemistries at around 80–100 metric tons.

Anode. Approximately 800–1,100 metric tons of graphite is required for 1 GWh of cell manufacturing depending on the chemistry of Li-ion. LTO-LMO cells use LTO as the anode and hence do not require any graphite. The chemical formula of this LTO is $Li_4Ti_5O_{12}$. The additional Li required to form the anode active material has been included in the Li metal requirement.

Lithium. The Li requirement ranges from 80 to 120 metric tons for 1 GWh of cell manufacturing for all chemistries except LMO-LTO. For LMO-LTO, 254 metric tons of Li is required.

3.2 Global Raw Materials Availability and Production Statistics

Apart from Li, other key materials used in the electrode-making process in LIB are manganese, nickel, cobalt, copper, graphite, and aluminum. Figure 13 shows the country-wise production fractions of Ni, Mn, Co, Li, and natural graphite. In the previous section, the raw material requirements for manufacturing of 1 GWh of batteries of various battery chemistries was presented. In this section, we discuss the global statistics of raw materials availability and production. The acquisition of any metal starts with the mining process, in which the mineral is recovered from the ground either through an open pit or closed mine. The ore is then concentrated by removing the undesired minerals, and the metal in its pure form is recovered in the next step of smelting. Further purification may be carried out if required, by electrorefining or other methods.

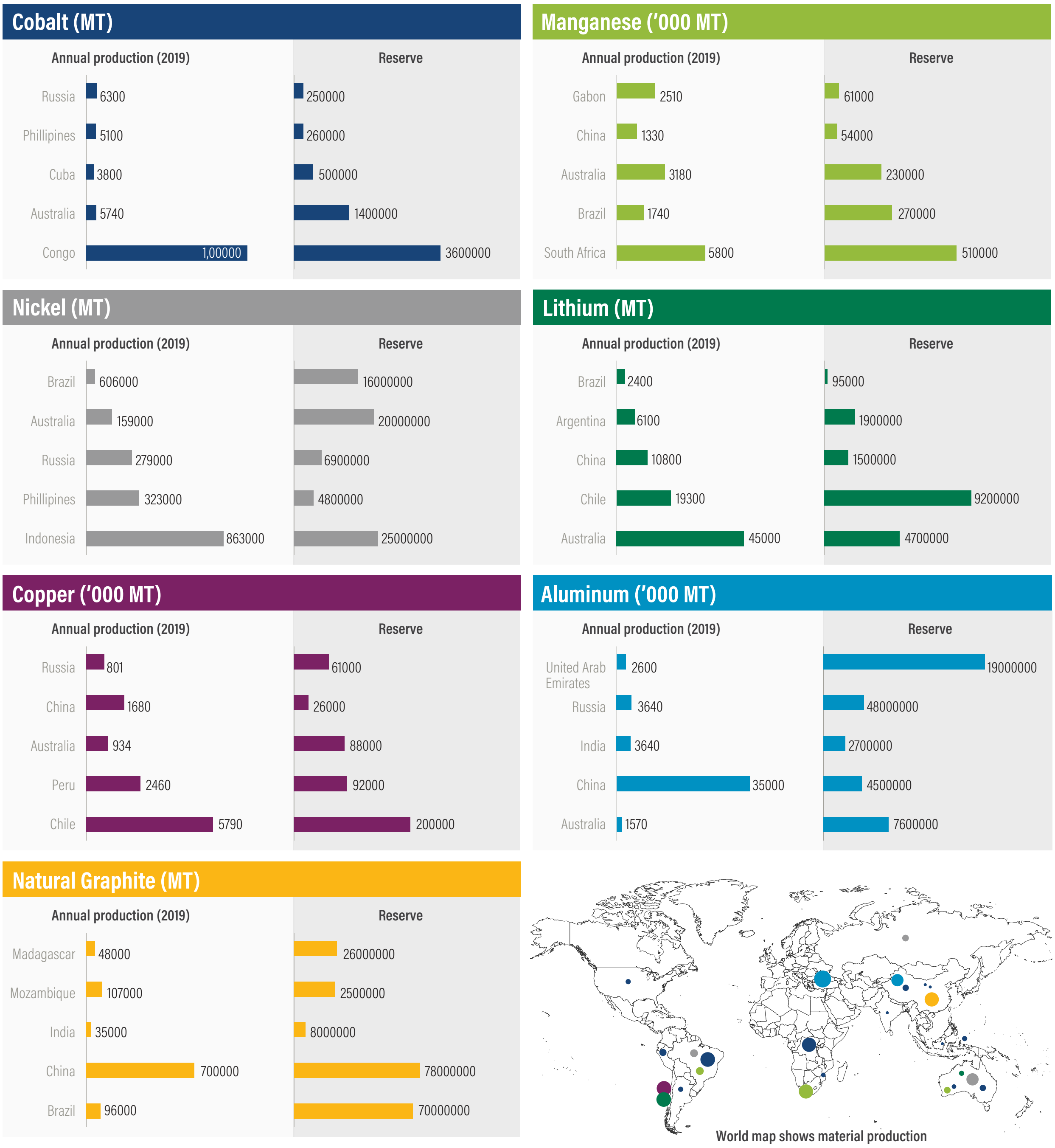
Nickel. The world reserves of nickel are estimated at around 94 million metric tons. Nickel reserves are in Indonesia (22 percent), Australia (21 percent), Brazil (17 percent), Russia (7 percent), and the Philippines (5 percent). Nickel deposits are mainly found in laterite (60 percent) and sulfide (40 percent) forms. Extensive nickel deposits are present in the deep sea as manganese crusts and nodules, and it covers large areas of the ocean floor. The Pacific Ocean floor is rich in nickel resources.

In 2019, globally, nickel production was 2.6 million metric tons of metal content. The demand for nickel for battery manufacturing will rise with the growing market share of nickel-rich chemistries such as NMC 811. The requirement for 100 GWh of NMC 811 cell manufacturing will be approximately 78,100 metric tons, which is only ~4 percent of the current global production.

The principal producers were Indonesia (33 percent), Philippines (12 percent), Russia (11 percent), and Australia (6 percent). Approximately 45 percent of the primary nickel consumed goes into stainless and alloy steel production and 43 percent into nonferrous alloys and superalloys.

Manganese. The world reserves of manganese are approximately 1,300 million metric tons of metal content. Reserves are distributed in South Africa (40 percent), , Brazil (21 percent), Australia (18 percent), Gabon (5 percent), and China (4

Figure 13 | **Country-Wise Annual Production (2019) of Key Raw Materials Required for Li-Ion Manufacturing and Estimated Global Reserves per U.S. Geological Survey**



Notes: Materials cost contributes more than half of the total system cost. Within the materials cost, the cathode active material is the highest contributor. The above data are shown for the NMC 622 chemistry..
Source: CES authors.

percent). Only a fraction of the global reserves of manganese can be economically recovered. Deep-sea manganese nodules constitute an enormous untapped resource and have the potential to meet the future demand. Most of the nodules are located at a water depth of 5 to 7 km on the deep-sea floor. The Pacific Ocean alone is estimated to contain about 25 percent of manganese deposits, which is similar in abundance to low-grade land-based deposits.

The estimated amount of manganese production in 2019 was around 20 million metric tons. The top producers of manganese are South Africa (30 percent), Australia (16 percent), Gabon (13 percent), Brazil (9 percent), and China (7 percent). Most manganese ore consumption was related to steel production, either directly in pig iron manufacturing or indirectly in upgrading the ore to ferroalloys.

Among Li-ion batteries, LTO-LMO and LMO types require the maximum amount of manganese metal for their cathodes. For 100 GWh of LTO-LMO batteries manufacturing, approximately 213,200 metric tons of manganese would be required. This is still a small percentage of the current annual global production, which is over 18 million metric tons.

Aluminum. Globally, the total aluminum reserves are estimated at 74 billion metric tons and are located mainly in the United Arab Emirates (26 percent), Australia (10 percent), Russia (6 percent), China (6 percent), and India (4 percent).

The total global aluminum mine production in 2019 was 63 million metric tons. China was the leading producer with a share of about 55 percent, followed by India and Russia (6 percent each), and the United Arab Emirates (4 percent). For 100 GWh of Li-ion cell manufacturing, approximately 30,000 metric tons of aluminum would be required, except in the case of LTO-LMO, for which approximately 80,000 metric tons of aluminum would be required. More aluminum is needed for LTO-LMO as the LTO anode also uses an aluminum current collector. This is less than 1 percent of the total current annual production. Note that additional aluminum is required in pack manufacturing as part of the thermal management system.

Copper. The total world reserves of copper are estimated at 870 million metric tons of metal content. Chile has the largest reserves, accounting for about 23 percent of the world reserves. Other countries with copper reserves are Peru (11 percent), Australia (10 percent), Russia (7 percent), and China (3 percent).

Copper and copper alloy products are used in building construction (44 percent), transportation equipment (20 percent), electrical and electronic products (19 percent), consumer and general products (11 percent), and industrial machinery and equipment (6 percent). For 100 GWh of Li-ion manufacturing, approximately 75,000 metric tons of copper would be required, except for LTO-LMO batteries, whose negative current collector is also made of aluminum, and therefor there is no copper requirement.

Graphite. The global natural graphite reserves are estimated at approximately 320 million metric tons. The graphite reserves are mainly found in Turkey (28 percent), China (23 percent), Brazil (22 percent), Mozambique (8 percent), Madagascar (8 percent), and India (3 percent). In 2019, the world production of natural graphite was estimated at around 1.1 million metric tons. China was the leading producer and accounted for about 64 percent of the total production, followed by Mozambique (10 percent) and Brazil (9 percent). Canada and Brazil are the leading countries in natural graphite development. Natural graphite is classified as extra-large, large, medium, and fine flake. Only extra-large-flake graphite is suitable for use in battery anode applications. Natural graphite can be used as is after purification and milling to give the well-known spherical graphite particles. Approximately 100,000 metric tons of graphite is required for 100 GWh of cell manufacturing. However, for LTO-LMO batteries, graphite is not required as an active material because the active anode material is lithium titanate.

Synthetic graphite competes with natural graphite for application as an anode active material. Synthetic graphite is produced by heating petroleum coke or needle coke in an oxygen-free atmosphere at 3,000°C for 25–30 days. This process of graphitization converts the coke to graphite. In general, synthetic graphite is considered beneficial for the cycle life of battery packs, whereas natural graphite is considered better for energy density. Graphite anode performance also depends on the quality and presence of impurities, along with its conductivity, surface area, and particle size. Currently, Japan and Korea depend primarily on natural graphite for battery applications, whereas China typically uses a blend of natural and synthetic graphite.

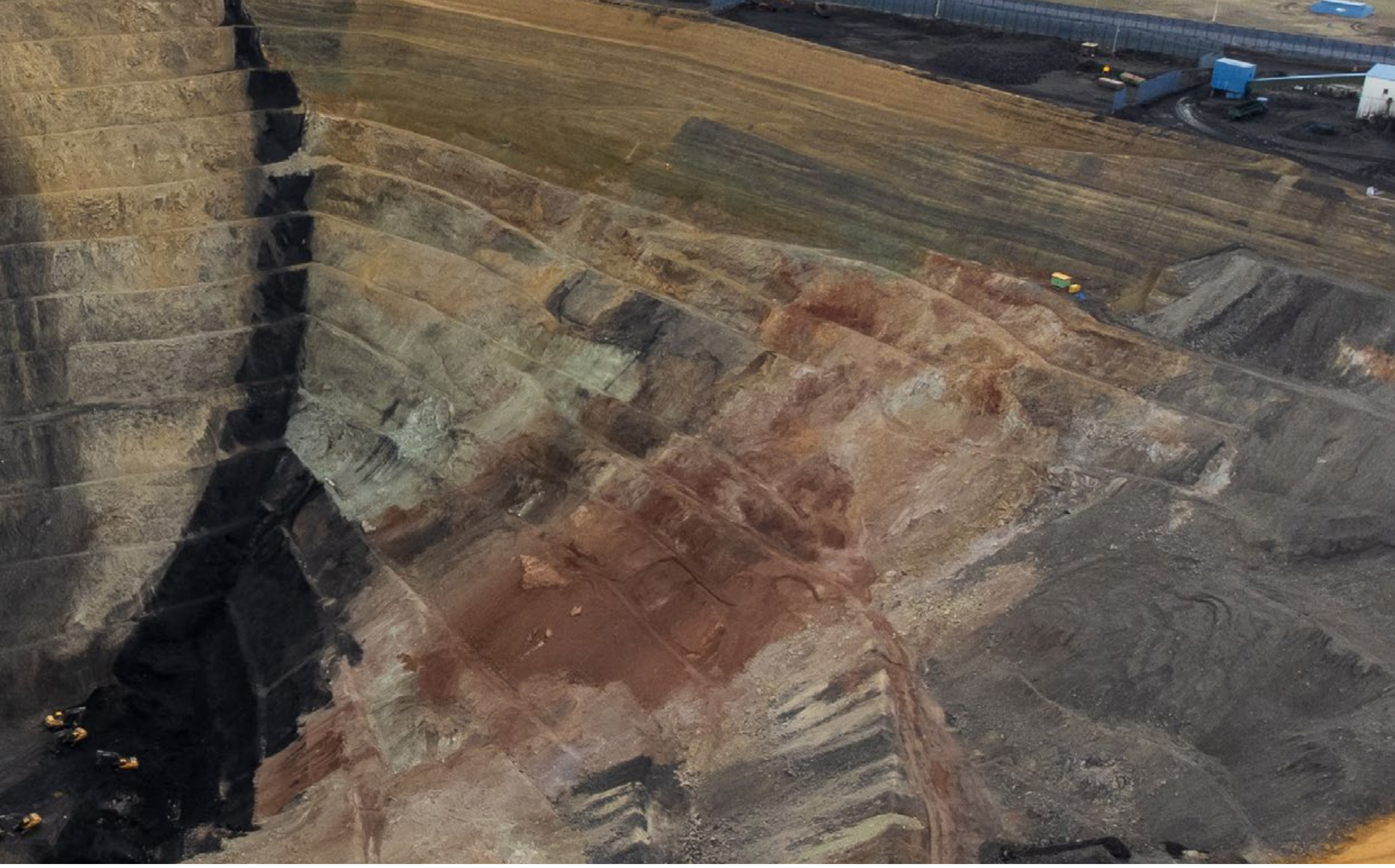
Fine graphite flakes have another application in both the cathode and anode as conductive additives. The conductive additives are only 3–5 percent of the total weight of the anode or cathode active material. Approximately 10,000 metric tons of conductive additives are required for 100 GWh of manufacturing. The conductive additives are produced by milling the fine graphite flakes to a very small particle size. They may also be

sourced as a by-product of large-flake graphite milling. New graphite deposits are being developed in Madagascar, Mozambique, Namibia, and Tanzania, and mines are projected to begin production in the near future.

Cobalt. Among different key materials, cobalt is more prone to supply-chain risk given that only a few countries control most of the supply. For instance, in 2019, Congo produced about 69 percent of the world's cobalt. China's cobalt imports from Congo accounts for almost 40 percent of the total global trade value ($3.1 billion). A majority of cobalt is produced as a by-product during extraction of Ni and Cu. Globally, 50 percent of cobalt production comes from the leaching of nickel-bearing laterite ores and smelting of nickel sulfide ores, whereas 35 percent comes from the copper industry.

About 46 percent of the cobalt consumed in the United States is used in superalloys, mainly in aircraft gas turbine engines; 8 percent in cemented carbides for cutting and wear-resistant applications; 15 percent in various other metallic applications; and 31 percent in a variety of chemical applications. In contrast, in China, more than 80 percent of its consumption is used by the Li-ion battery industry. The annual production of cobalt is approximately 110,000 metric tons. NMC 622 would need about 20,000 metric tons of cobalt for 100 GWh of cell manufacturing, which is a sizable fraction of the current world production.

Lithium. The primary source of lithium is sea brine or hard rock. Among different hard rocks, pegmatite has significant lithium content. Lithium minerals mainly occur as a subset of pegmatite. The theoretical percentage of lithium in spodumene (3.7 percent) and petalite (2.2 percent) is high compared with other minerals, and so they are preferred for lithium extraction. In general, lepidolite is not considered for lithium extraction because the lithium content is very small, and there is also the risk of fluoride contamination in the environment, unless it occurs in large enough quantities. Spodumene is processed to lithium carbonate or lithium hydroxide, which is used as a lithium precursor in cathode active material production. Australia produces the largest amount of lithium, mainly from hard rocks. In 2019, Australia accounted for around 52 percent of the global production, and



it has 22 percent of the world's lithium reserves. The world's largest lithium rock deposit is in Greenbushes, Western Australia. Another source of lithium is sea brine. South American countries like Chile and Argentina are the main sources of sea brine. Chile has the largest lithium reserves (around 44 percent), and it accounted for 22 percent of the world's lithium production in 2019. Many countries like China, South Korea, and Japan import lithium concentrates and process them to produce lithium carbonate or lithium hydroxide.

For 100 GWh of Li-ion cell manufacturing, the approximate requirement of lithium is 10,000 metric tons. In the case of LTO-LMO batteries, the demand is higher at 25,400 metric tons as there is additional lithium in the anode ($Li_4Ti_5O_{12}$ = LTO).

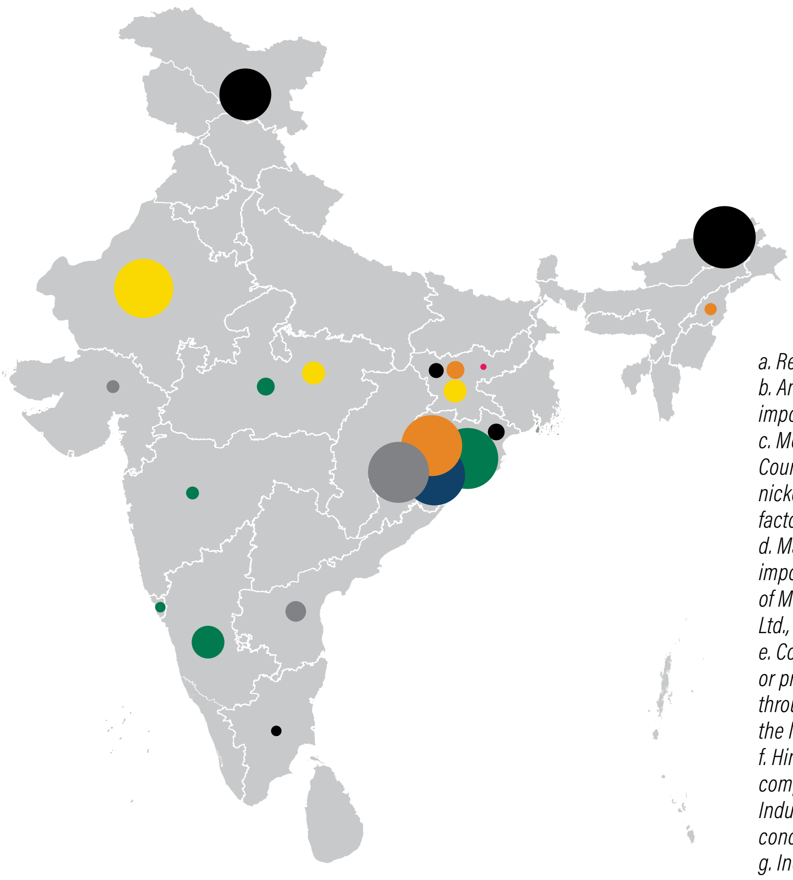
3.3 Mineral Resource Availability in India

Lithium. India has very limited known reserves compared to lithium-rich countries such as Chile, Argentina, and Australia. According to the Geological Survey of India, the lithium ore lepidolite is present in the Bihar mica belt, and pegmatite is present in the Chitalnar, Mundwal, and Govindpal areas of Chhattisgarh. Also, the Marlagalla–Allapatna area in the eastern parts of Srirangapatna, Karnataka, contains spodumene, whereas Kabbur and Doddakadanur, also in Karnataka, contain the lithium ore hiddenite. India should consider having trade agreements with the lithium-rich countries to ensure a continuous supply of lithium ores and concentrates.

The two main sources of lithium used in cathode manufacturing are lithium hydroxide and lithium carbonate. The shelf life of these materials is approximately six months, and the purity of lithium compounds is crucial for obtaining high cycle life from the batteries. Due to the delays associated with shipping across continents, it is considered more suitable to locate lithium processing plants closer to the cathode powder fabrication plants. In this case, the ores or concentrates are shipped, and the final processing is done close to the place of utilization. This opens up an opportunity for India to set up processing facilities with imported lithium ores.

Figure 14 | **Availability of Reserves of Key Raw Materials and Annual Production in India for Supporting Li-Ion Manufacturing**

	NICKEL[C]	MANGANESE[D]	COBALT[E]	COPPER[F]	ALUMINUM[G]	GRAPHITE[H]
Existing Reserves[a] (million tons)	1.3	151.8	0.052	12.16	824.28	22.68
Annual Production[b] (million tons)	Nil	0.79	Nil	0.787	2.9	0.037
Average Cost ($/ton)	15790	2471	38411	6775	1896	1300
Battery Component	Cathode	Cathode	Cathode	Anode current collector	Cathode current collector, Cell casing	Anode, Conductive additive
Main other uses	Special alloys/ super alloys	Steel and iron-making industries (93%)	Special alloys/ super alloys	Electrical and tele-	Electrical sector (48%), Automobile and transport (15%)	Crucible and Pencil industry (76%)



a. Reserves + remaining resources
b. Annual production from domestic ore production and imported ores and concentrates.
c. Most nickel is produced as a by-product of other refining. Country's entire demand is met through import. High purity nickel for battery applications is produced in a refining factory in Goa (NiCoMet).
d. Main ore of Mn is pyrolusite. India is one of the major importers of manganese ore in the world. Principle producers of Mn ore are MOIL Ltd., The Sandur Manganese & Iron Ores Ltd., Mangilal Rungta, Orissa Manganese and Minerals Ltd.
e. Cobalt is extracted as a by-product of copper, nickel, zinc or precious metals. The demand for cobalt is usually met through imports. NiComet Industries Ltd. Gujarat is among the leading producers of cobalt.
f. Hindustan Copper Limited is the only vertically integrated company involved in mining to refine copper. HindalCo Industries Ltd and Vedanta Ltd rely on imported copper concentrates.
g. India is one of the largest producers of Al in the world. Four major primary producers are National Aluminium Co. Ltd., Bharat Aluminium Co Ltd., and Vedanta Aluminium Ltd.
h. India produces both types of natural graphite, crystalline (flaky) graphite and amorphous graphite. Synthetic or artificial graphite is manufactured on a large scale in electric furnaces.

Source: Indian Minerals Handbook 2017.

Cobalt. India does not have any known primary cobalt reserves. Two possible secondary sources of cobalt are nickel-bearing laterite deposits in Odisha and copper slag, mainly produced by Hindustan Copper Ltd (HCL). Other places where small-scale cobalt resources have been reported are Singhbhum district, Jharkhand; Kendujhar and Jajpur districts, Odisha; Jhunjhunu district, Rajasthan; Tuensang district, Nagaland; and Jhabua and Hoshangabad districts, Madhya Pradesh.

To meet the cobalt demand in India, cobalt ore is imported and the refining is done in India. The total refining capacity in India for cobalt is 2,060 metric tons per year. Currently it produces about 1,000 metric tons of copper-cobalt alloy per year. Recycling of cobalt from used items is an important activity, and work is underway at the Council of Scientific and Industrial Research (CSIR) labs like the National Metallurgical Laboratory (NML) in Jamshedpur and Advanced Materials and Processes Research Institute (AMPRI) in Bhopal using hydrometallurgical/pyrometallurgical processes.

Nickel. Nickel is recovered as a by-product of copper production in the form of nickel sulfate crystals. Globally, there are two major sources of nickel: laterites (60 percent) and sulfide (40 percent) deposits. The annual demand for pure nickel in India is 45,000 metric tons. Nickel is not produced through any primary resources in the country, and the entire demand is met through imported ores. India imports ores mainly from Guinea and Australia as ores and concentrates. The other form of import is as alloys and scrap, mainly from Russia, Norway, Australia, Canada, and South Africa. High-purity nickel from ores for battery-grade applications (not Li-ion) is produced in refining companies in Goa and Gujarat.

As of 2013, the total reserves of nickel ore in India were estimated at 189 million metric tons, 92 percent of which is distributed in Sukinda valley in Odisha and the remaining 8 percent in Jharkhand and Nagaland. In East Singhbhum district of Jharkhand, nickel is present in sulfide form along with copper mineralization. Limited nickel deposits occur in Karnataka, Kerala, and Rajasthan.

Nickel sulfate crystals are obtained from copper production by the Ghatsila copper smelter of HCL in Jharkhand. The plant was commissioned in 2016 and is poised to achieve a production capacity of about 50 metric tons per annum.

Graphite. India was the world's second largest producer of natural graphite in 2016 and the fifth largest in 2019. India imported 37,046 metric tons of natural graphite in 2017 and produced 122,000 metric tons. Most of the graphite is consumed by the graphite product industry; for example, the crucible/pencil industry has a share of almost 76 percent. Information as to the flake size of graphite is not available. An analysis is required for estimating the percentage of large-flake graphite in the existing reserves that is suitable for Li-ion battery anode applications. Expanded graphite, which is used in electrodes and bipolar plates in flow batteries and FCs, can also be synthesized from this by using acid treatment and heating. India imports approximately 47,000 metric tons of synthetic graphite for non-battery applications. Synthetic graphite is produced from coke via a graphitization process involving heating the coke at 3,000°C for 28 days in an oxygen-free atmosphere. In Li-ion battery anodes, some companies use a 7:3 blend of synthetic and natural graphite.

Manganese. India ranks sixth globally in the production of manganese, which is largely used in steelmaking. India is the one of the major manganese importers. Odisha is the top source of manganese, accounting for 44 percent of the country's manganese reserve, whereas Madhya Pradesh is the leading manganese producer, accounting for 27 percent of the country's production in 2016–17. There are 142 operational mines.

The domestic production of manganese ore was 2.39 million metric tons in 2017 with an average of 30–35 percent manganese content. This corresponds to approximately 0.76 million metric tons of manganese metal. The quantity of manganese ore imported was 1.90 million metric tons, which consisted of 30–46+ percent manganese content.

For Li-ion battery cathode applications, $MnSO_4$ (manganese sulfate) is the input raw material. This is produced from 35 percent manganese ore by a process that involves heating MnO_2 to 850°C

with natural gas (reduced to MnO). Subsequently the MnO is reacted with sulfuric acid to produce $MnSO_4$.

Aluminum and copper. In Li-ion battery fabrication, aluminum and copper foils are used as current collectors for cathode and anode, respectively. High-purity aluminum and copper are needed for battery applications. The required foil thickness is in the range of 5–15 µm with low tolerances. Additional surface chemical treatments are required to improve the stability and adhesion of the coating in Li-ion battery applications.

India is the one of largest producers of aluminum in the world. Indian industry mainly fulfills its aluminum demand from its own rich bauxite mineral base.

India imports copper concentrates for its smelters and also produces ore and concentrates. In 2017, India produced 3.85 million metric tons of copper, in which the metal content was 33,673 metric tons. In the ore, the average copper content was 0.88 percent. Although the total production of refined copper in 2017 was very low—about 0.787 million metric tons—the total import of refined copper was 0.035 million metric tons, whereas exports were 0.337 million metric tons in 2017.

The domestic demand for copper alloys primarily is met through domestic production, recycling of scrap, and also by imports.

3.4 Recycling

As the volume of battery manufacturing grows, a parallel system of disposal and recycling will be essential to minimize the detrimental impact on the environment. Li-ion batteries contain lower levels of toxic materials as compared to other batteries, which could contain toxic metals such as lead or cadmium. Currently, the recycling industry for Li-ion batteries is in the nascent stage, with only a few companies worldwide engaged in it. Potentially, all the metal elements used in a Li-ion battery—namely Li, Co, Ni, Mn, Co, and Al—could be recovered and reused for either batteries or other applications. However, currently only cobalt is partly recovered due to its high cost and concerns regarding its availability. Strict regulations regarding the disposal of batteries need to be enacted to give an impetus to the Li-ion battery recycling industry. In terms of recycling, the lead-acid battery industry is very advanced, with almost 96 percent of the batteries being recycled worldwide. This is thanks to a robust and scalable recycling technology, strict regulations prohibiting improper disposal, and a well-established supply chain for collecting used batteries from the customer.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SECTION IV

R&D NEEDS, PRIORITIES, AND CHALLENGES

In response to the growing need for advanced electrochemical energy storage systems, the global R&D community has begun to set up various mechanisms to focus its efforts. In this section, we examine the programs operating in the United States, Europe, Japan, China, and Australia.

4.1 Global Status of Energy Storage Research: Funding, Incubation Centers, Research Centers, and Consortia

In most countries, the starting point for research activities is the declaration of a broad vision for vehicle electrification by the central government agencies. Following this, specific goals and milestones are outlined by the relevant government bodies, with timelines assigned to the various objectives. This builds the framework for setting up appropriate funding schemes, incubation centers and testing facilities, consortia and associations, and more recently, specialized research centers. In this section, we present an overview of the activities underway in various regions, to identify measures that have proved to be effective in stimulating rapid advances.

Table 9 | **Global Energy Storage Programs**

TYPE	NAME	REGION
Government programs	■ Advanced Research Projects Agency for Energy (ARPA-E) ■ Small Business Innovation Research (SBIR) ■ Battery500 (based out of PNNL)	United States
Incubation centers	■ Cyclotron Road (LBNL) ■ Innovation Crossroads (UCB) ■ Chain Reaction Innovations (ANL) ■ Los Angeles Cleantech Incubator (LACI	
Consortia	■ New York Battery Energy Storage Technology (NY-BEST) ■ U.S. Advanced Battery Consortium (USABC)	
Battery materials research centers	■ Joint Center for Energy Storage Research (JCESR) ■ Center for Energy Research (UCSD) ■ University of Maryland Energy Research Center (UMERC)	
Government programs	■ Horizon Funding under European Union (EU) ■ LAVOISIER 2020 Programme	Europe
Incubation centers	■ InnoEnergy (Netherlands, France, Germany, Sweden, Spain)	
Consortia and associations	■ Faraday Institution ■ UK Battery Industrialisation Centre (UKBIC) ■ Energy Storage–Henry Royce Institute	
Battery materials research centers	■ Fraunhofer ISIT and ISE ■ Helmholtz-Zentrum Dresden Rossendorf (HZDR) ■ Helmholtz Institute Ulm (HIU) ■ EnergyVille (supported by VITO)	
Government programs	Advanced Low Carbon Technology Research and Development Program–Specially Promoted Research for Innovative Next Generation Batteries (ALCA-SPRING)	Japan
Government programs	Storage projects by Australian Renewable Energy Agency (ARENA)	Australia
Government programs	2nd Energy Master Plan	Korea

Sources: U.S. DOE, European Energy Research Alliance-Energy Storage, Japan Science and Technology

4.1.1 United States

A large part of the government support for funding energy storage R&D has been provided by two agencies: the Advanced Research Projects Agency for Energy (ARPA-E) and the Small Business Innovation Research (SBIR) program. ARPA-E funds are given to academic institutions, whereas SBIR caters to companies and enterprises.

ARPA-E focuses on high-potential, high-impact energy technologies that are too futuristic for private sector investment. Normally, the funding is given for a period of three years, and the main objective is to bring the technology to the stage of a commercial prototype. ARPA-E was formed in 2009, and since then it has funded approximately 600 projects, which have produced about 245 patents. There are three EV-battery-focused programs: BEEST (Batteries for Electrical Energy Storage in Transportation), AMPED (Advanced Management and Protection of Energy Storage Devices), and RANGE (Robust, Affordable Next Generation Energy Storage Systems). These programs have been operating since 2010, 2012, and 2014 and have each funded 24, 30, and 44 projects, respectively. Another program, called IONICS (Integration and Optimization of Novel Ion-Conducting Solids), focuses on solid-state batteries and funded the original work on LIPON electrolytes at Oak Ridge National Laboratory that led to the formation of several spin-offs. The success of the ARPA-E programs is judged on the basis of licensing and uptake of technologies following funding by the private sector.

Some of the key features of this funding mechanism are the following:

- Desired performance outcomes of the technology are outlined based on the broad vision and goals laid out by the Department of Energy (U.S. Government). The performance parameters also include the expected cost ($/kWh), and potential applicants are required to estimate the cost of the technology based on raw materials costs and cell fabrication costs.

- Typically, the potential applicants would have already built lab-scale prototypes (TRL = 4) and published the outcomes in peer-reviewed journals. The request for ARPA-E funding is made with the objective of scaling up to commercial prototypes.

- Quarterly evaluations are made by the team of experts from ARPA-E to gauge the extent of progress. In case the progress is considered unsatisfactory, the funding may be stopped prematurely at the end of the first or the second year. This is to prioritize projects with the best potential for successful commercialization.

- The funding amounts are quite large ($200,000 to $1.5 million). They cover the costs of purchasing commercial-scale equipment for battery fabrication, and can be used to continue work after expiry of the funding.

The SBIR program is a highly competitive program that encourages domestic small businesses to engage with academic institutions to focus on manufacturing technologies that have the potential for commercialization. A number of technologies developed through ARPA-E funding have been taken up by the private sector through the support of the SBIR program. This ensures continuity of the high-impact research in academic institutes and encourages industry to maintain the spirit of innovation and improvement. As a result, it ensures better outcomes from government-sponsored R&D in academic institutes and research centers.

A number of government-funded (U.S. DOE) research centers focused entirely on energy storage and conversion technologies have also been set up in various institutes. Some of the notable ones are the University of Maryland Energy Research Center (UMERC) and Joint Center for Energy Storage Research (JCESR). In addition to this, there are large-scale testing facilities at Sandia National Labs, National Renewable Energy Laboratory, and Center for Energy Research at the University of California, San Diego for field-testing various technologies. Such facilities also serve as a platform for performance demonstration and certification under actual operating conditions.

In recent years, a number of technology incubators have been set up that have energy storage as one of the main focus areas. Most of these have been set up with public-private partnership funding, and they select companies to support through a competitive process. A nongovernmental body called U.S. Advanced Battery Consortium (USABC) has also been active in promoting industrial research in the field of batteries. USABC mainly seeks to promote long-term R&D

within the domestic electrochemical energy storage (EES) industry and to maintain a consortium that engages automobile manufacturers, EES manufacturers, the National Laboratories, universities, and other key stakeholders.

4.1.2 Europe

In Europe, the major government initiatives are led by the Horizon 2020 funding under the European Union (EU). The performance goals and cost goals for EV battery packs have been outlined by the Strategic Energy Technology (SET) Plan in consultation with multiple stakeholders to make European batteries competitive in the global market. Under the Horizon 2020 funding by the EU, in 2019, €114 million was made available to fund projects in seven areas related to battery development for various applications. The research and innovation activities are structured around three focus areas: material/chemistry/design and recycling, manufacturing, and application and integration. This includes €25 million for solid-state batteries for electric vehicles, €30 million for R&D on next-generation materials for Li-ion batteries, €13 million for cell and battery pack modeling and simulation R&D, and €2 million for developing a network of cell-manufacturing pilot lines. The objective of the pilot manufacturing lines is to push toward the development of industrial-scale production in Europe. Such pilot lines are accessible to industry as well as academia and can serve as a tool for not only skill development but also for easing the transition of lab-tech to commercialization. Pilot plants are also very effective for trying out several different variations in the manufacturing process to optimize the final product's performance.

At the level of individual countries, several initiatives and government programs have been launched and operated, as described in the following text.

France. A government-supported programmed called LAVOISIER has been set up to focus on the design and fabrication of materials for energy-related applications, including batteries, hydrogen FCs, and storage. The LAVOISIER program is managed by Le Studium Institute of Advanced Studies and has the University of Tours, University of Orleans, and CEA Le Ripault as member organizations. The program was funded by a grant of €10.2 million from the government of the Centre Val-de-Loire region, and one of the objectives was to attract international experts from around the world to come for short stays in the associated universities and labs. Such programs can be used to attract Indian experts from around the world to set up battery R&D laboratories in Indian institutes for short durations (2–5 years).

United Kingdom. The UK government has set up a new initiative under the name Faraday Challenge to fast-track the development and adoption of next-generation batteries for vehicles and other applications. Through this challenge, the government is investing £246 million in research and innovation projects and the construction of new facilities and institutes to scale up and advance the production, use, and recycling of batteries. One of the notable companies that has received support from the Faraday Challenge is OXIS Energy, which is developing high-energy-density LiS batteries.

Under this program, a £80 million automotive battery industrialization center (UKBIC) has been set up. It will allow companies to quickly develop their capabilities to manufacture batteries and get them to market and scale up. It is being led by Coventry and Warwickshire Local Enterprise Partnership, Warwick Manufacturing Group, and Coventry City Council. Through industrial collaboration, accelerated opportunities for the most promising early and mid-stage research (TRL = 3–5) and development activities were available to feed through into scale-up and commercial exploitation (TRL = 7–9).

Under the same Faraday Challenge, an independent institute for EES research and skills development called The faraday Institution has been established via a £78 million grant. In addition to its research projects, which began early in 2018, the Faraday Institution will be launching projects in four additional research areas in the autumn of 2019. Up to £12 million per annum per award is available as part of the Industrial Strategy Challenge Fund. The projects will run for 48 months subject to the outcome of a comprehensive spending review,.

Germany. In Germany, the Federal Ministry for Economic Affairs and Energy is pursuing an ambitious research strategy. The Federal Government is currently providing funding for developing ESS under its Energy Storage Funding Ini-

tiative. Since 2012, about €200 million has been awarded to a total of around 250 projects. The projects covered by the funding initiative range from batteries in EVs to hydrogen FCs. Lithium-based electrochemical storage is currently regarded as a promising option for use in vehicles that are partially or fully electrically driven. According to the National Electric Mobility Platform targets, the Federal Government aims to have more than a million EVs on the roads by 2020. The Federal Ministry for Economic Affairs and Energy has also set up the funding priority called "Key Energy Industry Elements of e-Mobility." In the long term, electrochemical storage is also regarded as an option for balancing the electricity grids.

4.1.3 Japan

In Japan, the Advanced Low Carbon Technology Research and Development Program–Specially Promoted Research for Innovative Next Generation Batteries (ALCA-SPRING) project was launched in 2013. The main aim of the program is to accelerate R&D on high-capacity secondary batteries and to fabricate them. Under this program, next-generation advances over existing Li-ion batteries are selected, such as all-solid-state batteries, LiS, and metal-air batteries. The program is massive in scale, comprising over 40 institutions, among them Iwate University, Tohoku University, National Institute for Materials Science, Tokyo University of Science, Tokyo Metropolitan University, Yokohama National University, Osaka Prefecture University, Kansai University, Yamaguchi University, and Nagasaki University.

4.1.4 Korea

To drive the storage-related activities in Korea, the Ministry of Trade, Industry and Energy (MOTIE) published a report, "K-ESS 2020," in May 2011, announcing ambitious plans for Korea to hold 30 percent of the global market share by 2020, and also fixed the target for the installed energy storage system, which was 1.7 GW. In 2013, MOTIE revised the installed capacity target to 2 GW by 2020 and published a detailed roadmap in a report titled "The Sixth Electricity Supply Plan (2013-2027)." In 2014, MOTIE published another report, "2nd Energy Master Plan," and laid out the plans for Korea's energy growth by 2035. The focus was on reducing the cost of the storage system by one half by 2020 through innovative research. According to the report, the R&D focus was on futuristic battery technologies other than Li-ion batteries, redox flow, and NaS batteries. Much of the emphasis was devoted to medium- to large-sized projects; that is, 50–100 MW storage systems including a 100 MW compressed air system and a 50 MW Li-ion battery storage system connected to wind power.

4.1.5 Australia

The key agency through which the Australian government supports R&D activities on energy storage technology is the Australian Renewable Energy Agency (ARENA). To support energy storage projects, ARENA had issued more than $98 million by the end of 2016. The fund has exceeded $197 million with the addition of third-party matching support. Over 27 projects such as battery technology development and testing, and utility-scale battery systems are supported.

The Australian Research Council (ARC) is also investing heavily in energy storage technology development. ARC has contributed over $318 million for fundamental science research, including eight projects related to solar and energy storage technology. Various public sector organizations are involved in energy storage research, such as the Australian National University's (ANU) Energy Change Institute, the Commonwealth Science and Industrial Research Organisation (CSIRO), Curtin University's Fuels and Energy Technology Institute, Deakin University's Institute for Frontier Materials, Monash University's Energy Materials and Systems Institute (MEMSI), and the Queensland University of Technology.

4.2 The Vision of Indian Government: Need for Defining Goals and Milestones for Battery Technologies

Although the government has shown a very strong interest in promoting vehicle electrification by offering subsidies, clear guidelines regarding the expected performance of battery packs for vehicles have not yet been developed. The main performance parameters for EV battery packs include the energy density (Wh/kg and Wh/L), cycle life (at 25°C and 45°C), RTE (percent), self-discharge (percent/month), and fast charging capability. A clear definition of the expected performance metrics gives direction to the global pool of battery technology developers and suppliers, and helps them to benchmark their technology against the desired performance. It also serves as a guideline that potential Indian battery manufacturers and car OEMs can use when shortlisting candidate technologies to focus on. Further, establishing such clear criteria also lays down a baseline for domestic R&D organizations, which can fix their minimum and aspirational goals for developing battery technologies.

In Table 10, the minimum qualifying criteria for all the performance metrics of a battery technology for EV applications have been worked out after discussions with government agencies, automotive OEMs, battery manufacturers, end users, and others. By defining the minimum expectations, the range of prospective technologies is kept open and broad, allowing all current and next-generation technologies to compete solely on performance. Since the average ambient temperatures in a tropical country such as India are quite high, an additional clause for a minimum cycle life at 45°C has been included. This will help in filtering out technologies that are highly temperature sensitive and therefore not optimal for Indian driving conditions. Additional criteria for the 2025–35 time period have been included in view of the expected developments in storage technologies, and can serve as a roadmap for the battery development ecosystem in the country.

4.2.1 ACC PLI Program

On June 9, 2021, the DHI released a gazette notification on the PLI scheme, National Programme on Advanced Chemistry Cell (ACC) Battery Storage, for the implementation of gigascale ACC manufacturing facilities in India.

Through this scheme, the GoI intends to optimally incentivize potential investors, both domestic and overseas, to set up gigascale ACC manufacturing facilities with an emphasis on

Table 10 | **Performance Goals for EV Batteries (2Ws, 3Ws, 4Ws)**

	2020	2025	2030	2035
Energy density[a] Wh/kg	>120	>200	>250	>400
Energy density[a] Wh/L	>300	>400	>500	>700
Cycle life Ambient temp. = 25°C	>3,000	>5,000	>8,000	>10,000
Cycle life Ambient temp. = 45°C	>1,500	>2,000	>3,000	>6,000
Round-trip efficiency[b] (%) Includes parasitic losses	>80	>85	>90	>90
Acceptable c-rates[c]	C/2–C/8	C/2–C/8	1C–C/8	2C–C/8
Fast charging[d] Minutes for 100 km range	<30 min	<20 min	<10 min	<5 min
Self-discharge[e] %/month	<5	<5	<3	<1
System cost ($/kWh)	300	250	200	150

Notes: a. System-level energy density (Wh/L and Wh/kg) measured at ambient temperature = 25°C and at the recommended c-rates. It includes the weight and volume of all balance of plant (BoP) components.
b. DC-DC round-trip efficiency takes into account the energy consumption of all BoP components, excluding inverter losses.
c. Energy density, efficiency, and cycle life values must be demonstrated at acceptable c-rates.
d. The time required to charge the battery enough to be able to provide 100 km of driving range.
e. Measured at ambient temperature 25°C.
2Ws = two-wheelers; 3Ws = three-wheelers; 4Ws = four-wheelers; EV = electric vehicle.
Source: CES authors.

maximum value addition and quality output and the achievement of the pre-committed capacity level within a predefined time period. Incentives will not be offered to the conventional battery pack segment of the industry, as such incentives are already being provided.

ACC battery mineral supply is one of the critical challenges to building a world-class ACC battery industry in India. This is why the government's program design has emphasized value addition both for the selection of companies and for the subsidy volume. The actual subsidy is prorated; that is, the higher the local value addition such as domestic processing of minerals, the greater the subsidy the cell maker gets. This also incentivizes local recycling. ACC battery recycling is not only an environmental issue but also a rare opportunity to secure critical battery mineral supply for India, as domestically recycled materials are considered for local value addition. Comprehensive waste management rules will attract investments to this critical sector and will spur innovation to make India one of the key players in the global "circular economy" movement.

4.2.2 Scheme Parameter: ACC Technology

The scheme covers ACCs and integrated advanced batteries (single units) that meet the minimum performance specifications shown in the shaded part of Table 11.

Incentives will be offered to only those firms that have been allocated ACC production capacity (with a cumulative capacity of 50 GWh for all beneficiary firms combined) under the program, through a transparent mechanism by inviting a request for proposal (RFP). The beneficiary firms will have to commit to setting up a minimum of 5 GWh of ACC manufacturing facility. The total annual cash subsidy to be disbursed by the government will be capped at 20 GWh per beneficiary firm. In addition to 50 GWh of cumulative ACC capacity, 5 GWh of cumulative capacity would be offered to "niche" higher-performance ACC technologies with a minimum threshold capacity of 500 MWh. This initiative would also be technologically agnostic; higher performance parameters alone would be the prerequisite for eligibility.

4.3 Bridging the Gap: Fostering Academia–Industry Collaboration

4.3.1 Battery Development Ecosystem

The performance goals define a clear set of objectives for all members of the battery development ecosystem. The ecosystem consists of three main components:

- Academic institutions and national research laboratories
- Energy storage incubation centers, and field-testing and certification facilities
- Enterprises such as battery manufacturing companies and car manufacturers

Academic Institutions. India has a large number of academic institutions and national laboratories with facilities for research in electrochemical storage technologies. The Central Electrochemical Research Institute (CECRI) located in Karaikudi is one such example, with a complete focus on electrochemistry-based tech-

Table 11 | **Minimum Performance Specifications of Cell Technology for Obtaining Subsidy under the PLI Scheme**

ACCS		ENERGY DENSITY (WH/KG) ~ (SPECIFIC DENSITY)				
		≥ 50	≥ 125	≥ 200	≥ 275	≥ 350
CYCLE LIFE	<1000	N.A	N.A	N.A	N.A	ACC (1/5)
	≥ 1000				ACC (2/4)	ACC (2/5)
	≥ 2000			ACC (3/3)	ACC (3/4)	ACC (3/5)
	≥ 4000		ACC (4/2)	ACC (4/3)	ACC (4/4)	ACC (4/5)
	≥ 10000	ACC (5/1)	ACC (5/2)	ACC (5/3)	ACC (5/4)	ACC (5/5)

Notes: kg = kilogram; N.A. = not applicable; PLI = Production Linked Incentive; Wh = watt-hour.
Source: NITI Aayog.

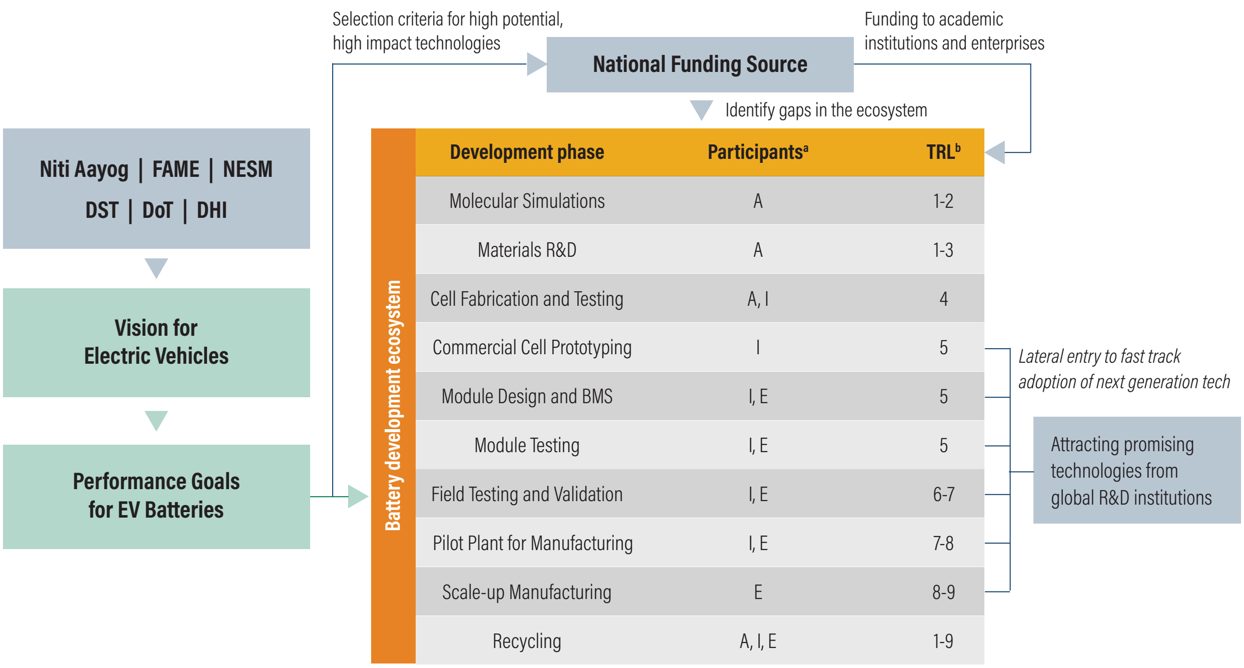
nologies. In addition, several research groups in the Indian Institute of Technology (IIT) Bombay; IIT Delhi; Indian Institute of Science (IISc), Bangalore; IIT Kanpur; IIT Guwahati; IIT Roorkee; Centre for Materials for Electronics Technology (C-MET), Bangalore; and many other institutions are working on the materials development aspects of battery technologies.

Typically, the laboratories in academic institutions are well equipped for TRL 1–4 (some even up to TRL-7) development work. This includes modeling and simulation of materials properties, synthesis of new electrodes and electrolyte materials, characterization of materials with analytical instruments, and finally testing the new materials in lab-scale prototypes. The lab-scale prototypes are usually coin cells or Swagelok-type cells. These cells are convenient and fast to assemble, and require very little active material. As a result, they are ideal for testing many variations with minimum resources.

Commercial prototypes are either pouch cells, prismatic cells, or cylindrical cells. The amount of material and the type of instrumentation required for producing these cells are not available in academic institutions, although they may be accessible to a few.

Energy storage incubation centers. These are specifically equipped for commercial prototype development (TRL = 5) of technologies emerging from academic institutions (TRL = 3–4) (Figure 15). All the equipment related to synthesis of materials, fabrication of electrodes, cell assembly, and testing are essentially scaled up and in some cases automated versions of those used in academic institutions. One of the important considerations while setting up such facilities is that many of the storage technologies for EVs require a lot of common equipment in the incubation stage. This means that if such a facility exists, it could be utilized by a variety of stakeholders for their R&D needs and for problem solving during various stages of technology development. This would include start-ups and spin-offs from academic institutions and also industry-sponsored research. This will greatly reduce the up-front cost that a manufacturing partner would otherwise have to spend on buying new equipment. At the same time, it will ensure maximum utilization of equipment in the incubator. An additional soft benefit of such incubators is that it allows researchers to gradually transition from an academic environment to an industrial environment and become potential job creators.

Figure 15 | **Interrelationship between the Various Components of the Battery Development Ecosystem**



Development phase	Participants[a]	TRL[b]
Molecular Simulations	A	1-2
Materials R&D	A	1-3
Cell Fabrication and Testing	A, I	4
Commercial Cell Prototyping	I	5
Module Design and BMS	I, E	5
Module Testing	I, E	5
Field Testing and Validation	I, E	6-7
Pilot Plant for Manufacturing	I, E	7-8
Scale-up Manufacturing	E	8-9
Recycling	A, I, E	1-9

Source: CES and WRI India authors.

Field-Testing Facilities. These are equipped to provide standardized, independent, third-party performance, safety testing and validation of battery packs, and advanced storage technologies along with the capability to provide environmental control during testing. The environmental control aspect is especially important from the Indian perspective because the ambient temperatures are generally high (30°C–45°C) during most parts of the year. Sustained operation at the temperatures can significantly lower the longevity and shelf life of battery packs. Sandia National Laboratories based in the United States has established such a facility for testing stationary storage battery systems under government funding from the U.S. Department of Energy. These facilities are the Energy Storage Test Pad (ESTP) and the Energy Storage Analysis Laboratory (ESAL). Another similar facility located in Belgium is the EnergyVille battery-testing lab, which was set up under a public-private partnership, as a collaboration between KU Leuven, University of Hasselt, VITO, and imec.

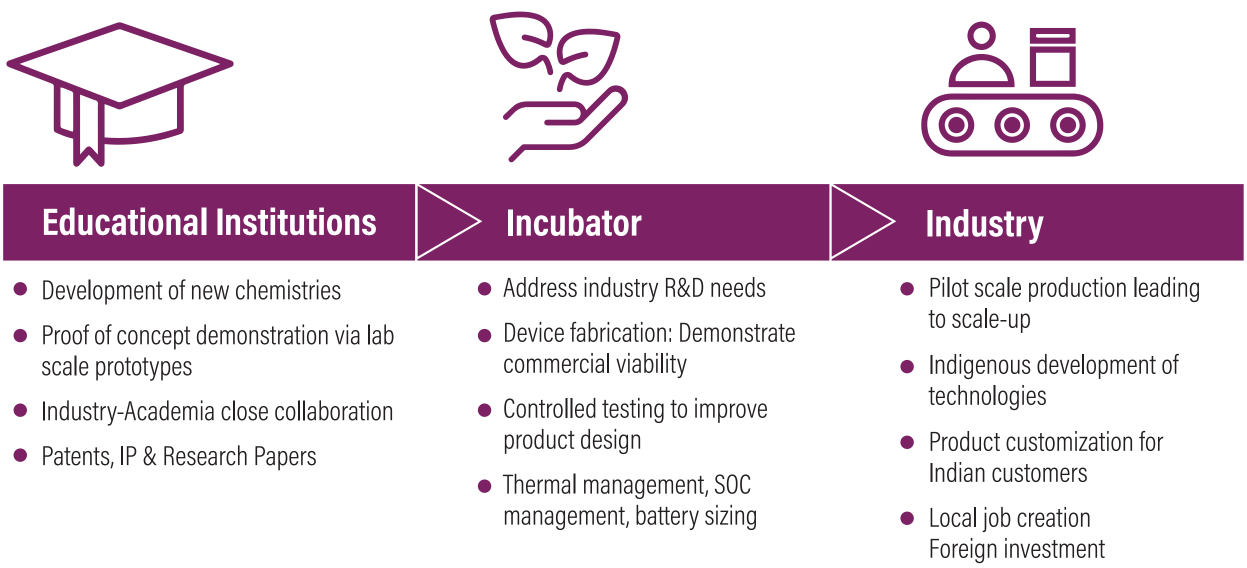
Along with the testing battery technologies, another responsibility of such centers is to develop new testing procedures, and support the development of new energy storage standards in accordance with Indian conditions and applications. Such facilities are used directly in a number of ways by the following:

- Academic institutions and incubation centers that have developed new technologies and want to demonstrate performance through a recognized third-party institution
- Battery-manufacturing companies that are interested in partnering with a start-up or a company that has developed a new technology
- Car manufacturers that are looking for next-generation technologies for their electric vehicles

4.3.2 Attracting Next-Generation Technologies (TRL = 5–7) from the Global R&D Network

Materials-level R&D is a time-intensive process, and often the entire journey from lab-scale prototypes (TRL = 3–4) to setting up large-scale manufacturing can take 10–15 years. It will take even longer if the new technology does not improve on the existing technology with partial replacement of components or processes, but with a completely new technology for which a different manufacturing process is required.

Figure 16 | **Bridging the Gap between Academia and Industry**



Source: CES and WRI India authors.

As a result, it is necessary to keep options open for lateral entry of next-generation technologies developed at R&D institutions globally. These technologies should be at a TRL level of 5–7, which means that they have already demonstrated good performance at the commercial prototype scale. The Indian manufacturing industry can greatly benefit by identifying and supporting such technologies in the short term.

Such collaborations can be fast-tracked by setting up of multiple field-testing centers in different states where Indian battery manufacturers can get independent third-party testing and certification of these new technologies.

4.3.4 Role of National Funding Agency

Based on the performance goals, which flow from the vision of the concerned ministries and the departments of the central government, a national funding agency should be set up. This agency should be entrusted with the following goals:

- **Plug the gaps in the battery development ecosystem (incubation and field-testing centers):** There is a lack of storage-technology-focused incubation centers equipped to support technologies developed at academic institutes (TRL = 3–4) through lab prototypes and help transform them into commercial prototypes (TRL = 5–6). There is a lack of field-testing centers where performance demonstration of developed technologies can be conducted, thus paving the way for uptake by manufacturing companies.

- **Upgradation of existing battery-testing and prototyping facilities:** A number of battery-testing facilities exist throughout the country. The agency could provide incentives to modernize and upgrade the facilities for testing next-generation technologies. This includes skill development of technicians and other personnel involved in the facilities. Developing healthy testing infrastructure will lead to faster adoption of newer technologies.

- **Selection and funding of high-potential/high-impact research from academic institutes:** Based on the vision for vehicle electrification, the agency could prepare a list of desired performance metrics for battery packs for EVs. This should define the minimum expected values of energy density, cycle life, RTE, self-discharge, cost, and fast charging capability. Based on these criteria, a small number of high-potential/high-impact technologies (TRL = 3–4) could be selected for ARPA-E-type funding.

- **Support for setting up pilot plant manufacturing of next-generation technologies:** Appropriate support measures to private enterprises for setting up pilot plant manufacturing of next-generation technologies will pave the way for faster adoption of these technologies. Global R&D initiatives have led to the development of a number of promising technologies, through start-ups and small companies, that are on the brink of commercialization. Offering such initiatives can encourage these companies to consider India as a potential manufacturing destination. Demonstrations of manufacturing of robust technologies at the pilot plant scale can attract private sector funding for the setting up of large manufacturing plants.

4.3.5 Vision and Goals for Battery Recycling

As battery usage in EVs surges, a robust recycling industry will need to be set up alongside for effective handling of battery waste. In the previous section, the raw materials requirement for batteries was quantified. The main raw materials—Li, Ni, Co, Mn, Cu, Al, and Fe (iron)—have uses in many other fields. In fact, the minerals other than Li and Co also have major non-battery-related applications. As a result, appropriate treatment of battery waste can recover a large quantity of high-value minerals that can then be used for any application, including batteries, depending on the level of cross-contamination.

Developing battery recycling is even more challenging because it is a moving target. However, the recycling efforts can initially target established chemistries such as NMC, LTO, and LFP. Having a robust setup for battery recycling is not only imperative from an environmental sustainability point of view, but can also lead to a rich source of minerals through what is often referred to as "urban mining." Currently, the Li-ion battery recycling industry is in a nascent stage globally. Taking the initiative in this space can also lead to the import of "used batteries" from other regions as the EV market continues to grow.

SECTION V

RECOMMENDATIONS

This section highlights the primary findings and recommendations from this study with regard to manufacturing as well as R&D of EV battery technologies.

5.1 Impact of Changing Chemistries on Existing Manufacturing Facilities

Li-ion batteries are well adapted for EV applications due to their high energy density. Emerging chemistries are moving toward high nickel and reduced cobalt content due to cobalt availability limitations and price volatility. The next generation of Li-ion batteries will have solid electrolytes that will permit the use of lithium metal as the anode, leading to an approximately 25–30 percent improvement in energy density at the cell level.

Other promising high-energy-density storage technologies are LiS and aluminum-air batteries, which are in a very late stage of development although manufacturing scale-up has not yet been achieved. PEMFCs are technologically mature enough for applications in transportation. The high energy density of hydrogen makes PEMFCs ideal for heavy-duty applications such as trucks, buses, trains, medium-sized boats, and aerial applications. Given the criticality of the electrolyzer cost to the cost reduction pathway and the significant manufacturing opportunity it represents, a roadmap should also specify the timeline and scale of manufacturing support for electrolyzers. This could be in the form of a PLI scheme similar to what the government has announced for advanced chemistry batteries and solar cells. India should envisage a production capacity that not only caters to Indian demand but also factors in the burgeoning global demand.

Since the manufacturing process of Li-ion cells is at present largely invariant across chemistries, the evolving landscape of new materials does not pose a threat of obsolescence to the existing manufacturing facilities in the near future. This conclusion has been confirmed through detailed discussions with many global cell-manufacturing companies. The ongoing tweaks to the existing chemistries between Li-ion and solid state are developed with the intention of using the existing manufacturing lines with minimal modifications. Hence, the transitional stage between two technologies will be smooth for the battery industry as a whole.

5.2 Ensuring a Robust Supply Chain of Raw Materials for Gigafactories and Indigenization of Cell Component Manufacturing

Li-ion battery production in Gigafactories is supported by a large and complex supply chain of the essential raw materials. Global and Indian production statistics of key raw materials are presented in this study. India has reserves of Mn, Ni, Cu, and Al, and an attempt should be made to produce high-value battery components from these ores that can be used by local and international cell-manufacturing companies. These key components are MnSO4, NiSO4, copper foil current collectors, and aluminum foil current collectors.

In the case of graphite, existing reserves should be evaluated for large-flake graphite content, which is directly used as anode material. Synthetic graphite produced from coke is finding increased use as an alternative anode material. Even if reserves are inadequate, facilities for processing ore and producing a high-value product for Li-ion batteries can be set up locally. Increasingly, silicon is being used as an additive in anode materials. Local production of silicon can also benefit cell manufacturing.

For the other raw materials—Co and Li—for which India has no reserves, adequate arrangements for procuring ores or concentrates from other countries should be made. For example, strategic assets could be acquired in the same manner that the government acquires or invests in oil fields in other countries. Localized processing of lithium concentrates benefits the battery industry from the perspectives of reliability and purity. Purity of lithium raw materials such as Li_2CO_3 and LiOH is crucial for achieving a long cycle life.

Infrastructure for recycling Li-ion batteries should be set up in parallel with the development of Gigafactories and other battery-industry-related efforts. The initial setup could be in the form of pilot plants for recycling small volumes of Li-ion batteries. These can serve as valuable tools for skill development and for recycling process optimization. The raw materials requirements presented in Section 3.1 allow one to estimate the quantity of various metals that can be recovered by recycling 1 GWh of cells of different chemistries.

5.3 Strengthening Feedback Mechanisms between Industry and the R&D Community

As EV and renewable energy penetration increases in the near future, batteries will attract the attention of researchers, manufacturers, and application developers. Many Indian researchers are actively working on advanced battery technologies. There are, however, some major gaps in facilities that need to be addressed immediately to foster an active collaborative engagement between industry and academia.

- **Develop research labs and implement projects in institute campuses:** Electrochemical testing facilities at academic institutes in energy-related R&D centers need a major upgrade if they are to attract international funding for research activities. Faculty and researchers working on such projects could be given incentives in the form of funded 1–3 year stints at internationally renowned research centers and should be provided with adequate resources to promote ongoing and future research activities through all media platforms.

- **Commercial prototyping centers within universities:** Selected institutes should be equipped with facilities for commercial prototyping and testing to demonstrate the performance of new developed materials in commercial size cells (TRL = 5). These types of demonstrations are key to attracting the interest of industry, which can then take the technology further.

- **Technology incubators and field-testing centers:** Field-testing centers should be established where real application testing of commercial prototypes (TRL= 5–6) can be evaluated. Such centers can serve as a good meeting point for technology developers and potential manufacturing partners. Technology incubators are a good medium for grooming PhD and postdoctoral researchers in the commercialization of technologies. The translation of technological inventions in institutions (TRL = 2–4) to commercial prototyping (TRL = 5–6) is one of the main objectives of technology incubators.

- **Skill development programs and knowledge sharing on energy storage and EVs:** Institutions or private companies should conduct capacity-building training programs and provide current market trends on different technologies and different policies/guidelines.

- **Development of research labs focusing on recycling:** IITs and CSIR labs need to focus on recycling activities, and they should work closely with battery industries.

5.4 Technology and R&D Priorities

In addition to offering incentives for setting up Li-ion battery-manufacturing Gigafactories in India, the government should start planning for the development of a robust supply chain for the required raw materials. The cost of cells and the battery pack is largely determined by the price of the raw materials.

- A plan for recycling Li-ion batteries should be formulated alongside establishment of Gigafactories. Used batteries will be a huge source of several important raw materials (several 100 to 1,000 metric tons per GWh) as detailed in Section 3. These could be used for battery applications, other industries such as steel and alloy making, and chemical industries.

- Development of a network of pilot manufacturing plants would require a very small investment compared to large factories, but could play an important role in skill development and industrial R&D. Central and state governments should work together to create an ideal atmosphere to attract next-generation technologies from the global R&D community.

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RAW MATERIALS AND LI-ION SUPPLY CHAIN

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LIST OF ABBREVIATIONS

BEV	battery electric vehicle
BMS	battery management system
CEA	Central Electricity Authority
CoE	center of excellence
DCAAI	Development Council of Auto & Allied Industries
DHI	Department of Heavy Industry
DoD	depth of discharge
DST	Department of Science and Technology
EOL	end-of-life of battery
ESS	energy storage system
EV	electric vehicle
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles
IPCC	Intergovernmental Panel on Climate Change
ITC	Industry Technology Consortia
LCO	lithium cobalt oxide
LFP	lithium iron phosphate
LGPS	lithium germanium phosphorus sulfide
LIB	lithium-ion battery
LIPON	lithium phosphorus oxynitride
LiS	lithium-sulfur
LLZO	lithium lanthanum zirconium oxide
LMO	lithium manganese oxide
LTO	lithium titanate oxide
MHE	material handling equipment
MoRTH	Ministry of Road Transportation and Highways
MoP	Ministry of Power
MoUD	Ministry of Urban Development
NaS	sodium sulfur
NBEM	National Board for Electric Mobility
NCA	nickel cobalt aluminum
NEMMP	National Electric Mobility Mission Plan
NMC	nickel manganese cobalt
NML	National Metallurgical Laboratory
OEM	original equipment manufacturer
PCS	public charging stations
PEMFC	proton-exchange membrane fuel cell
PHEV	plug-in hybrid electric vehicle
PMP	Phased Manufacturing Program
RTE	round-trip efficiency
SEI	solid electrolyte interphase
SoC	state of charge
TFB	thin-film battery
TPEM	Technology Platform for Electric Mobility
TRL	technology readiness level

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ABOUT WRI INDIA

World Resources Institute India is a research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our e orts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our e orts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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