Towards a Sustainable Battery Manufacturing Industry

The Case for Effective Reuse and Recycling

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About Us

About RMI

RMI is an independent non-profit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing. RMI has been supporting India's mobility and energy transformation since 2016.

About RMI India

RMI India is an independent think tank. RMI India takes inspiration from and collaborates with RMI, a 40-year-old non-governmental organisation. RMI India's mission is to accelerate India's transition to a clean, prosperous, and inclusive energy future.

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Executive Summary

Executive Summary

The Government of India has pledged to achieve net-zero greenhouse gas emissions by 2070, the first time India has established such a target. This ambitious target aims for deep decarbonization of India by building on existing policy targets. These include installing 500 gigawatts (GW) of non-fossil fuel electricity generation capacity and reaching 30% sales share of electric vehicles (EVs) by 2030.[1] Reaching these targets will require deployment of a high volume of effective energy storage technologies.

Rapid improvements in lithium-ion battery (LiB) performance over the past decade, combined with declining costs and increased global demand, put this technology at the forefront of electrochemical energy storage markets. Total demand for LiBs in India could be between 105 and 263 GWh annually by 2030. This rapid increase in LiB demand in India will be largely in the transportation sector, where EV sales could compose up to 70% of new vehicle sales by 2030. Meeting this demand will require build-out of battery manufacturing capacity, access to adequate resources, and battery management to avoid risks to human health and the environment. The National Programme on Advanced Chemistry Cell (ACC) Battery Storage, implemented by the Department of Heavy Industries and NITI Aayog, aims to establish 50 GWh of local manufacturing capacity by 2030.

The material supply chain will be critical to making LiB manufacturing truly secure and sustainable. The supply chain is currently dominated by China, with Australia, the Democratic Republic of the Congo, and Chile being key suppliers of many necessary raw materials. These materials are often mined via carbon-intensive processes and procured from politically unstable regions. For lithium alone, CO_2 equivalent emissions can range from 3 to 17 tonnes per tonne extracted and processed. Physical scarcity may have impacts on price, with bottlenecks already being faced for nickel and cobalt. Concentration of these materials in specific geographies also creates risk for long-term viability for LiB production.

Successfully establishing a sustainable domestic manufacturing industry requires India to evaluate the lifecycle impact of LiBs. This includes cultivating opportunities to implement circular economic principles for LiB stakeholders by establishing a policy framework that promotes proper end-of-life management.

Embracing a circular economic model complements India's domestic policy goals by increasing control of the LiB supply chain and reducing reliance on imports to meet growth in domestic demand. By 2030, EV LiB retirements could range between 3.5 and 17 GWh of nameplate capacity (30,000 and 145,000 tonnes), depending on the level of EV penetration. Available capacity will be approximately 70% of retiring nameplate capacity. Developing the recycling capacity to meet these needs will require a clear policy framework with strong monitoring and enforcement capabilities to prevent growth of informal markets, as well as heavy investments in recycling infrastructure.

The Ministry of Environment, Forest, and Climate Change (MOEFCC) introduced "Battery Waste Management Rules, 2020" (draft rules) for proper management of battery waste in February 2020. As introduced, the draft rules establish an Extended Producer Responsibility (EPR) program covering battery stakeholders, mandating collection of 30% of end-of-life batteries (by kg) effective two years after implementation. The policy target then graduates to 70% of end-of-life batteries by the seventh year.

Under this policy, materials recovered from recycled EV LiBs could provide 5% of domestic manufacturing needs for minerals such as lithium, nickel, cobalt, and graphite by 2030. If EV sales accelerate due to effective market development policies, recovered materials may exceed 20% of domestic LiB manufacturing demands for certain materials. Utilization of recovered minerals to meet domestic LiB manufacturing demand will avoid upstream emissions from mineral extraction, processing, and

transportation. While the LiB recycling process also produces emissions, primarily through energy use, the avoided upstream emissions outweigh recycling-based emissions. Implementation of the draft rules will reduce upstream emissions by 50,000 to 180,000 tonnes by 2030. Further, as the grid decarbonizes, the LiB manufacturing process will become less carbon intensive.

While the draft rules would provide strong benefits for India's domestic battery manufacturing sector and decarbonization efforts, the policy can be improved. This report suggests the following:

1. **Include specific language on hazardous material transport and handling guidance relevant to LiBs**
   Lack of guidance on clear labelling of LiBs (and the various chemistries) or rules on transportation, collection, and sorting of LiBs may result in LiBs commingling with lead-acid battery (LAB) waste. Comingling may pose health and safety risks to recycling centres and staff. Clear guidance that distinguishes LiB and lead-acid battery handling and transport, and distinct standardized labels for battery chemistries can reduce risk.

2. **Establish reuse targets**
   While collection and recycling end-of-life LiBs will recover the value of the minerals, the value of the residual capacity can be captured through second-life applications. Reuse prolongs the use of an EV LiB, delaying the need for recycling. Second-life applications could include firming renewables, battery energy stationary storage (BESS), behind-the-meter storage, or breaking the battery down to cells or battery packs. Reuse targets for four-wheel passenger and commercial vehicles and e-buses could provide between 1.2 and 5.9 GWh of storage capacity by 2030.

3. **Formalize second-life performance standards and warranties**
   To improve the market for second-life LiBs and become a global leader in LiB reuse, India should work with industry stakeholders to devise a methodology for certifying refurbishers, as well as metrics for assessing and guaranteeing performance standards, and establish incentives for innovative approaches for second-life applications.

4. **Considerations for costs**
   Establishment of a battery recycling program will create cost implications. While the EPR framework passes costs on to appropriate stakeholders, key considerations for regulatory authorities are to ensure that the associated funding mechanism is adequate, that the estimated program costs are realistic for achieving the collection and recycling targets, and that the funds raised are not inappropriately used for activities that do not benefit the program.

5. **Incentivizing consumer compliance**
   In addition to costs for recycling and collection infrastructure, another key component will be incentivizing consumers to return end-of-life EV batteries to the appropriate collection agent. Any submitted plan should include an incentive mechanism for consumers, which may include a rebate for returned batteries or a deposit system. Regulatory authorities must ensure that a submitted plan includes some form of incentive program to ensure compliance.

6. **Enforcement and penalties**
   Regulatory authorities should develop a transparent methodology for identifying issues, and steps for remediation or penalties.

Introduction

Introduction

At COP 26, the Government of India pledged to achieve net-zero greenhouse gas emissions by 2070, the first time India has established such a target. Currently, India contributes the fourth highest amount of carbon dioxide on a global scale, and deep decarbonization will require massive investments in carbon-free technologies and infrastructure. India's climate pledges at COP 26 build on existing policy goals to meet new energy demand from low-carbon or carbon-free sources. India has set a goal of 500 GW of non-fossil fuel electricity capacity by 2030,[2] and the FAME II Scheme aims to achieve sales of 6–7 million hybrid or electric vehicles (EVs) annually by 2020.[3] These policies will be key for India to achieve decarbonization in the power and transportation sectors and reach the net-zero target. However, the successful green energy transition, in India and across the globe, will rely on deployment of a high volume of effective energy storage technologies.

Rapid improvements in lithium-ion battery (LiB) performance over the past decade, combined with declining costs and increased global demand, has led to major investment in the battery ecosystem. Innovative technologies are rapidly advancing to the commercialization stage, driven by diversification of applications across the energy sector. LiBs are at the forefront of electrochemical energy storage markets, with improvements driving costs to approach US$87/kWh by 2025.[4] Growth in LiB manufacturing and installation will be an enabling factor for achieving the green energy transition.

However, LiBs are often reliant on scarce minerals, mined in carbon-intensive processes, procured from politically unstable regions, and carry safety and toxicity risks. India needs to evaluate the lifecycle impact of LiBs and cultivate opportunities to implement circular economic principles. This requires establishing a policy framework for LiBs that promotes proper end-of-life management. The policy framework must encompass second-life applications, recycling, and proper disposal. A strong LiB end-of-life management policy will ensure India is able to achieve its ambitious environmental targets, foster domestic industries that fully capture the value of LiBs, and reduce reliance on importation of high-cost materials.

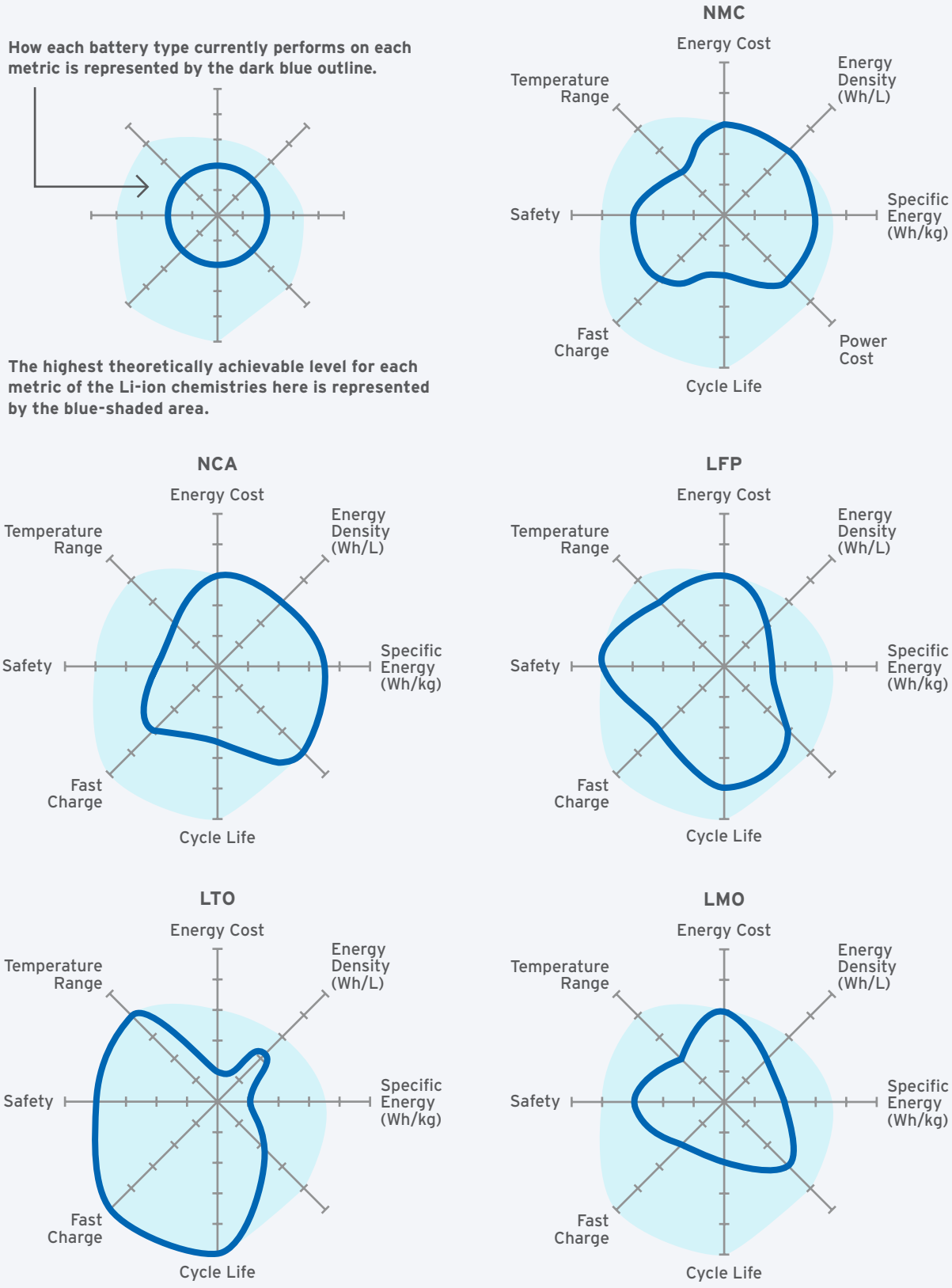
Lithium-Ion Batteries

LiB technology was developed in the early 1970s and today outperform other commercial rechargeable technologies (including nickel-cadmium and nickel-metal-hydride) on multiple metrics. These include:

- Energy density (the amount of energy stored per unit volume)
- Specific energy (the amount of energy stored per mass)
- Cycle life (number of charge and discharge cycles a battery completes before losing performance)

However, performance across these metrics varies by LiB composition (see Exhibit 1). Continued investment in LiB technology has led to the development of multiple battery chemistries, which vary across performance standards. For example, "[c]ompetition between EV manufacturers will continue to fuel the search for more space- and weight-efficient batteries. Li-nickel manganese cobalt oxide (NMC) and Li-nickel cobalt aluminium (NCA) chemistries have the most effort directed toward increasing energy density at an affordable cost."[5]

Exhibit 1 Relative Performance Characteristics of Major Li-ion Battery Chemistries[6]



Note: LiB anodes are usually graphite and differences in the chemistries are based on the material for cathode.

NMC Nickel Manganese Cobalt
NCA Nickel Cobalt Aluminium
LFP Lithium Iron Phosphate
LTO Lithium-Titanium-Oxide
LMO Lithium-Manganese Oxide

Lithium-Ion Battery Manufacturing

EV LiB systems consist of a battery pack and control/protections such as the battery management system and cooling measures. Battery packs are composed of battery modules, which are composed of battery cells. Unlike consumer electronics, LiBs must withstand high degrees of physical shock resulting from driving while maintaining high performance standards. Assembly of cells into modules and modules into packs allows the batteries to perform to required standards while also maintaining low temperatures to avoid thermal runaway, i.e. an overheated battery affecting other batteries in close proximity.[7]

A battery cell is a single unit device used to convert chemical energy into electric energy. Cells are grouped together to form a battery.[8] LiB battery cell production consists of three main steps: electrode manufacturing, cell assembly, and cell finishing (see Exhibit 2). The smallest unit of an LiB cell consists of two electrodes and a separator, with an ion-conducive electrolyte filling the pores of the electrodes. The cathodes are made of metallic materials, in LiBs this typically includes rare minerals such as cobalt, nickel, or manganese. Anodes are typically composed of graphite, however recent innovations have pushed alternative materials such as silicone.

Exhibit 2

Lithium-Ion Battery Cell Production Process[9]

Electrode Manufacturing	Mixing	Raw materials are combined to form a slurry
	Coating	Foil is coated with slurry
	Drying	Active material is dried in a continuous process
	Calendering	Electrode foil is statically discharged and cleaned
	Slitting	Wide electrode coil is divided into smaller coils
	Vacuum Drying	Coated coils stored in vacuum oven
Cell Assembly	Separation	Separation of anode, cathode, and separator sheets
	Stacking	Electrode sheets are stacked in a repeating cycle
	Packaging	Cell stack is positioned in the pouch foil
	Electrolyte Filling	Pouch cell is filled with electrolyte and sealed
Cell Finishing	Roll Pressing	Optional process to maximize capacity of the cells
	Formation	First charging and discharging process of battery cell
	Degassing	Gas from charging process is sucked off and disposed
	Aging	Cell characteristics and performance are measured
	EOL Testing	Variety of tests undertaken in end-of-line test rig

Global Battery Trends

The global demand for LiBs has grown rapidly over the past decade—increasing more than 700% from 2011 to 2020. While consumer electronics drove early applications, passenger EVs are now the dominant market. Passenger EVs are projected to be the primary end use of LiBs for the coming decade.[10] China, the United States, and Europe will be the largest markets for LiBs, but India will have the greatest demand growth from 2020 to 2030.[11] Demand and prices create a feedback loop: declining prices drive demand, which motivates continued investment into expansion of mining, refining, and manufacturing capacity. Research and development targeting efficient designs and chemistries, as well as rapid commercialization of new technologies, further reduce costs. Battery pack prices demonstrate how rapidly costs have declined, having annual drops since 2010, when they averaged US$1,191 per kWh. In 2020, battery pack costs decreased to US$137 per kWh, an overall decline of 89%.[12]

The LiB supply chain is largely dominated by China, with Australia, the Democratic Republic of the Congo, and Chile being key suppliers of necessary raw materials. China has made strong investments across the supply chain over the past decade, controlling over 50% of battery-grade metals refining capacity

across all key materials, with Chinese corporations making heavy investments in mining assets globally.[13]

While China has 1% of global cobalt reserves, it controls over 80% of the cobalt refining industry and owns eight of the fourteen largest cobalt mines in the Democratic Republic of Congo.[14] Reserves for graphite, which is required in all current LiBs, are also located within China, which controls over 60% of graphite extraction.[15] China also "leads deployments in battery cell manufacturing and component capacity, with around 80% market share in cell manufacturing capacity in 2021," and China's cell manufacturing capacity is anticipated to grow to 2.2 TWh by 2026.[16] China's heavy investment in refining and manufacturing capacity results in high exports.

Box 1 Future Battery Trends and Innovations

LFP BATTERY INNOVATIONS

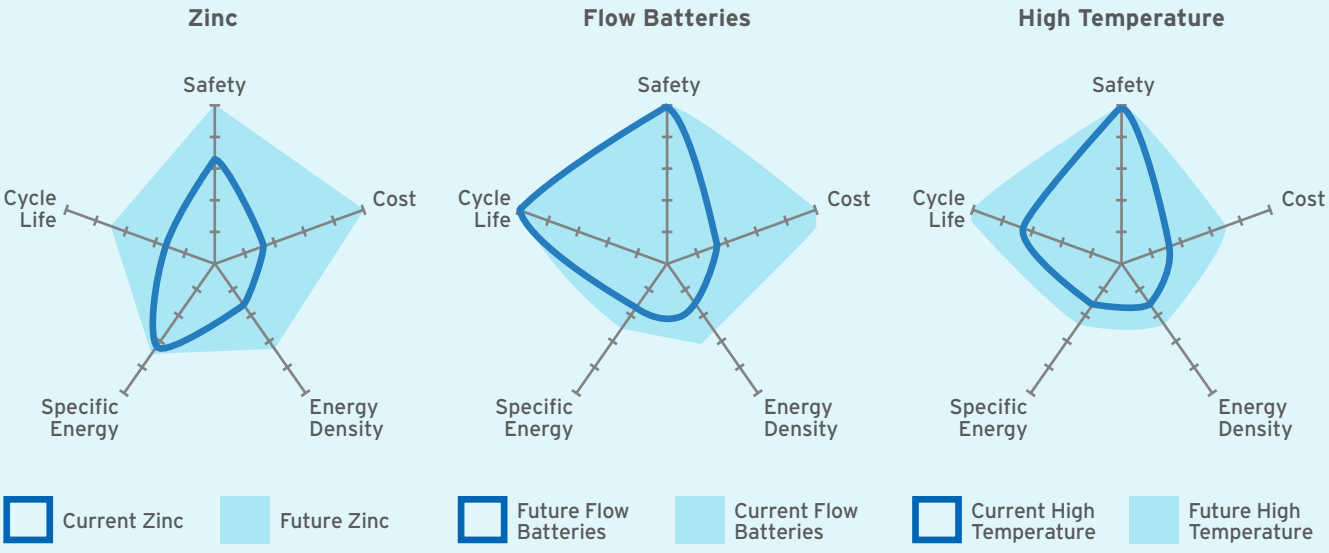
In the conventional LiB space, NMC and NCA have been the primary chemistries utilized for EVs and BESS globally. Research has focused on improving the efficiency of these chemistries, reducing the need for scarce and toxic minerals. However, some signs indicate that industry trends are pushing towards LFP batteries. LFP batteries are predominant in smaller EVs in China, and present certain advantages over NMC and NCA batteries. By replacing nickel, manganese, and aluminium in the cathode, LFP batteries avoid requiring scarcer and more expensive materials (though they are not yet cheaper on a $/kWh basis). Some innovative LFPs have demonstrated higher cycle life and power density, while avoiding many of the safety hazards in NMC and NCA batteries and using materials with lower risk to human health and the environment.[17]

BATTERY ENERGY STORAGE AND FLOW BATTERIES

Achieving deep decarbonization will require technologies capable of long-duration storage. While LiB chemistries often have a discharge duration limited to 4–6 hours, flow battery technology may be a viable pathway. An example is iron flow battery where the electrolyte is composed of iron, salt, and water, stacked between carbon plates.[18] This technology avoids the need for scarce minerals, since iron, salt, and water are abundant.[19] In 2021, the first commercial iron flow BESS system was installed. It can provide 6–12 hours of storage, with a cycle life of 20,000 cycles, and an anticipated operating life of over 20 years. Iron flow battery technology could cost US$200 per kWh or less by 2025, compared with LiB grid-scale storage prices of approximately US$350 per kWh.[20]

Achieving deep decarbonization requires low-cost, long duration technologies to ensure high levels of variable renewable energy penetration into the grid. Capacity will be required to meet needs beyond 20-minute to 2-hour ramping reserves, but also intraday, interday, and seasonal balancing. This requires storage technologies with durations of beyond 12 hours. Zinc batteries and high-temperature liquid-metal batteries are potential technologies that may reach commercialization by 2025 and open new possibilities for meeting growing long-duration storage demand.[21]

Exhibit 4 Performance Characteristics of Niche Chemistries[22]



BEYOND 2025

In the longer term, alternate chemistries like sodium-ion and new technologies like advanced solid-state batteries and lithium air could also achieve commercial scale resulting in a marked shift in the material and supply chain challenges of the energy transition. The scope of the study is limited to currently commercially viable LiB battery chemistries that could impact the material and waste management questions within the timeframe of the study. But it is important to have a perspective on the long-term evolution of battery technologies that may impact the material supply chain and sustainability of energy transition efforts.

India

Much like China, the United States, and the European Union, demand for LiBs is anticipated to grow extensively in India. Total demand in India could grow to between 105 and 263 GWh annually by 2030 depending on the aggressiveness of the uptake of EVs and battery energy storage.[23] The rate of demand growth outpaces all other geographies in the same period, but still represents a small fraction of potential energy demand relative to India's population and must take into consideration a delayed demand growth for LiBs relative to other geographies.

Key drivers of this demand include the EV sector, where national and state policy measures have accelerated sales. RMI analysis indicates that under an **accelerated scenario** of aggressive actions, EVs could make up 70% of all new vehicle sales in India by 2030 (see Appendix for details) led by high adoption in two wheelers, commercial four wheelers, and buses. In a more **conservative scenario**, RMI expects a weighted average EV penetration of 35% in new sales in 2030 across all vehicle segments. Facilitating this demand will require increasing battery manufacturing capacity, adequate resources, and end-of-life management to avoid risks to human health and the environment.

India currently ranks 15th for LiB supply chain adequacy, with opportunities to improve its standing through 2026.[24] As a result of demand growth, LiB imports grew four-fold from fiscal year (FY) 2016–17 to FY 2018–19. Of the US$1.23 billion (INR 8,777 crore) of imports, US$773 million (INR 5,516 crore) was sourced from China.[25] In addition, India's domestic reserves for key materials for LiBs, including lithium, graphite, cobalt, and nickel, are minimal and insufficient to meet the growing demand. There are ample reserves of magnesium and iron, materials vital for NMC and LFP chemistries, respectively.[26] In February 2021, India's first lithium deposit was discovered, with the Atomic Minerals Directorate estimating a total of 14,100 tonnes.[27] Despite the resource challenges, growing India's domestic LiB manufacturing capacity will be key to address the growing energy storage needs, while minimizing energy security risks created through over reliance on fossil fuel imports.

Policies to Incentivize Domestic Manufacturing

In recognition of the emerging importance of energy storage, the Indian government passed the National Mission on Transformative Mobility and Battery Storage (the Mission) in March 2019. The Mission targets establishing large-scale, export-competitive integrated battery and cell-manufacturing gigafactories in India, as well as localizing the EV production value chain by 2024.[28]

As an outcome of roadmaps to achieve the vision established by the Mission, India approved a proposal for a Production Linked Incentive (PLI) Scheme, "National Programme on Advanced Chemistry Cell Battery Storage" (the PLI Scheme). The PLI Scheme is being implemented by the Department of Heavy Industries and NITI Aayog. The PLI Scheme earmarks INR 18,100 crore (US$2.49 billion), with the target of establishing local manufacturing capacity of 50 GWh for ACC.[29] Manufacturers under the PLI Scheme are eligible for an investment of up to INR 225 crore per GWh. The scheme aims to boost domestic manufacturing, cut down on import bills, and strengthen energy security.

Successful implementation of the PLI Scheme can make India a global leader in battery manufacturing. However, success will also require an expansion of end-of-life collection and recycling capacity. This will enable the extension of the useful life of these batteries while enhancing recovery of materials such as lithium and cobalt, of which India lacks adequate natural reserves.

Lithium-Ion Battery Challenges

Lithium-Ion Battery Challenges

The anticipated growth of demand for LiBs, their critical role for deep decarbonization and meeting India's net zero target, and the burgeoning domestic manufacturing sector make it critical to understand the impact and challenges associated with a mass deployment of LiBs. This includes understanding the life-cycle assessment (LCA) of the environmental impact and emissions of LiBs, the sustainability of the LiB supply chain, and the risks of improper end-of-life management.

Life-Cycle Assessment

Performing an LCA of batteries presents fundamental challenges, as the assessment will vary depending on application. Also, assumptions regarding the use phase will vary between studies, particularly for early-stage technologies with insufficient use data. While the full scope of an LCA may vary, understanding the impact of LiBs means determining the effects of raw mineral extraction, materials processing, component manufacturing, cell manufacturing, and module assembly.

There are three major considerations in the raw material extraction phase: resource availability and depletion risk; geopolitical risk, price instability, and artificial shortages that may occur; and the environmental and social impacts of mining operations.[30] Resource extraction and mining operations often utilize diesel fuel and have high associated carbon emissions. For lithium alone, CO_2 equivalent emissions can range from 3 to 17 tonnes per tonne of lithium extracted and processed, depending on the source and processing methodology. In addition to raw material extraction, refinement, and transportation, other phases of LiB manufacture require high energy demand. Particularly, the multiple phases of cell manufacturing require heat and electricity, and the emissions for this process are correlated to the carbon intensity of the local electricity grid.

Supply Chain Sustainability

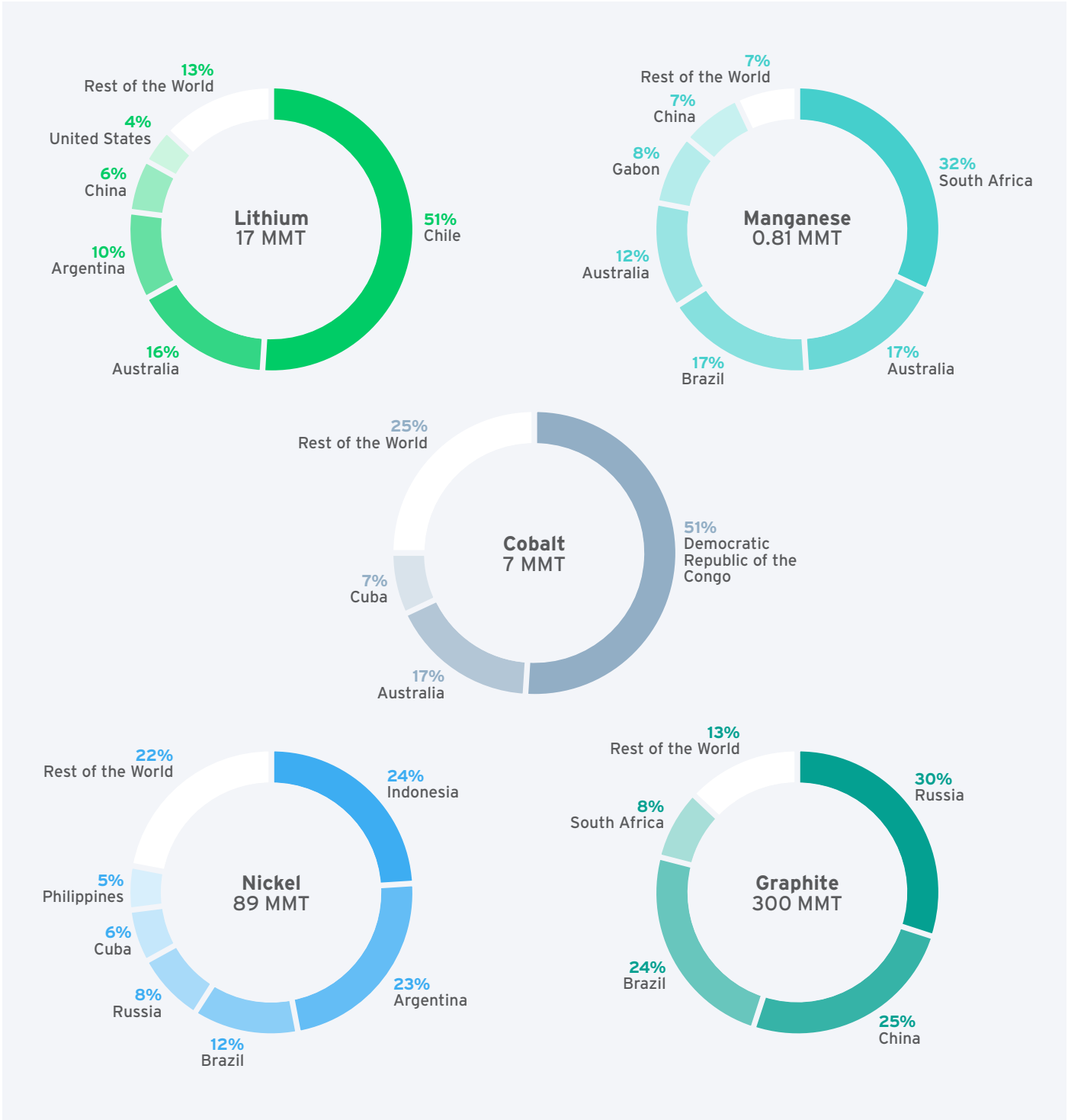
Outside life-cycle-associated emissions, the sourcing of minerals critical for LiBs presents complex ecological, ethical, and long-term sustainability challenges. First, the booming growth of mining capacity for lithium, cobalt, and nickel has the potential to incur drastic environmental costs. In Tagong, a town on the Tibetan plateau, a toxic chemical leak from a lithium mine damaged local waterways resulting in extensive harm to wildlife, and in South America, lithium mining uses a lot of water—approximately 500,000 gallons per tonne of lithium mined.[33] The Democratic Republic of the Congo (DRC) supplies the majority of the world's cobalt, with EV production representing approximately 24% of global cobalt demand.[34] The cobalt mines are often in areas with low regulation and high corruption, and are prone to human rights abuses including child labour and exposure to toxic chemicals.[35]

Ethical and environmental issues aren't the only challenges in the LiB supply chain. Lithium, cobalt, and nickel are scarce minerals facing a massive growth in demand. Physical scarcity may have potential impacts on price, causing bottlenecks for nickel and cobalt. Concentration of these materials in specific geographies creates risk for long-term viability for LiB production.[35]

In order to reduce reliance on new mining, and address looming supply bottlenecks, the LiB industry must push towards innovative chemistries with higher densities and longer cycle life, while also fostering a circular economic framework to reduce unnecessary and potentially harmful risks to human health and the environment. This can help achieve long-term sustainability for LiBs both up- and down-stream.

Exhibit 4

Reserves of Materials Used in Lithium-Ion Batteries (Adapted from Union of Concerned Scientists)[36]



Safety and Environmental Hazard Concerns

LiBs also pose safety risks, particularly thermal runaway. Thermal runaway occurs when undesirable parasitic reactions occur due to excessive heat, either external due to the environment or internal due to an inability to fully dissipate generated heat or other mechanical failures.[37] Thermal runaway issues have been the source of fires and contribute to the need for proper storage and handling of LiBs. Another concern is with improper disposal, which may expose LiBs to liquid. This can trigger chemical reactions or cause fires when comingled with other waste.[38]

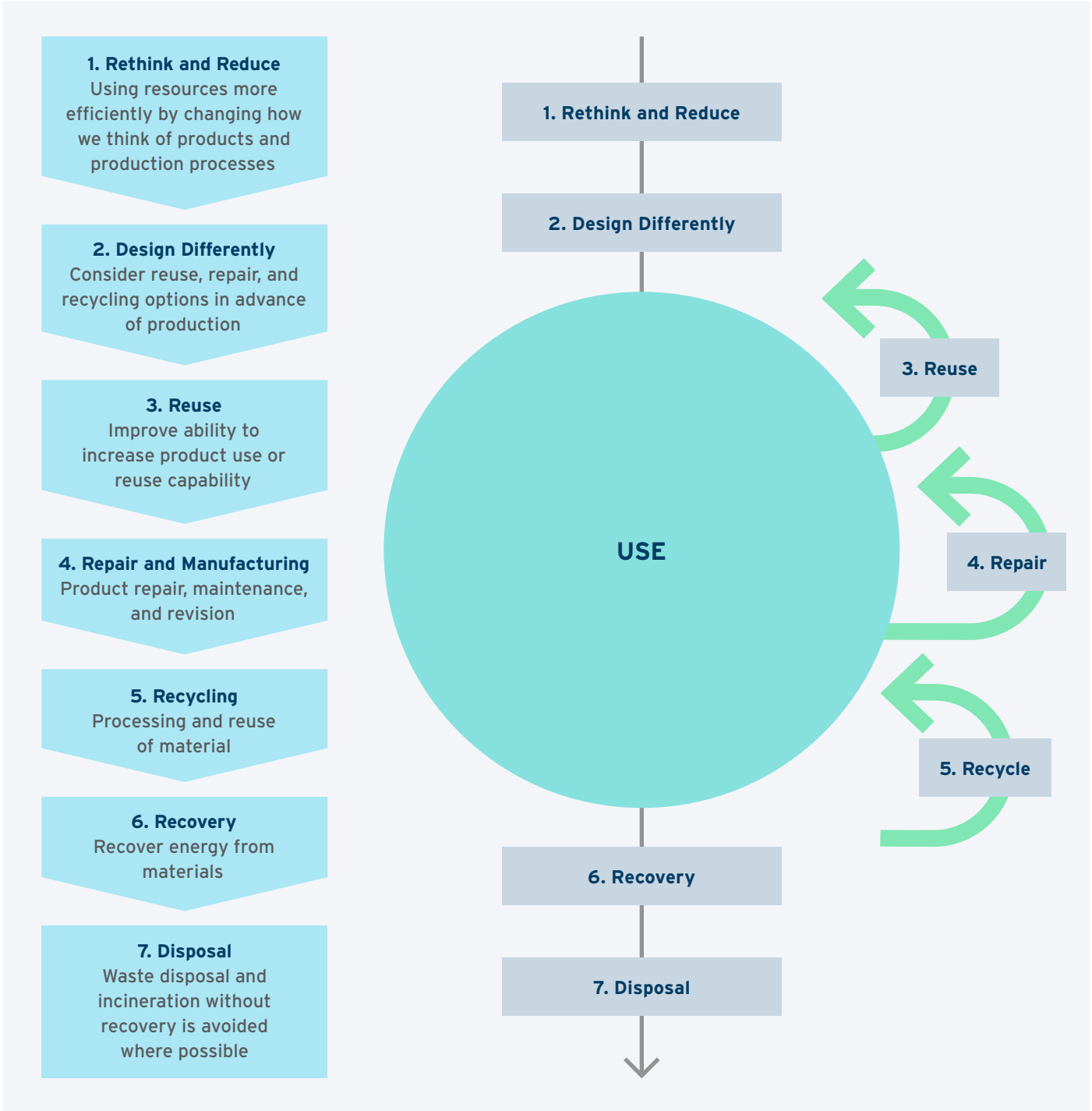
These risks highlight the need for proper disposal, storage, and transportation for end-of-life management, particularly avoiding comingling with other waste.

Circular Economy

To ensure the success of the PLI Scheme and the efficient use of earmarked funds, as well as to establish India as a global leader in the LiB market, concerted efforts must be made to embrace circular economy principles within the LiB space. Under a circular economy model, disposal should be avoided to the extent possible, with hazardous materials kept on a reuse/recycle mode. Globally, moving from a linear to circular economic model for LiBs "could result in a reduction of 34 Mt of greenhouse gas (GHG) emissions while creating an additional economic value of approximately US$35 billion."[39]

Exhibit 5

The Circular Economy (Source: Adapted from the World Bank)[40]



For LiBs, which heavily depend on scarce resources, the circular economic model not only reduces the LCA impacts of mineral extraction, refinement, and manufacturing, but may also alleviate price and supply risks. India lacks domestic resources for many minerals key for LiB manufacturing, including lithium, nickel, and cobalt. Embracing a circular economic model complements the goals of the Mission and the PLI Scheme policies by increasing control of LiB supply chain and reducing reliance on importations to meet domestic demand growth. Adoption of a circular economic framework relies on clear policy that incentivizes reuse and recycling, as well as innovations and redesigns that reduce upstream material demand.

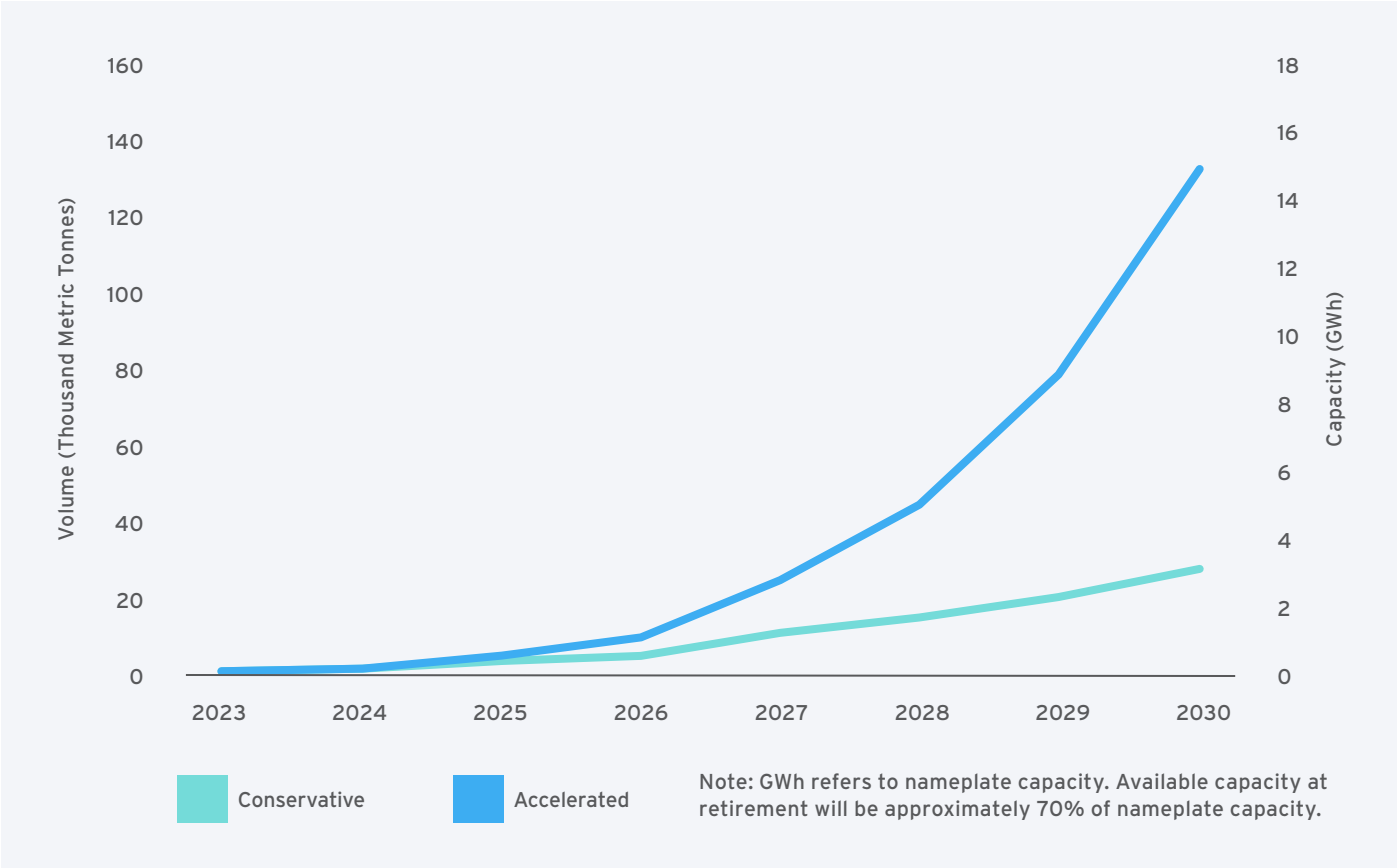
Outlook for India's EV Batteries

As India's EV sector matures and EV sales increase, it will be critical to establish an effective collection and recycling process to manage end-of-life for LiBs, and to avoid the health and environmental impacts associated with improper LiB disposal. By 2030, EV LiB retirements could range between 3.5 and 16.7 GWh of nameplate capacity, or 31,000 and 148,000 tonnes (see Exhibit 6).

Developing the recycling capacity to meet these needs will require a clear policy framework with strong monitoring and enforcement capabilities to prevent growth of informal markets. It will also require heavy investments in recycling infrastructure.

Exhibit 6

Outlook for EV LiBs Reaching End-of-Life



Note: GWh refers to nameplate capacity. Available capacity at retirement will be approximately 70% of nameplate capacity.

The State of Battery Waste Management

The State of Battery Waste Management

The broad spectrum of applications for LiBs creates a unique challenge for proper management of end-of-life. Existing policies within India establish regulations for general electronic waste (e-waste), and for conventional battery technologies, such as lead-acid batteries (LAB). Regulators may view LiBs utilized in consumer electronics as the former, while LiBs from EVs may be managed as the latter. Yet the safety and toxicity concerns of LiB chemistries will require an approach to management that ensures minimal co-mingling with other similar waste streams. Any policy framework for managing LiBs must take this into consideration, while also attempting to ensure an LiB waste stream that can be effectively reused or recycled.

Lithium-Ion Battery Recycling

The introduction of an LiB collection and recycling policy in India reflects similar trends globally, as many nations anticipate a wave of EV LiBs reaching end of life. The value extracted for battery recycling is highly dependent on metal pricing, recovery efficiency, and market for materials.[41] Current capacity is dominated by China. In 2018, China recycled approximately 67,000 tons of LiBs, representing 69% of all stock available.[42]

China began to first address the issue of consumer electronic batteries in the mid-1990s and issued regulations on EV end-of-life LiB management in 2018. The 2018 regulations require EV manufacturers to establish collection and recycling networks, including temporary storage facilities and long-term operational facilities. Manufacturers that sell more than 8,000 new EVs within an administrative area are required to establish a storage facility.

India's current LiB capacity lags many global markets. Stakeholders expressed that operating capacity is capable of processing 1% of annual end-of-life LiBs, but expansion is underway and should be 9% of the waste stream by the end of 2022. As more EV LiBs reach end-of-life, it is critical that LiB recycling capacity grows rapidly.

In India, lack of existing policy creates a key hurdle for LiB recycling. Currently, recyclers take on the burden of battery procurement. End-of-life batteries can be sourced from three classifications of users: formal sector (manufacturing facilities), service centres, or the informal sector (consumers and small-and-medium-sized enterprises). In the absence of a formalized collection and transportation plan, the burden, particularly for procurement from the informal sector, falls to recyclers. This is reflected in the costs of recycling, where procurement makes up the largest expense.

Adoption of an EPR program could address this issue by formalizing collection and transportation agreements, and establishing a methodology for the formal sector to incentivize the informal sector to collect or dispose of end-of-life LiBs in an appropriate manner. Stakeholders currently anticipate that, without a proper incentive, EV end-of-life LiBs will largely be supplied by the informal sector, creating a hurdle for effective collection and limiting potential reductions for a recycler's procurement costs.

Though the recycling industry and markets for e-waste and conventional batteries (such as LABs) are well established, LiB recycling is still comparatively nascent. An effective domestic recycling industry will reduce costs by capturing residual value of the materials used in LiB manufacturing, while also limiting the need for growing importation of scarce metals.

Battery Recycling Process

The recovery process for LiB materials is highly efficient. Across the globe, recycling processes typically recover 94%–95% of materials. Recyclers in India have stated that innovative recycling technologies can recover approximately 98% of materials from LiBs. This technology is chemistry agnostic, able to

process and recover materials from all prominent LiB types.

Battery recycling typically falls into three technological processes: pyrometallurgy, hydrometallurgy, and direct recycling. Under these processes, batteries are shredded into a slurry known as "black mass" and then metals are extracted from the mass.[44] In the pyrometallurgic process, metals are extracted through application of intense heat, while in the hydrometallurgic process this is achieved through use of an aqueous solution.[45] Hydrometallurgy is the most common technology as it generates the lowest quantity of waste and is less energy intensive.[46]

Given the nascent stage of LiB recycling, stakeholders are concerned about the quality of materials recaptured through the recycling process. As with the recycling of other products, impurities could theoretically be introduced, which would affect the performance of recycled materials. However, research into recycled LiB materials has shown that the recycling process does not demonstrate degradation of performance. In fact, results of industry-level tests indicate that in some instances, recovered materials outperformed virgin materials.[47] LiBs composed of recycled materials demonstrated higher cycle lifetime before reaching end-of-life—11,600 cycles to 70% capacity retention compared to 7,600 for the control.[48] Utilizing the circular economic framework may not only reduce costs, but also enhance LiB battery performance and prolong battery life.

Box 2 Case Study: Attero Recycling[49,50]

Attero Recycling is India's largest electronic asset management company, aiming to implement a circular economic framework for a diverse blend of e-waste. Currently, Attero has 1,000 metric tonnes of lithium-ion battery recycling. Attero Recycling will be investing INR 300 crore to ramp up lithium-ion battery recycling capacity to 11,000 metric tonnes per annum by October 2022.

India's Draft Battery Waste Management Rules

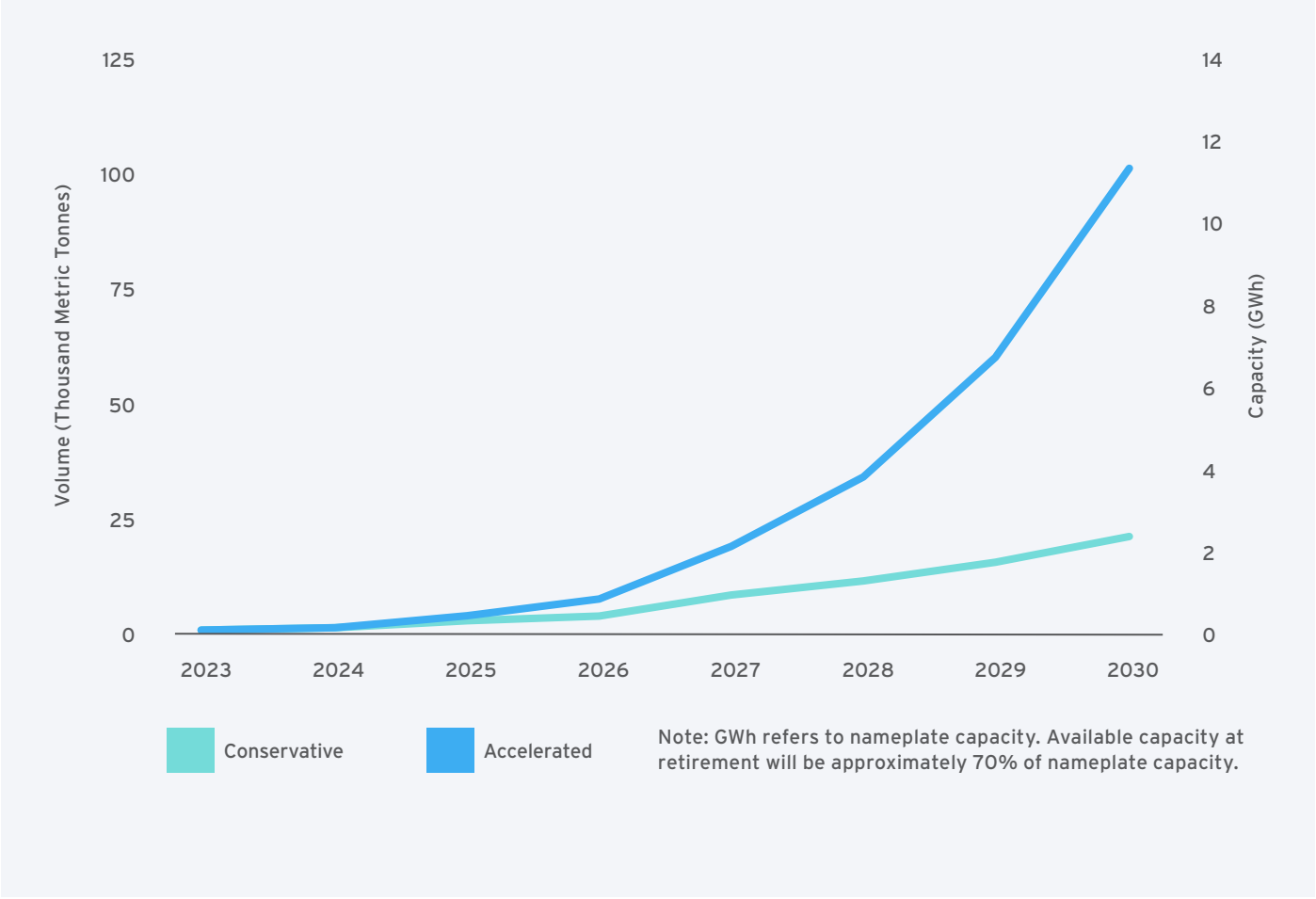
To address proper end-of-life management of LiBs, the Ministry of Environment, Forest, and Climate Change (MOEFCC) introduced "Battery Waste Management Rules, 2020" (draft rules) for proper management of battery waste in February 2020.[51] Existing battery management and handling policy was insufficient to adequately address LiB battery technology and the anticipated volume of EV LiBs reaching end-of-life by 2030. The draft rules will supersede the "Batteries (Management and Handling) Rules, 2001," which only apply to LABs. Instead, the draft rules will cover all types of batteries.

As introduced, the draft rules establish an Extended Producer Responsibility (EPR) program covering battery stakeholders, including manufacturers, producers, and importers. MOEFCC will require battery industry stakeholders to establish collection centres, and the draft rules establish LiB collection targets. The initial collection target is set at 30% of end-of-life batteries (by kg), effective two years after implementation. The policy target increases to 70% by the seventh year.

Meeting these policy targets will require a substantial build out of LiB collection and recycling capacity. Assuming the first policy target of 30% is enacted by 2023, the required capacity would need to be between 20,000 and 102,000 tonnes (equivalent to between 2.4 and 11.7 GWh) by 2030 (see Exhibit 7). This would require recycling capacity to grow a minimum of 135% annually between 2021 and 2030 to meet EV LiBs in the base case. The required growth rate would be significantly greater should EV sales outpace the base-case scenario.

Exhibit 7

Required Recycling Capacity



Note: GWh refers to nameplate capacity. Available capacity at retirement will be approximately 70% of nameplate capacity.

Understanding the Extended Producer Responsibility (EPR) Framework

EPR is a policy framework that places the responsibility for end-of-life management of a product on the producers, aiming to internalize the previously external costs of environmental impact and waste management.[52] In a typical EPR program, industry stakeholders (often encompassing manufacturers and importers) are required to form a Producer Responsibility Organization (PRO). The PRO is required to submit an Extended Producer Responsibility Plan to the relevant regulator, and PRO members will only be allowed to sell covered materials once the plan has been approved.

This framework shifts responsibility from a public waste management entity to industry, but also allows flexibility to the producers to meet policy goals in ways that are most appropriate for their product and allows management plans to evolve with technology innovations. This is not a novel approach for India, as the Central Pollution Control Board (CPC) already oversees an EPR program for e-waste, including cell phones and computers.

Under the draft rules, the EPR Plan must be submitted to and approved by the CPC, with State Pollution Control Boards sharing responsibility for oversight. Once the draft rules have been finalized, the CPC should begin developing criteria for consideration of EPR Plans. The CPC must be able to determine that the submitted plan is sufficient to meet the outlined policy goals, and that costs necessary for achieving the policy goals are adequately calculated. Some key considerations include evaluating that the collection centre capacity development outlined in the plan is satisfactory, that transportation strategies are safe and will prevent co-mingling, and that metrics for evaluating success are clearly defined.

Impact of Effective Recycling of LiBs

Domestic Manufacturing

The PLI Scheme aims to establish 50 GWh of domestic LiB manufacturing capacity by 2030. LiBs require minerals such as lithium, cobalt, and nickel, of which India has inadequate domestic reserves. MOEFCC's draft waste battery policy will allow some of the growing manufacturing demand to be met by recovered and recycled materials. In the EV sales base-case scenario, recycled materials could provide 5% of domestic manufacturing needs for minerals such as lithium, nickel, cobalt, and graphite by 2030. If EV sales accelerate due to effective market development policies, recycled materials could exceed 20% of domestic LiB manufacturing demands (see Exhibit 8). Recycling efficiencies typically recover 94%–95% of materials, but innovations may increase this further. Industry experts have indicated that up to 98% of materials may be recoverable, further increasing the volume of minerals able to meet domestic manufacturing demand.

Exhibit 8

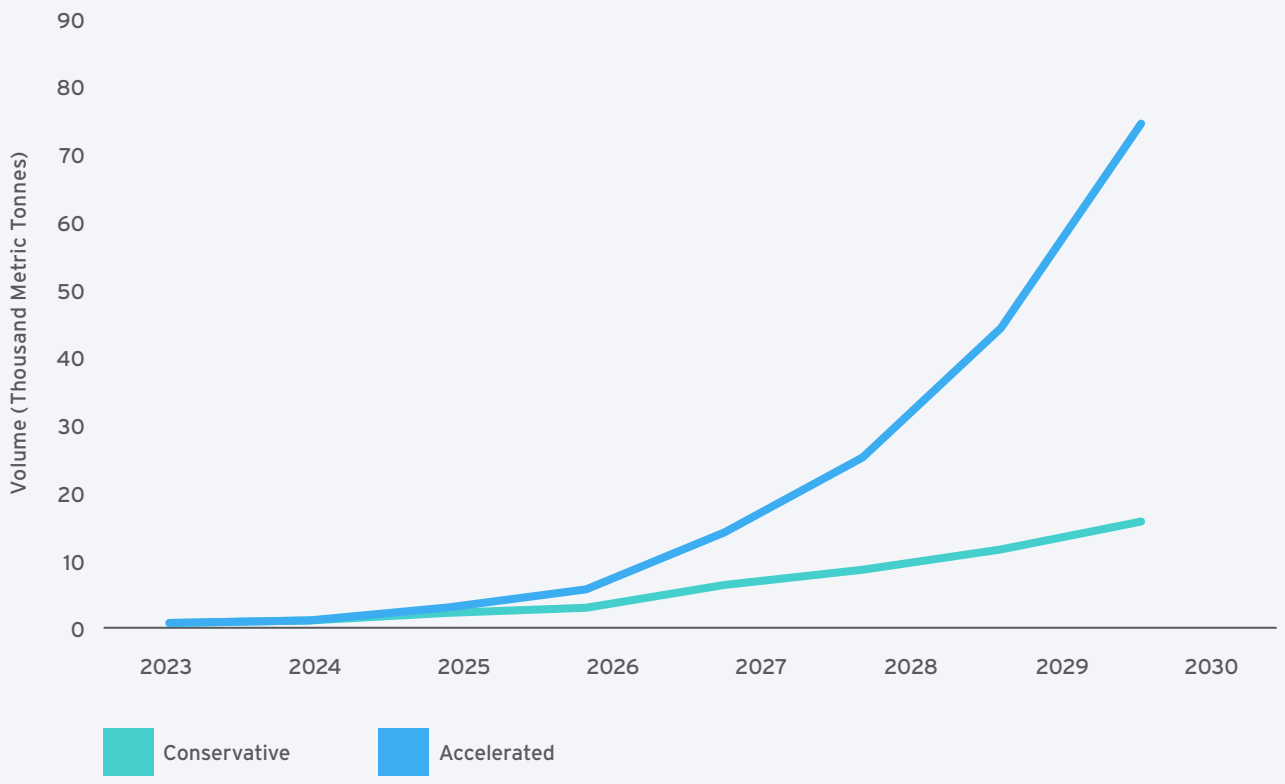
Potential Minerals Recovered as a Range of Share of Domestic Manufacturing Mineral Demand

Emissions Reductions

Utilization of recovered minerals to meet domestic LiB manufacturing demand will avoid upstream emissions associated with mineral extraction, processing, and transportation. While the LiB recycling process also produces emissions, primarily through energy use, the avoided upstream emissions outweigh recycling-based emissions producing a net emissions reduction. In the conservative case EV sales scenario, net emissions will be reduced cumulatively by over 186,000 tonnes by 2030 in the accelerated scenario, and emission reductions greater than 50,000 tonnes in the conservative scenario (see Exhibit 9).

LiB recycling can utilize various processes, including pyrometallurgical, hydrometallurgical, or direct recycling. The carbon intensities of these processes vary on a per kilogram basis, ranging from 0.7 to 2.3 kilograms of CO_2e emissions per kilogram of material recycled.[53] This includes a varying degree of energy intensity for the recycling process and its associated CO_2e emissions. This analysis took an average of these processes, in lieu of a projection of which technology might be most widely adopted in India, and did not account for the carbon intensity of the India grid over time.

Exhibit 9 Avoided GHG Emissions



Note: Avoided emissions is the net of upstream emissions reductions from avoided extraction and transportation and recycling-based emissions.

Establishment of a robust collection and recycling infrastructure will not address manufacturing-based emissions. The carbon intensity of the electric grid will have a major impact on a battery's lifetime emissions. In China, electricity consumption during the manufacturing phase can account for up to 46% of GHG emissions associated with LiB production.[54] If India achieves the grid decarbonization targets announced at COP26, emissions reductions associated with LiB manufacturing will decline on a per kWh basis.

The Case for Battery Reuse

LiBs utilized in EVs reach end-of-useful life when the battery capacity reaches between 70% and 80% of the nameplate capacity. While diminished capacity of EV battery packs may make LiBs no longer optimal for EV usage, they can be repurposed for secondary applications. Currently, RMI's model assumes passenger cars require batteries of approximately 15 kilowatt hours (kWh) of capacity, while electric bus batteries will be from 180 kWh to 250 kWh. Capturing residual value of these batteries through second-life application can drastically reduce total cost of ownership. Secondary applications are broad, including stationary storage, renewable power integration, or backup for commercial or industrial purposes.

Impact of Effective Reuse

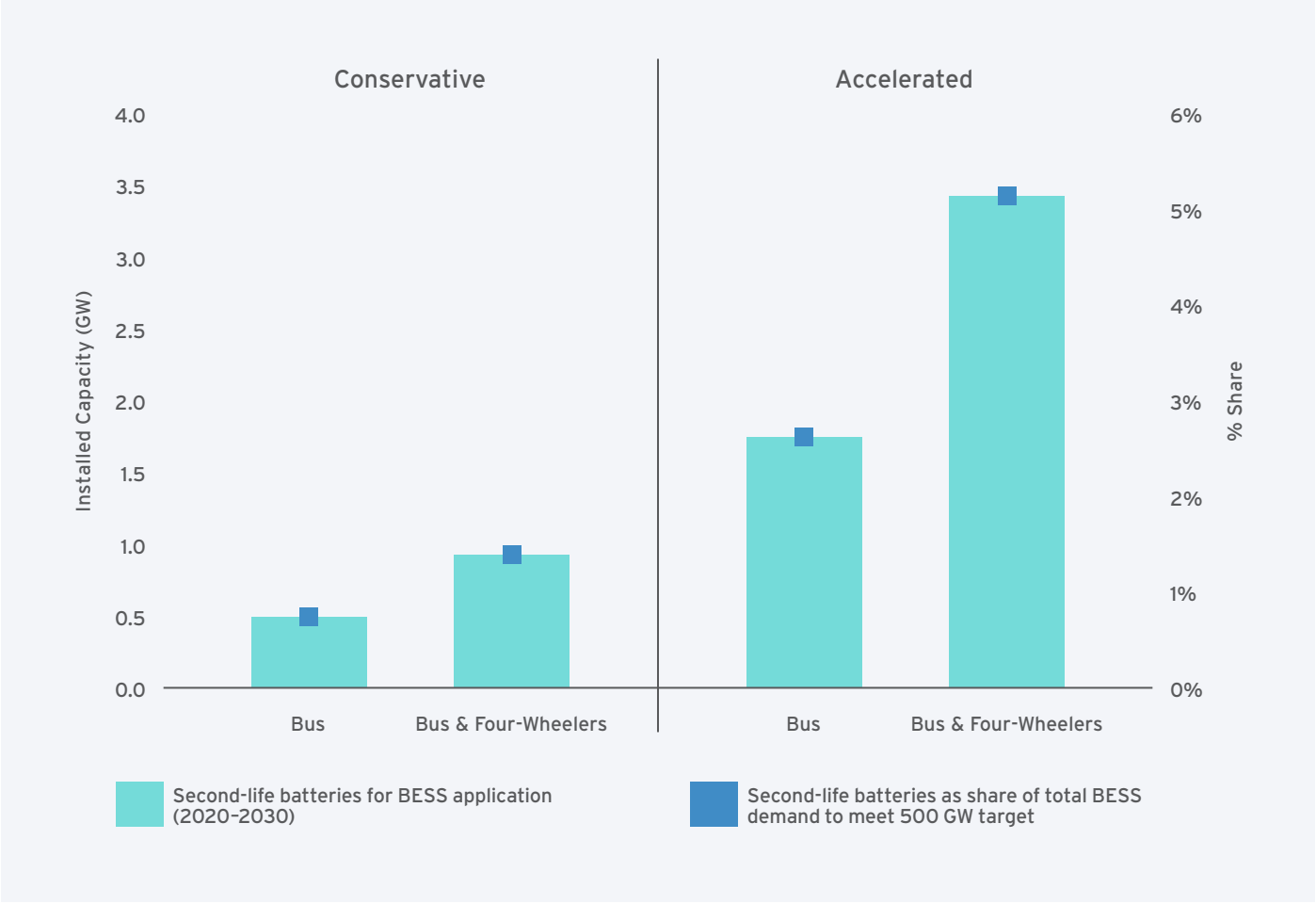
While collection and recycling will recover the value of the minerals included in the LiBs, the value of the residual capacity can be captured through second-life applications. Avoiding use of new batteries results in cascading savings across the supply chain, including decreased emissions associated with mineral extraction, refining, transportation, and manufacturing. Extending the battery life also reduces the LCA of EVs, accelerating progress to national net-zero targets.

A reuse policy target can also benefit grid stability, assisting in minimizing battery demand for front-of-meter BESS demand. To achieve the net-zero and 50% clean energy targets, India must deploy high levels of

variable renewable energy sources, requiring increased storage for the grid to ensure resilience and flexibility. Potential BESS applications for second-life use of EV batteries include front-of-meter uses such as providing ancillary services, energy shifting, and reducing transmission congestion. In an accelerated BESS deployment scenario, India will require over 65 GW (~260 GWh) of front-of-meter BESS installed capacity by 2030 if it is to meet its stated goal of 500 GW non-fossil fuel installed capacity by the same period. Were MOEFCC to establish reuse targets for four-wheel passenger and commercial vehicles and e-buses, between 1.2 and 5.9 GWh of storage capacity could be provided by 2030. These second-life applications could alleviate 8%–12% of BESS needs in 2023, and nearly 4% by 2030 in an accelerated deployment case. In terms of total installed capacity by 2030, this could mean 0.5–3.4 GW (2.1–13.2 GWh) accounting for 1%–5% of the total needs by 2030 (see Exhibit 10).

Exhibit 10

Second-Life LiB Potential as Share of Total Battery Demand Required to Meet India's 500 GW Non-Fossil Fuel Installed Capacity Target



The conventional approach to battery refurbishment includes disassembly, replacing non-functioning cells, and reassembly in a manner suitable for new use. The process of identifying and replacing non-functioning cells can be laborious, impacting the cost of reuse. However, there are innovative approaches to reduce labour costs.

Box 2 Case Study: B2U Storage Solutions[54]

B2U Storage Solutions, an LiB reuse start-up in California, aims to address labour costs associated with LiB reuse. B2U creates BESS projects with end-of-EV-life Nissan Leaf batteries. By utilizing full battery packs, B2U reduces labour associated with dismantling and testing individual battery cells. B2U reports that projected costs at the installed project in Lancaster are below US$200 per kWh, approximately two-thirds the cost of comparable storage projects made with new batteries.

Growth of the second-life BESS market will be further incentivized with additional applications created through policy. Draft regulations introduced in May 2021 permit energy storage resources to provide secondary and tertiary reserve ancillary services.[56] Eligibility requires participants to be able to provide a signal within 30 seconds and 15 minutes, respectively. In these draft regulations, energy storage systems are not eligible to provide primary reserve ancillary services, which are resources fired immediately in the event of a sudden change in frequency. Piloting BESS systems as a primary reserve ancillary service can more fully capture the value of these systems. This would reflect the utilization of grid-scale BESS projects globally. In both Germany and Australia, ancillary services provide the overwhelming majority of BESS end use.[57] By Q4 2020, BESS systems provided over 25% of Australia's frequency control ancillary services, exceeding all other fuel sources other than black coal.[58]

Impact on EV Financing

The battery pack is the single most expensive component of an EV, representing approximately 35%–45% of total cost.[59] While battery pack costs are declining, in most cases the up-front costs for EVs have not yet reached market parity with internal combustion engine vehicles. This creates additional challenges for financing, including higher interest rates, low loan-to-value ratios, limited financing options, and high insurance costs.[60] Operations and maintenance risk is a key factor driving financing barriers, including lack of understanding regarding battery replacement. In addition, financial institutions see EVs as having high resale risk as secondary markets are currently unstructured.

Establishing a formalized second-use market for end-of-life batteries can extend battery life, increase the total value of the battery, and reduce associated financial risk. While second-life use may not significantly reduce up-front costs, a strong market can offset a vehicle owner's end-of-service costs.[61] Adoption of a formal policy target for second use of EV end-of-life batteries that fosters a robust resale market can reduce the total cost of ownership for EVs, with a cascading effect addressing concerns for financing and accessibility.

Bettering the Battery Waste Management Plan

Bettering the Battery Waste Management Plan

The draft rules could be improved by incorporating amendments that recognize the unique challenges for managing end-of-life LiBs. In addition, the draft rules should be amended to recognize and incentivize reuse of EV LiBs that have residual value that can be captured through second-life.

Safe Transportation

As drafted, draft rules are inadequate for ensuring safe transport and storage of LiBs. These rules should be amended to include specific language or reference to language on hazardous material transport and handling guidance relevant to LiBs.

The draft rules require that manufacturers and other relevant stakeholders are responsible for ensuring that covered batteries are safely transported, and no environmental damage occurs in storage or transit. Unlike "E-Waste (Management) Rules 2016," the draft rules do not require transport to adhere to any relevant hazardous waste regulations. Lack of clear labelling of LiBs (and the various chemistries) or rules on collection and sorting of LiBs may result in LiBs comingling with LAB waste. Comingling may pose health and safety risks to recycling centres and staff. Clear guidance that distinguishes LiB and LAB handling and transport, and distinct standardized labels for battery chemistries can reduce risk and improve reuse and recycling.

Battery Reuse

Currently, the draft regulations have only set battery collection targets. In addition, manufacturers, importers, assemblers, and re-conditioners are required to ensure that the used batteries collected are sent only to registered recyclers. As drafted, these regulations may dissuade second-life applications. Instead, the Producer Responsibility Organization should be required to establish reuse targets for collected LiBs over a certain capacity. Policy can further be used to bolster the market for second-life batteries by establishing qualifications for reuse organizations and set performance standards for second-life batteries. No language in the draft rules would apply to an organization or person testing or certifying an LiB for secondary use. Included definitions of refurbishment and re-conditioning only apply to preparing batteries for the same market or returning them to the owner. Recyclers, as defined, must meet guidelines established by the Central Pollution Control Board. Revised language should include an explicit definition for an organization or person that prepares LiBs for secondary applications. Guidelines should be established for such an organization to be certified by the Central Pollution Control Board to ensure consumer confidence in the quality of LiBs intended for secondary applications.

Formalizing Performance Standards and Warranties

LiB consumers have expressed concerns with utilizing recovered battery packs for second-life purposes. Key hurdles for adoption of recovered LiBs for secondary use include the lack of a transparent system for assessing battery health or a warranty ensuring performance standards. The Ministry should work with battery stakeholders to establish criteria for assessing battery pack health for secondary use, along with a certification process to improve consumer confidence for reuse.

New batteries are sold with performance guarantees and warranties, and for many BESS operators the declining price of LiBs creates concern over utilizing products that lack such backing. For refurbishers, there are high costs associated with verifying the quality of the LiB, as conventional methods are labour intensive. To improve the market for second-life LiBs, and become a global leader in LiB reuse, India could devise a methodology for certifying refurbishers, as well as metrics for assessing and guaranteeing performance standards, and establish incentives for innovative approaches for second-life applications.

Considerations for Costs

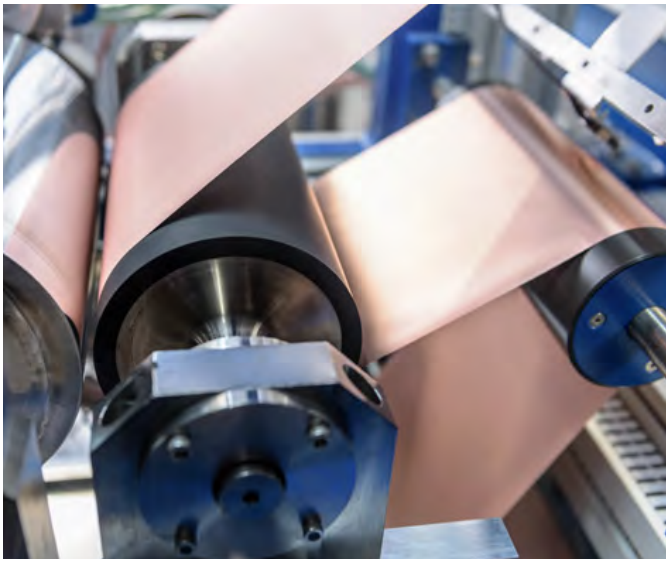
Establishment of a battery recycling program will create costs associated with the transportation, collection, and recycling of LiBs. In an EPR program, the covered industry stakeholders will take on the cost burden, generally by including a fee on the product being reused. Key considerations for regulatory authorities are to ensure the associated funding mechanism is both sufficient to cover program costs while also not overly burdensome on consumers; that the estimated program costs are realistic for achieving the collection and recycling targets; and that the funds raised are not inappropriately used for activities that do not benefit the program. Given the need for EVs to reach market parity with internal combustion engine vehicles, it is important that any associated cost be well tailored and not impact the competitiveness of EVs. Amendments for the draft rules may consider explicitly limiting the activities that funding may be utilized for, as to deter misuse.

Incentivizing Consumer Compliance

In addition to costs for recycling and collection infrastructure, another key component will be incentivizing consumers to return end-of-life EV batteries to the appropriate collection agent. EPR plans may vary as to who receives end-of-life batteries from consumers, but could include retailers, recyclers, collection centres, or original equipment manufacturers (OEMs). Any submitted plan should include an incentive mechanism for consumers, which may include a rebate for a returned battery or a deposit system. For example, consumers could have reduced costs for a replacement battery in exchange for the end-of-life battery. In a deposit system, consumers would pay a cost at the time of purchase, which is then retrieved upon return of the battery. Regulatory authorities must ensure that a submitted plan includes some form of incentive program to ensure compliance, and that the proposal is sufficient while also not creating cost burdens that would deter consumers from purchasing an EV.

Enforcement and Penalties

Under an EPR program, the designated regulatory authority must review and approve the submitted EPR plan and ensure covered entities are complying with responsibilities outlined in the plan. In stakeholder interviews, regulators have expressed that enforcement will be undertaken through monitoring of barcode scans, and that enforcement actions such as site visits will occur when discrepancies are identified in barcode scans. Regulatory authorities may also want to outline a penalty hierarchy. Under an EPR program, disapproval or revocation of an EPR plan that fails to meet the goals of the program should be considered a last step as it may disrupt sales of EVs. Regulatory authorities should develop a transparent methodology for identifying issues, as well as steps for remediation or penalties.



Conclusion

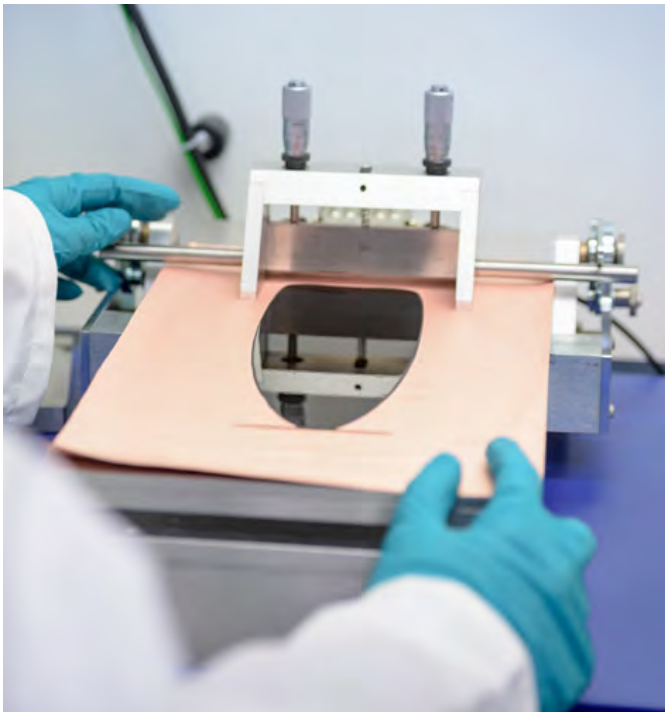
Conclusion

Lithium-ion batteries will play a critical role in India's energy transition by enabling deep decarbonization of the transportation and power sectors. Demand for LiBs is growing globally, enabled by improved performance and declining prices. India has the opportunity to assume a leadership role for expansion of LiB manufacturing, particularly one that can meet growing demand while reducing life-cycle impacts.

Establishing a strong and long-term sustainable LiB industry in India will require implementing circular economic principles, including capitalizing on the full value of batteries through reuse and recycling. This requires an alignment of efforts from the national government, state regulators, battery industry stakeholders, and consumers. The introduced draft battery waste management policy is a strong signal of intent. Adoption of this policy, with recommended amendments, will set a global standard for battery recovery, reuse, and recycling.

But actions must go beyond policies. The next step will be aligning industry plans to meet the ambitious policy goals in a manner that neither hinders sales of EVs nor bolsters an informal resale sector. A key challenge will be identifying a mechanism to incentivize consumers to return batteries while avoiding restrictive cost increases. Regulatory authorities must also consider criteria by which proposed EPR plans can be evaluated and approved, ensuring proper oversight, compliance, and long-term success.

India has the opportunity to become a key global player in the battery market. Adequate implementation of reuse and recycling of batteries will enhance the resource security implication of the country's vehicle electrification and energy transition ambitions. It will also result in economic development and job growth, while ensuring improved public health and environmental safety. Enabling this virtuous circular economy is the need of the hour as India embarks onwards to a sustainable future.



Appendix

Appendix

Key Scenario Assumptions and Methodology

This analysis is based on a conservative and accelerated scenario. The key distinction is the degree for the adoption of EV supportive policies, access to financing, and development of infrastructure. The conservative scenario is a business-as-usual with no new supportive policies. In the conservative scenario, EV sales make up less than 10% of all vehicle sales by 2030. In the accelerated scenario, EV sales exceed 70% of all vehicle sales.

RMI's projections of EV sales break into two primary segments: passenger vehicles and freight vehicles. In both scenarios, adoption of EV sales is driven by private two wheelers followed by commercial four-wheel vehicles (see Exhibits 11 and 12).

Exhibit 11 RMI Accelerated Scenario for EV Adoption

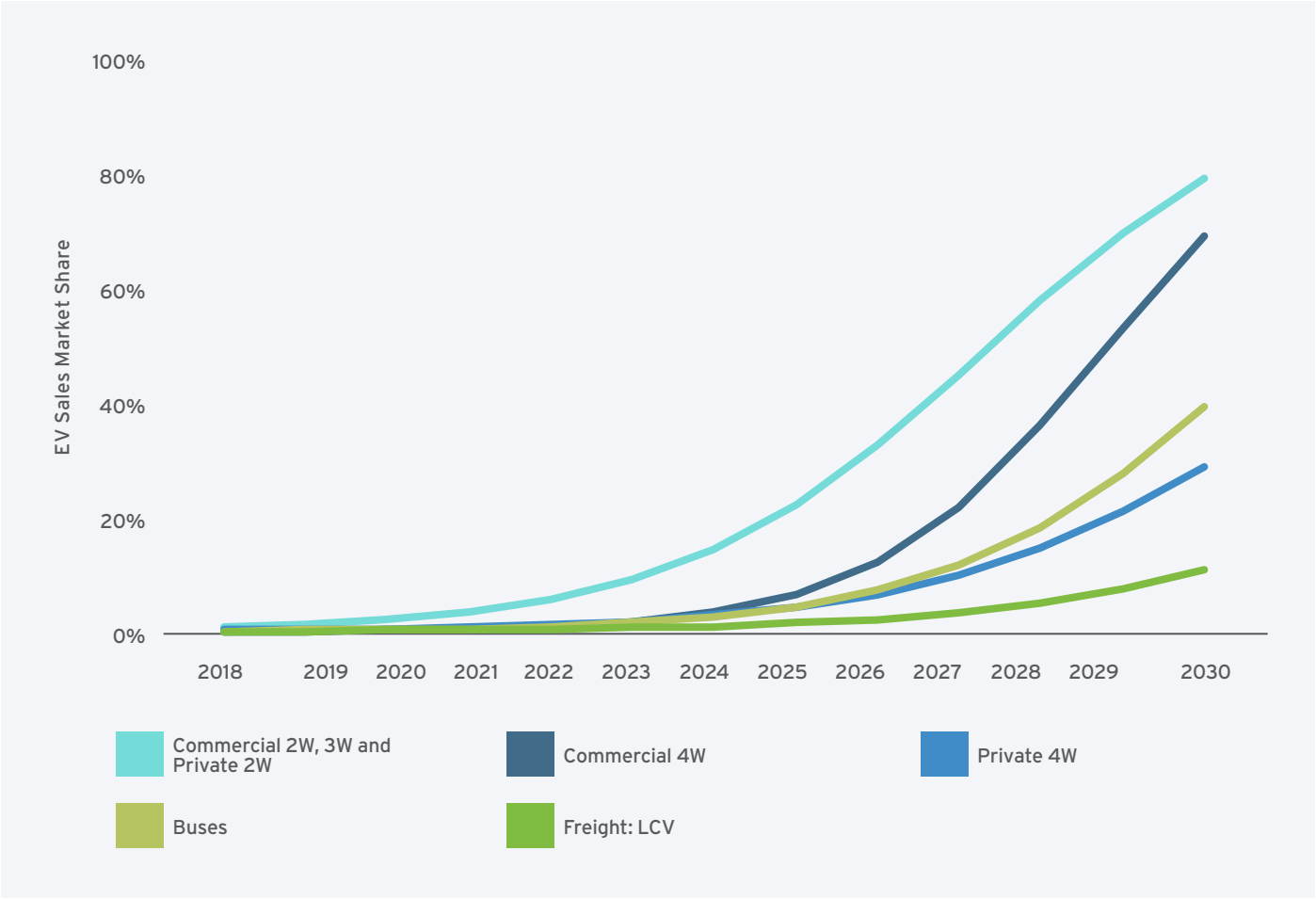
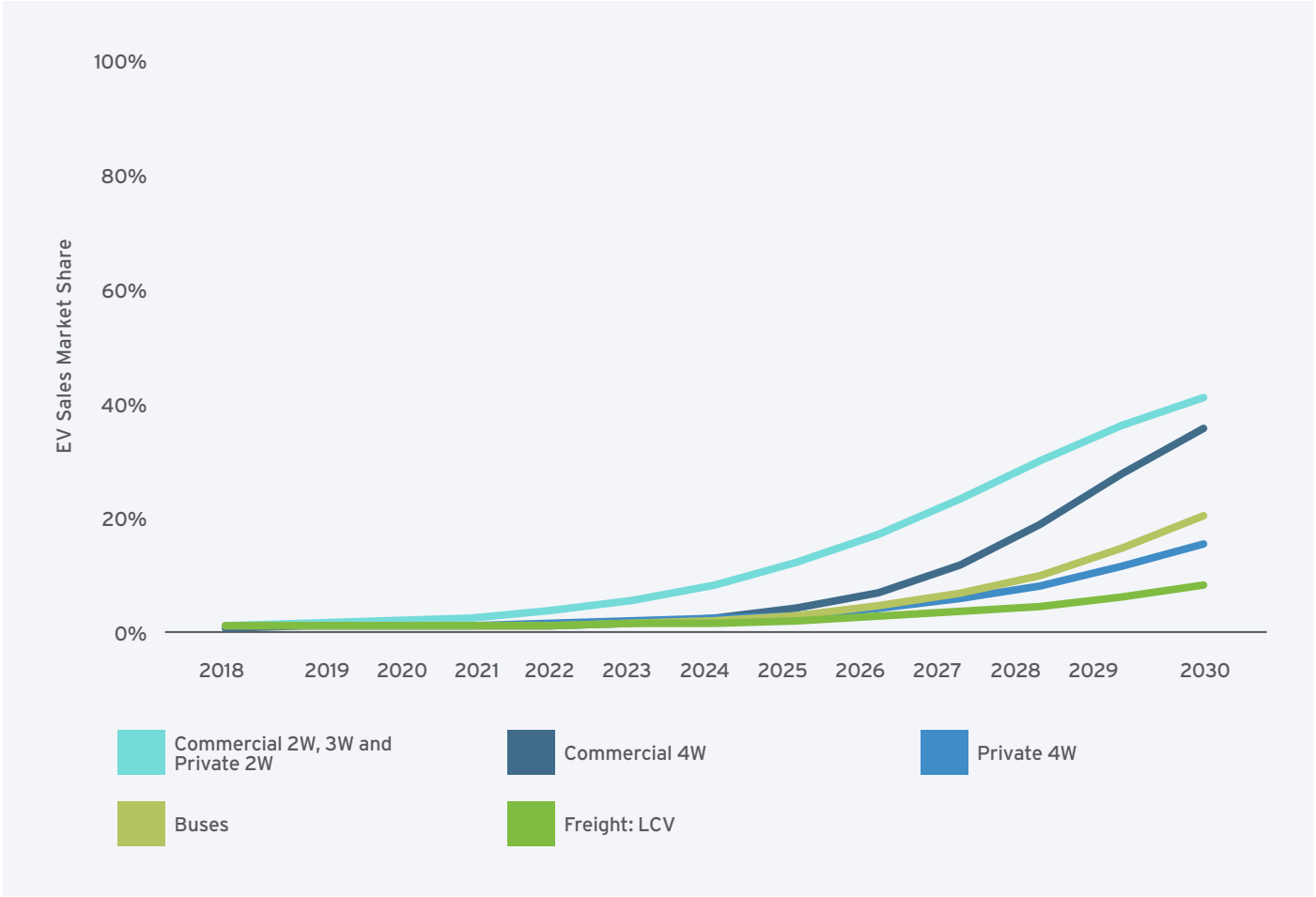


Exhibit 12 RMI Conservative Scenario for EV Adoption

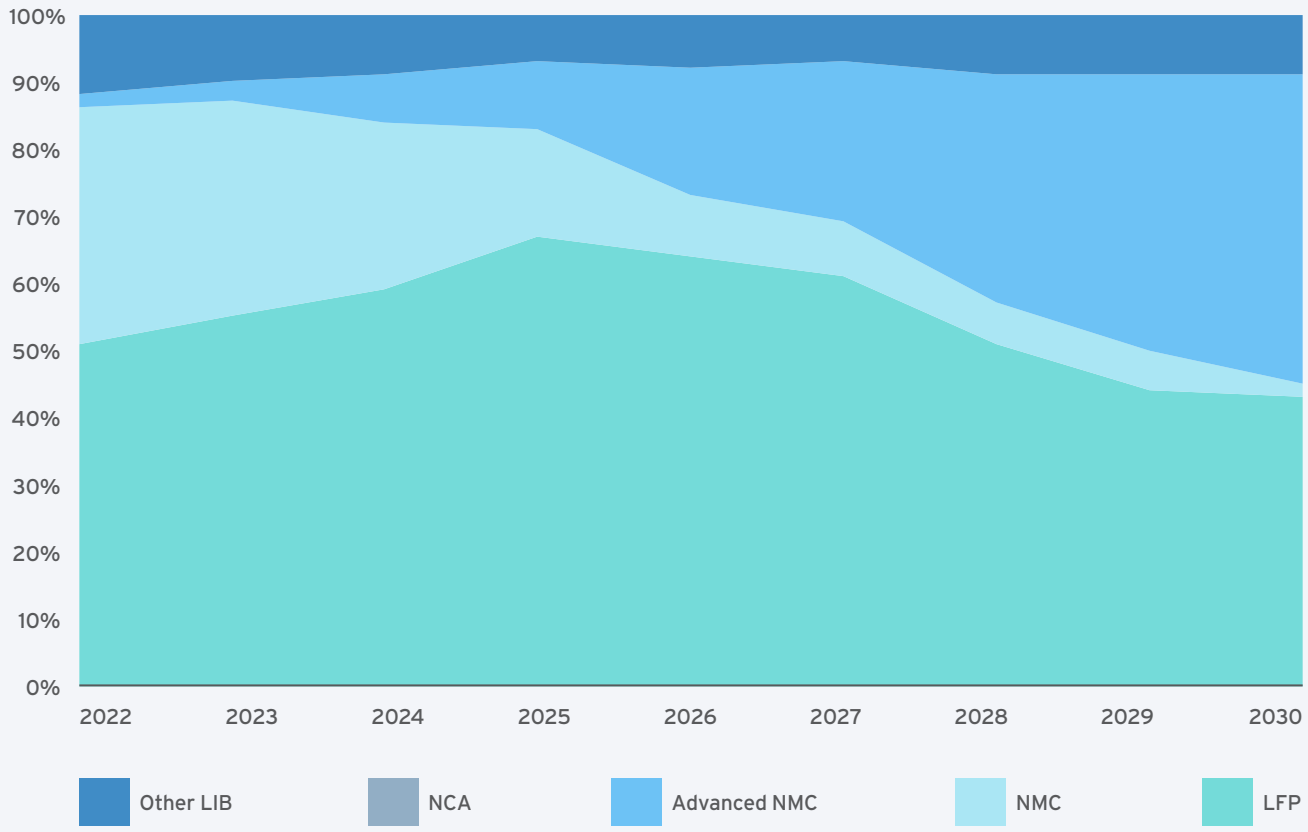


Each of the vehicle types maintains assumed battery capacity requirements, which remain static throughout the assumption. These range from 2 kWh batteries for commercial and passenger two-wheel vehicles to 492 kWh batteries for heavy-duty freight vehicles.

Battery retirement is a product of use and battery lifetime. RMI analysis provided vehicle utilization in kilometres per year, kilometres per battery charge, and battery life cycle. This analysis assumes a battery lifecycle of 1,000 cycles. Vehicle utilization, kilometres per battery charge, and battery life cycle have remained static. However, energy density improvements are realized as innovative chemistries penetrate sales. Energy densities by battery chemistry are sourced from BloombergNEF. Battery lifetime has been calculated for each of the fourteen vehicle types. The draft policy requires collection of batteries by weight. To determine battery weights, RMI created an outlook of potential LiB chemistry mix (see Exhibit 13).

This projection was informed by BloombergNEF's global LiB chemistry projections, with key distinctions made for India based on expert interviews. This includes higher-than-global levels of LFP batteries and an absence of NCA chemistries. Distribution of battery chemistries was weighed by sales of vehicle type, and weight was calculated by chemistry energy density divided by required capacity by vehicle type. While not impactful towards the conclusions of the report, this is the most subjective aspect of RMI's analysis. Any future emergence of new chemistries can move the resulting material demand implications of India's EV transition.

Exhibit 13 Potential Battery Chemistry Mix Scenario for India



Note:
NMC refers to current NMC chemistries, such as NMC (111), NMC (532), and NMC (622)
Advanced NMC refers to innovative chemistries such as NMC (811), NMC (721), NMC (9.5.5), NMC (442), Lithium and Manganese Rich NMC (LMR-NMC), Nickel Manganese Cobalt Aluminium (NMCA), and Cobalt Free (NMx)
NCA refers to all NCA chemistries, including NCA85, NCA90, NCA92, and NCA 95
Other LiB refers to chemistries containing Oxide, such as LNO, LMO, LNMO, and LCO
LFP refers to Lithium Iron Phosphate.

These inputs have been used to inform annual LiB retirements by both weight and capacity. Overtime, capacity retirements outpace weight as higher density chemistries make up a greater degree of batteries.

The required battery collection and recycling capacities comes from the goals set in the draft rules and have been divided into both the conservative and accelerated scenarios.

Endnotes

Endnotes

1. EV30@30, Clean Energy Ministerial, June 2019, **https://www.cleanenergyministerial.org/sites/default/files/2019-06/EV30%4030%20fact%20sheet%20%28June%202019%29.pdf**.

2. "COP26: India Commits to 500GW of Renewables by 2030, Net Zero by 2070," PV-Tech, November 2021. **www.pv-tech.org/cop26-india-commits-to-500gw-of-renewables-by-2030-net-zero-by-2070/**.

3. FAME India Scheme Phase II: Timeline, Ministry of Heavy Industries, National Automotive Board, **http://fame2.heavyindustries.gov.in/content/english/16_1_Timeline.aspx**.

4. Charlie Bloch, James Newcomb, Samhita Shiledar, and Madeline Tyson, Breakthrough Batteries: Powering the Era of Clean Electrification, RMI, 2019, pg. 7, **www.rmi.org/breakthrough-batteries**.

5. Bloch et al., Breakthrough Batteries: Powering the Era of Clean Electrification, pg. 18, **www.rmi.org/breakthrough-batteries**.

6. Bloch et al., Breakthrough Batteries: Powering the Era of Clean Electrification, pg. 19, **www.rmi.org/breakthrough-batteries**.

7. "The Composition of EV Batteries: Cells? Modules? Packs? Let's Understand Properly," Samsung SDI, accessed December 23, 2021, **www.samsungsdi.com/column/all/detail/54344.html**.

8. "The Composition of EV Batteries: Cells? Modules? Packs? Let's Understand Properly," Samsung SDI, **www.samsungsdi.com/column/all/detail/54344.html**.

9. Heiner Hans Heimes, et al., Lithium-Ion Battery Cell Production Process, PEM of RWTH Aachen University and the German Mechanical Engineering Industry Association (VDMA), December 2018, **www.pem.rwth-aachen.de/global/show_document.asp?id=aaaaaaaaabdqbtk**.

10. James Firth, "Lithium-Ion Batteries State of the Industry 2021," Bloomberg New Energy Finance, September 2021, **https://www.bnef.com/downloads/insights/27271/excel**.

11. Firth, "Lithium-Ion Batteries State of the Industry 2021," Bloomberg New Energy Finance, **https://www.bnef.com/downloads/insights/27271/excel**.

12. Firth, "Lithium-Ion Batteries State of the Industry 2021," Bloomberg New Energy Finance, **https://www.bnef.com/downloads/insights/27271/excel**.

13. Cecilia L'Ecluse, "Global Lithium-Ion Battery Supply Chain Ranking," Bloomberg New Energy Finance, October 2021, pg. 41, **https://www.bnef.com/insights/27437/view**.

14. "China Dominates the Global Lithium Battery Market," Institute for Energy Research (IER), September 2020, **www.instituteforenergyresearch.org/renewable/china-dominates-the-global-lithium-battery-market/**.

15. Jason Porzio and Corinne D. Scown, "Life-Cycle Assessment Considerations for Batteries and Battery Materials," Advanced Energy Materials, Volume 11, Issue 33, July 2021, **https://onlinelibrary.wiley.com/doi/10.1002/aenm.202100771?af=R**.

16. Porzio and Corinne, "Life-Cycle Assessment Considerations for Batteries and Battery Materials," Advanced Energy Materials, pg. 41, **https://onlinelibrary.wiley.com/doi/10.1002/aenm.202100771?af=R**.

17. David Roberts, "The Many Varieties of Lithium-Ion Batteries Battling for Market Share,"

Canary Media, April 2021, **www.canarymedia.com/articles/batteries/the-many-varieties-of-lithium-ion-batteries-battling-for-market-share**.

18. Catherine Clifford, "Bill Gates-backed ESS – which makes giant batteries out of iron, salt and water – Starts Trading," CNBC, October 2021, **www.cnbc.com/2021/10/11/ess-battery-company-backed-by-bill-gates-softbank-opens-on-nyse.html**.

19. "ESS Iron Flow Batteries," ESS, Inc., accessed December 23, 2021, **https://essinc.com/wp-content/uploads/2021/05/ESS_OnePager_FINAL_5-10-21_lowres.pdf**.

20. "ESS Iron Flow Chemistry," ESS, Inc., accessed December 22, 2021, **https://essinc.com/iron-flow-chemistry/**.

21. Bloch et al., Breakthrough Batteries: Powering the Era of Clean Electrification, pg. 31, 36-37, **www.rmi.org/breakthrough-batteries**.

22. Bloch et al., Breakthrough Batteries: Powering the Era of Clean Electrification, pg. 19, **www.rmi.org/breakthrough-batteries**.

23. Firth, "Lithium-Ion Batteries State of the Industry 2021," Bloomberg New Energy Finance, **https://www.bnef.com/downloads/insights/27271/excel**.

24. L'Ecluse, "Global Lithium-Ion Battery Supply Chain Ranking," Bloomberg New Energy Finance, pg. 45, **https://www.bnef.com/insights/27437/view**.

25. Uma Gupta, "India's Lithium-Ion Battery Imports Increase Fourfold in Two Years," PV Magazine, February 2020, **www.pv-magazine-india.com/2020/02/10/indias-li-ion-battery-imports-increase-four-fold-in-3-years/**.

26. Indian Mineral Industry at a Glance 2017-18, India Bureau of Mines, Nagpur, July 2020, **https://ibm.gov.in/writereaddata/files/09152020150205IMIG-2017-18.pdf**.

27. Alaina Ali Beg, "Lithium Reserves in India: Insights from Source to Lithium Metal Batteries," The Indian Wire, February 2021, **www.theindianwire.com/business/lithium-reserves-in-india-306400/**.

28. "Cabinet Approves National Mission on Transformative Mobility and Battery Storage," Office of the Prime Minister, News Updates, March 2019, **www.pmindia.gov.in/en/news_updates/cabinet-approves-national-mission-on-transformative-mobility-and-battery-storage/**.

29. Naina Bhardwaj, "India's PLI Scheme for ACC Battery Storage Manufacturing," India Briefing, May 2021, **www.india-briefing.com/news/indias-pli-scheme-for-acc-battery-storage-manufacturing-22349.html/**.

30. Porzio and Corinne, "Life-Cycle Assessment Considerations for Batteries and Battery Materials," Advanced Energy Materials, **https://onlinelibrary.wiley.com/doi/10.1002/aenm.202100771?af=R**.

31. "The Role of Critical Minerals in Clean Energy Transitions," International Energy Agency (IEA), May 2021, pg. 195, **https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf**.

32. Amit Katwala, "The Spiralling Environmental Cost of Our Lithium Battery Addiction," Wired, May 2018, **www.wired.co.uk/article/lithium-batteries-environment-impact**.

33. Hariana Sethi, "The Effects of Cobalt Mining in the DRC," The Borgen Project, November 2021, **https://borgenproject.org/cobalt-mining-in-the-drc/**.

34. "Is My Phone Powered by Child Labour?" Amnesty International, June 2016, **www.amnesty.org/en/latest/campaigns/2016/06/drc-cobalt-child-labour/**.

35. Jason Deign, "Why Lithium Isn't The Big Worry for Lithium-Ion Batteries," GreenTechMedia,

June 2015, https://www.greentechmedia.com/articles/read/Why-Lithium-Isnt-the-Big-Worry-for-Li-ion.

36. Hajro Ambrose and Jimmy O'Dea, Electric Vehicle Batteries: Addressing Questions about Critical Materials and Recycling, Union of Concerned Scientists, 2021, https://www.ucsusa.org/resources/ev-battery-recycling.

37. Yuqing Chen et al., "A Review of Lithium-Ion Battery Safety Concerns: The Issues, Strategies, and Testing Standards," Journal of Energy Chemistry, Volume 59, February 2021, pg. 83-99, https://www.sciencedirect.com/science/article/pii/S2095495620307075.

38. An Analysis of Lithium-Ion Battery Fires in Waste Management and Recycling, United States Environmental Protection Agency, EPA 530-R-21-002, July 2021, pg. 8, https://www.epa.gov/system/files/documents/2021-08/lithium-ion-battery-report-update-7.01_508.pdf.

39. Reuse and Recycling: Environmental Sustainability of Lithium-Ion Battery Energy Storage Systems, Energy Sector Management Assistance Program (ESMAP), The World Bank, Washington DC, August 2020, pg 10, https://documents1.worldbank.org/curated/en/593961599738208006/pdf/Reuse-and-Recycling-Environmental-Sustainability-of-Lithium-Ion-Battery-Energy-Storage-Systems.pdf.

40. Reuse and Recycling: Environmental Sustainability of Lithium-Ion Battery Energy Storage Systems, Energy Sector Management Assistance Program (ESMAP), The World Bank, pg 11, https://documents1.worldbank.org/curated/en/593961599738208006/pdf/Reuse-and-Recycling-Environmental-Sustainability-of-Lithium-Ion-Battery-Energy-Storage-Systems.pdf.

41. Peter Karlson, "Study of Large Format EV Lithium-Ion Battery Recycling in China: Executive Summary," NAATBatt, Avicenne Energy, March 2019, slide 12, https://naatbatt.org/wp-content/uploads/2019/03/Executive-Summary-of-China-Recycling-Study-v2-1.pdf.

42. Jason Deign, "How China is Cornering the Lithium-Ion Cell Recycling Market," GreenTechMedia, September 2019, https://www.greentechmedia.com/articles/read/how-china-is-cornering-the-lithium-ion-cell-recycling-market.

43. Chris Randall, "China Releases Battery Recycling Regulations," Electrive, November 2019, https://www.electrive.com/2019/11/11/china-releases-battery-recycling-regulations/.

44. "Lithium-ion Battery Recycling Process & Solutions," Met-Chem, Inc., accessed December 20, 2021, https://metchem.com/lithium-ion-battery-recycling-process-equipment/.

45. Elena Mosalli et al., "Lithium-ion Batteries Towards Circular Economy: A Literature Review of Opportunities and Issues of Recycling Treatments," Journal of Environmental Management, 264(30), June 2020, https://www.researchgate.net/publication/340393401_Lithium-ion_batteries_towards_circular_economy_A_literature_review_of_opportunities_and_issues_of_recycling_treatments.

46. Recycling and Second Life Use of Lithium-Ion Batteries, Deloitte Touche Tohmatsu India LLP, 2021, pg. 3, https://www2.deloitte.com/content/dam/Deloitte/in/Documents/energy-resources/in-enr-battery-recycling-and-second-life-noexp.pdf.

47. Xiaotu Ma et al., "Recycled Cathode Materials Enabled Superior Performance for Lithium-Ion Batteries," Joule, Volume 5, Issue 11, November 2021, pg. 2964, https://www.sciencedirect.com/science/article/abs/pii/S2542435121004335.

48. Ma et al., "Recycled Cathode Materials Enabled Superior Performance for Lithium-Ion Batteries," Joule, https://www.sciencedirect.com/science/article/abs/pii/S2542435121004335.

49. "About," Attero Recycling, accessed January 10, 2022, **http://attero.in/about/**.

50. "Attero to Invest Rs 300 crore on Ramping Up Battery Recycling Capacity," Devdiscourse, January 2022, **https://www.devdiscourse.com/article/business/1876878-attero-to-invest-rs-300-crore-on-ramping-up-battery-recycling-capacity**.

51. "Draft Battery Waste Management Rules, 2020," Journals of India, March 2020, **https://journalsofindia.com/draft-battery-waste-management-rules-2020/**.

52. Paul Ekins et al., "Extended Producer Responsibility: A Guidance for Government," Organisation for Economic Co-operation and Development, July 2019, pg. 17, **https://www.oecd.org/cfe/regionaldevelopment/Ekins-2019-Circular-Economy-What-Why-How-Where.pdf**.

53. Panpan Xu et al., "Efficient Direct Recycling of Lithium-Ion Battery Cathodes by Targeted Healing," Joule, Volume 4, Issue 12, November 2020, pg. 10, **http://smeng.ucsd.edu/wp-content/uploads/1-s2.0-S2542435120304979-main.pdf**.

54. Han Hao et al., "GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China," Sustainability, Volume 9, Issue 4, April2017 pg. 7, **https://pdfs.semanticscholar.org/47cc/2bd1590bd79f316e4979a907d3063e83bd58.pdf**.

55. Julian Spector, "Used EV Batteries are Storing Solar Power at Grid Scale – And Making Money At It," Canary Media, October 2021, **https://www.canarymedia.com/articles/energy-storage/used-ev-batteries-are-storing-solar-power-at-grid-scale-and-making-money-at-it**.

56. "Draft Ancillary Services Regulations," Central Electricity Regulatory Commission, May 2021, **https://cercind.gov.in/2021/draft_reg/Draft_Ancillary_Services_Regulations.pdf**.

57. Jan Figgener et al., "The Development of Stationary Battery Storage Systems in Germany – A Market Review," Journal of Energy Storage, Volume 29, June 2020, **https://www.sciencedirect.com/science/article/pii/S2352152X19309442**.

58. Guide to Ancillary Services in the National Electricity Market, Australian Energy Market Operator, November 2021, **https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/guide-to-ancillary-services-in-the-national-electricity-market.pdf**.

59. James Eddy, Alexander Pfeiffer, and Jasper van de Staaij, "Recharging Economies: The EV-Battery Manufacturing Outlook for Europe," McKinsey & Company, June 2019, **https://www.mckinsey.com/industries/oil-and-gas/our-insights/recharging-economies-the-ev-battery-manufacturing-outlook-for-europe**.

60. Amitabh Kant et al., Mobilising Finance for EVs in India, NITI Aayog and Rocky Mountain Institute, January 2021, pg. 20, **https://rmi-india.org/wp-content/uploads/2021/01/mobilising_finance_for_evs_in_india.pdf**.

61. "Battery Second Use for Plug-In Electric Vehicles," National Renewable Energy Lab, accessed January 6, 2022, **https://www.nrel.gov/transportation/battery-second-use.html**.

Towards a Sustainable Battery Manufacturing Industry: The Case for Effective Reuse and Recycling, RMI, and RMI India, March 2022. https://rmi-india.org/insight/towards-a-sustainable-battery-manufacturing-industry/

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