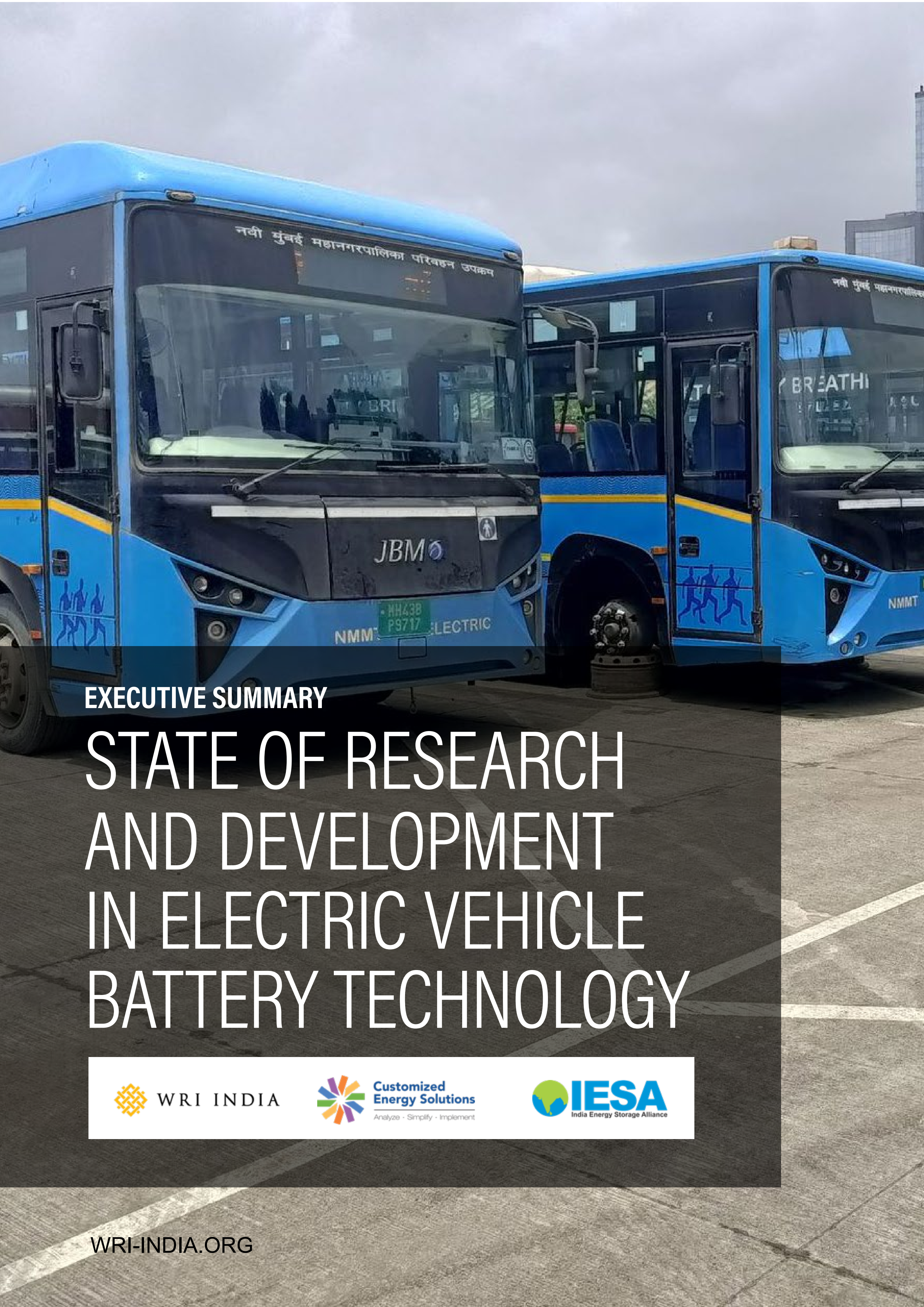

EXECUTIVE SUMMARY

STATE OF RESEARCH AND DEVELOPMENT IN ELECTRIC VEHICLE BATTERY TECHNOLOGY

WRI INDIA
Customized Energy Solutions
Analyze · Simplify · Implement
IESA
India Energy Storage Alliance

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ACKNOWLEDGEMENTS

The authors would like to thank all those who helped shape this report. We are especially thankful to Dr. Rahul Walawalkar, Dr. Sailesh Upreti, Dr. Robert Galyen, Dr. Jeff Dahn, Dr. Donald Sadoway, Dr. A S Prakash, Prof Sagar Mitra, and Prof. Manithram, Dr. Sanjay Bajpai (late) and Dr. Krishna Pai for their support and guidance for this report.

The report immensely benefited from reviews by Dr. Vijaymohan Pillai, Mr. Sohinder Gill, Mr. Balawant Joshi, Mr. Ankit Tyagi, Ryan Thompson Sclar, Bharath Jairaj, Neelam Singh, Dr. OP Agarwal, Ulka Kelkar and Madhav Pai.

Our special thanks to WRI's Research Development and Innovation Team, notably Shahana Chattaraj, Renee Pineda, and Laura Malaguzzi Valeri who supported us through the publication process and offered invaluable advice. The authors appreciate the support provided by copyeditor Santhosh Matthew Paul and the production team led by Dnyanada Deshpande and Garima Jain. We would also like to acknowledge the support provided by Megha Nath, Avanthika Satheesh and Epica Mandal during the drafting of the report.

This study was made possible thanks to the generous financial and institutional support from the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU) and MacArthur Foundation.

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

The target set in the Paris Agreement—to limit the global average temperature rise to well below 1.5°C above pre-industrial levels—is 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.

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.

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

2012 2013 2014 2015 2016 2017

2012

National Electric Mobility Mission Plan (NEMMP), 2020

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

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

Notes: ACC = Advance 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

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

2018 2019 2020 2021 2022

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.

Through this study, we attempted to fundamentally improve our understanding of technological solutions for EV batteries in India. Many promising developments are occurring around the world, with researchers engaged in different areas 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.

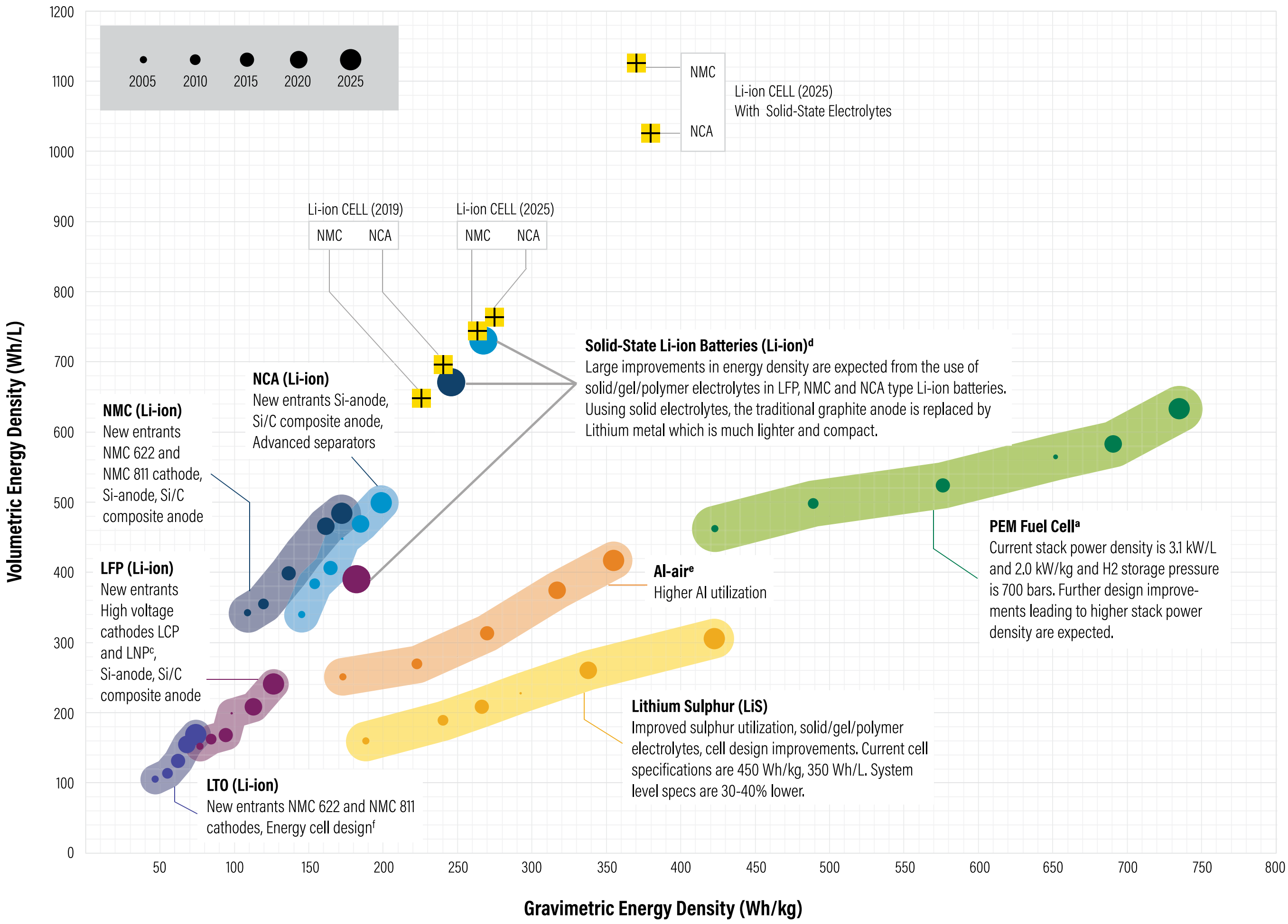
Key conclusions

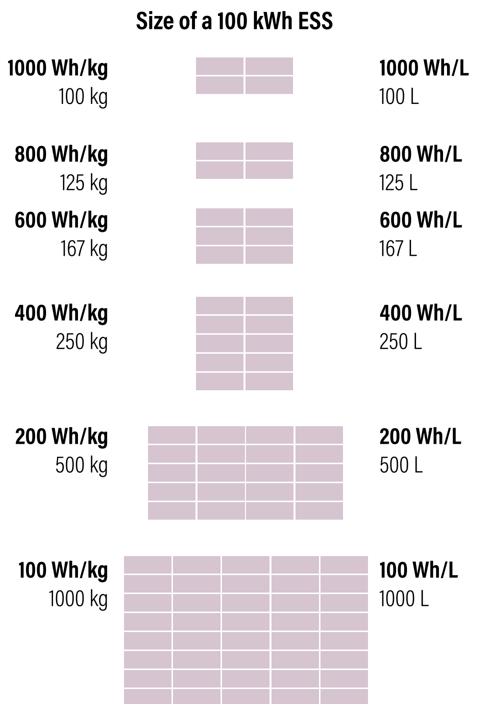
Several policies and initiatives have been introduced by the Indian government in to speed up the adoption of EVs in the country. These efforts span various central ministries, including the Department of Heavy Industries (DHI), NITI Aayog, Ministry of Power (MoP), Ministry of Urban Development (MoUD), 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 early movers such as 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 incentives and concessions to EV battery-manufacturing/assembly enterprises, 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, 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. Currently, Li-ion batteries are clearly 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. 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. Due to ongoing R&D activities, a number of new technologies with higher energy density are also making inroads in the EV sector (see Figure 2)

Figure 2 | Comparison of System-Level Energy Density of Technologies for EVs





Notes:
a. PEM Fuel Cell system includes tank + stack + boost convertor. 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: Customized Energy Solutions (CES) analysis.

Table 1 | **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 Pt-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: Customized Energy Solutions (CES) authors.

The existing Li-ion chemistries are expected to continue to develop 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.

In addition to batteries, Polymer Electrolyte Membrane fuel cells powered by hydrogen could be a suitable solution for heavy vehicles, including trucks, small boats, and airplanes requiring constant power and very long driving ranges. However, their eventual adoption will largely depend on the cost reductions in the technology and on the availability of hydrogen fuel. In this report, 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 response to the growing need for advanced electrochemical energy storage systems, the global R&D community has set up various mechanisms to focus its efforts. Within this paper, we examine the R&D programs operating in the United States, Europe, Japan, China, and Australia. In most areas, 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. Within this paper, we present an overview of the activities underway in the various regions of the world, to identify measures that have been shown to be effective in stimulating rapid advances in battery technology.

Table 2 | **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)	United States
Consortia	◻ New York Battery Energy Storage Technology (NY-BEST) ◻ U.S. Advanced Battery Consortium (USABC)	United States
Battery materials research centers	◻ Joint Centre for Energy Storage Research (JCESR) ◻ Centre for Energy Research (UCSD) ◻ University of Maryland Energy Research Center (UMERC)	United States
Government programs	◻ Horizon Funding under European Union (EU) ◻ LAVOISIER 2020 Programme	Europe
Incubation centers	◻ InnoEnergy (Netherlands, France, Germany, Sweden, Spain)	Europe
Consortia and associations	◻ Faraday Institute ◻ UK Battery Industrialization Center (UKBIC) ◻ Energy Storage–Henry Royce Institute	Europe
Battery materials research centers	◻ Fraunhofer ISIT and ISE ◻ Helmholtz-Zentrum Dresden Rossendorf (HZDR) ◻ Helmholtz Institute Ulm (HIU) ◻ EnergyVille (supported by VITO)	Europe
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

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

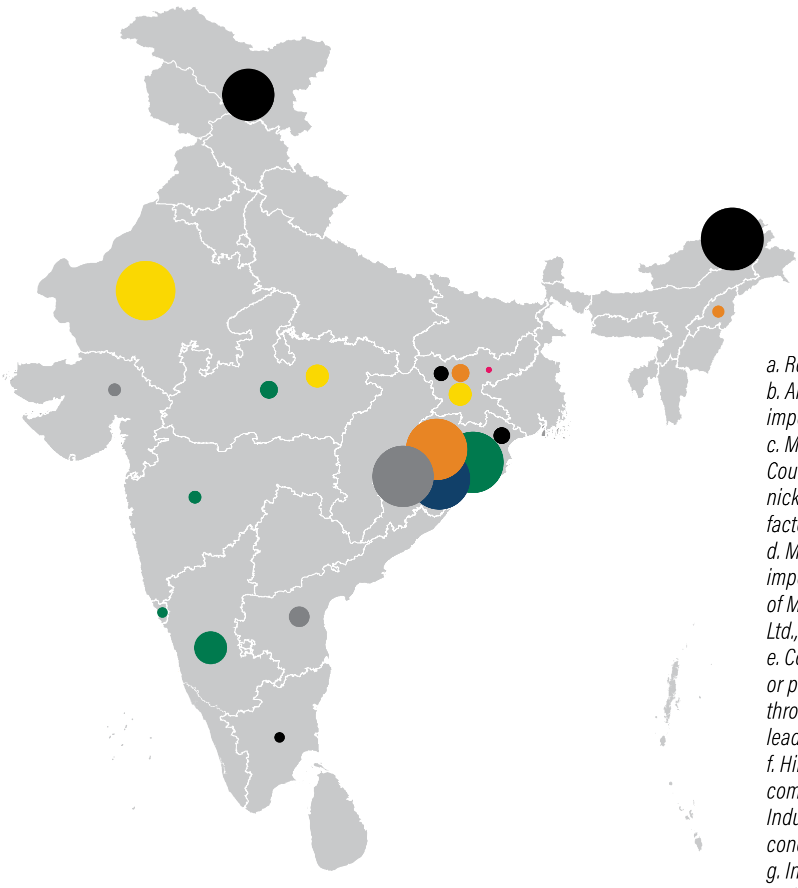
Way forward

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, Gr, and Ti), separator, and electrolyte in metric tons (1 metric ton = 1,000 kg) normalized for 1 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 $MnSO_4$, $NiSO_4$, copper foil current collector, and aluminum foil current collector. In the case of graphite, existing reserves should be evaluated for availability 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.

Figure 3 | **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%)

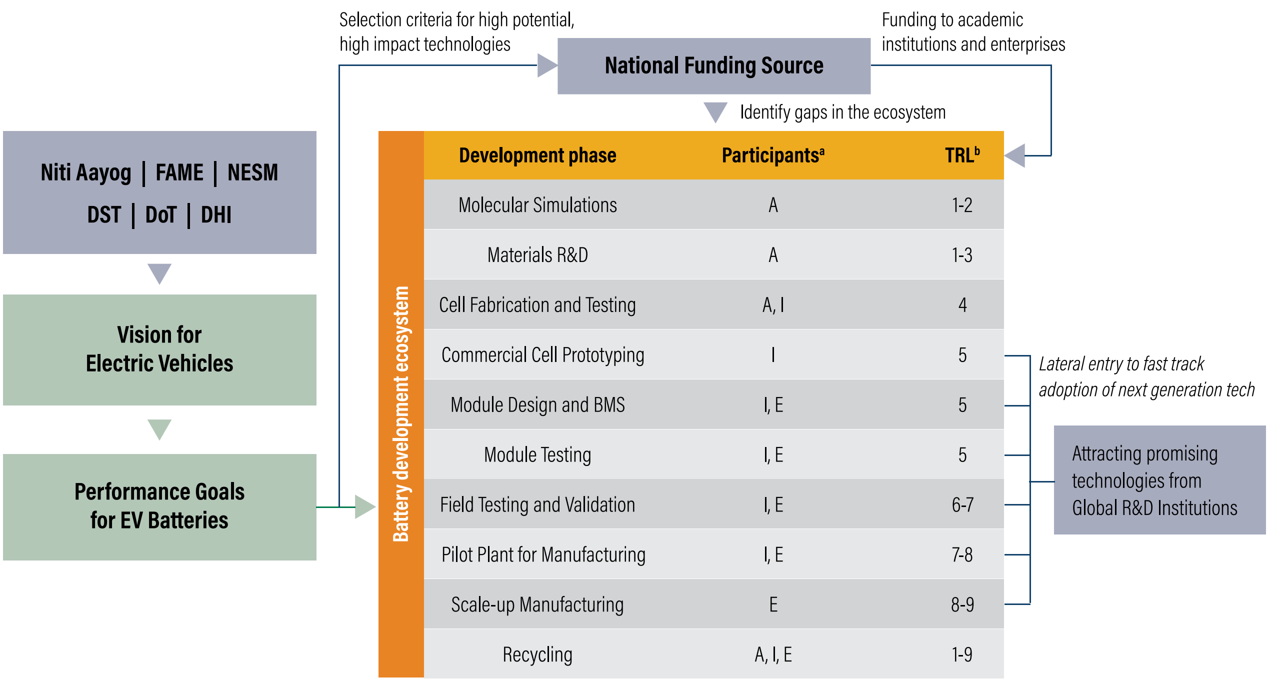


a. Reserves + remaining resources
b. Annual production from domestic ore production and imported ores and concentrates.
c. Most Nickel is produced as a by product of other refining. Country's entire demand is met through import. High purity nickle for battery applications is produced in a refining factory in Goa (NiCoMet).
d. Main mineral of Mn is pyrolusite. India is one of the major importers of manganese ore in the world. Priciple 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, nickle, zinc or precious metals. The demand for cobalt is usually met through imports. NiComet Industries Ltd. Gujarat is among 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, crystelline (flaky) graphite and amorphous graphite. Synthetic or artificial graphite is manufactured on a large scale in electric furnaces.

Source: Indian Minerals Handbook 2017

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. Central and state governments need to take measures to help create a favorable environment for India to be able to 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.

Figure 4 | **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

a. A = academic institutions, national research laboratories
I = Energy storage focused incubation centres, testing facilities
E = Enterprises, battery manufacturing companies, car OEM
b. Technology Readiness Level

Source: Source: Customized Energy Solutions (CES) and WRI India authors.

Recommendations for enhancing the Feedback Mechanism between Industry and R&D Community

- 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 activities through all media platforms.

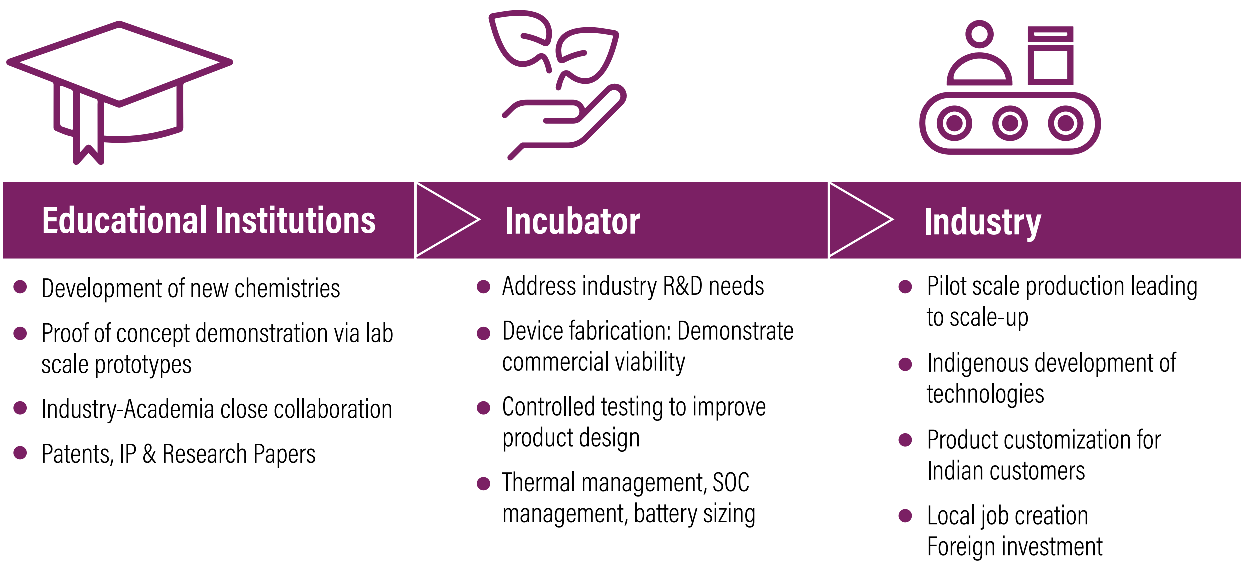
- Commercial prototyping centers within universities: Selected institutes should be equipped with facilities for commercial prototyping and testing to demonstrate the performance of new developed materials in commercial size cells (TRL = 5). These types of demonstrations are key to attracting the interest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

Figure 5 | **Bridging the Gap between Academia and Industry**



Source: Source: Customized Energy Solutions (CES) and WRI India authors.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ABOUT CUSTOMIZED ENERGY SOLUTIONS (CES)

Established in 1998, Customized Energy Solutions is an energy advisory and service company that works closely with clients to navigate the wholesale and retail electricity markets across the United States and globally. CES offers software solutions, back office operational support, and advisory and consulting services focused on asset optimization and energy market participation efficiency. CES is also a third-party asset manager of approximately 10,000 MWs of renewable and conventional generation resources across all ISOs in the United States and Ontario, Canada. CES empowers clients to achieve their goals by helping them navigate the evolving energy markets, complex market rules, and new energy technologies

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ABOUT INDIA ENERGY STORAGE ALLIANCE (IESA)

India Energy Storage Alliance (IESA) is the premier alliance focused on the advancement of energy storage, hydrogen, and e-mobility technologies in India. The alliance was founded in 2012 by Customized Energy Solutions (CES). IESA's vision is to make India a global hub for R&D, manufacturing, and adoption of advanced energy storage and e-mobility technologies. In the last nine years, the IESA member circle has grown from five to 140+ members and covering verticals from energy storage, EV manufacturers, EV charging infrastructure, research institutes & universities, renewable energy companies, hydrogen, microgrids, start-ups, and power electronics companies.

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ABOUT WRI INDIA

World Resources Institute, India (WRI India) inspired by and associated with World Resources Institute. WRI India has the capacity to convene key stakeholders, and forge strategic partnerships with governments, business, foundations, civil society organizations, institutes and NGOs, to scale-up solutions that can bring game-changing results for the sustainable management of natural resources in India.

WRI-India.org

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