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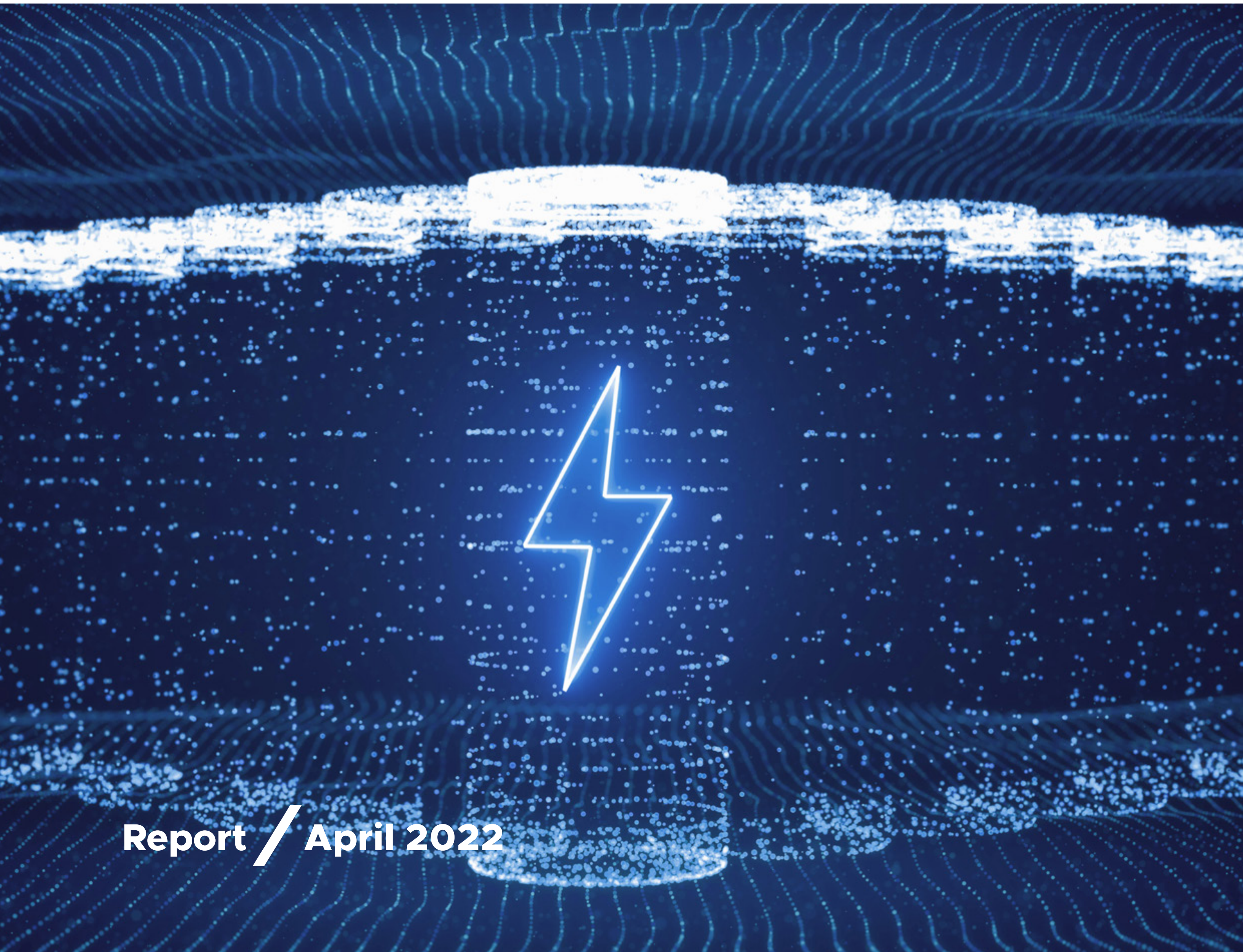
Need for Advanced Chemistry Cell Energy Storage in India

Part II of III



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About Us

About NITI Aayog

The National Institution for Transforming India (NITI Aayog) was formed via a resolution of the Union Cabinet on 1 January 2015. NITI Aayog is the premier policy think tank of the Government of India, providing both directional and policy inputs. While designing strategic and long-term policies and programmes for the Government of India, NITI Aayog also provides relevant technical advice to the Centre and States. The Government of India, in keeping with its reform agenda, established NITI Aayog to replace the Planning Commission instituted in 1950. This was done to better serve the needs and aspirations of the people of India. An important evolutionary change from the past, NITI Aayog acts as the quintessential platform of the Government of India to bring States to act together in the national interest, and thereby fosters cooperative federalism.

About RMI

RMI is an independent nonprofit 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 by at least 50% 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 and do tank. RMI India takes inspiration from and collaborates with RMI, a 40-year-old nongovernmental organisation. RMI India's mission is to accelerate India's transition to a clean, prosperous, and inclusive energy future.

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Abbreviations

LiB	Lithium-ion battery
NMC	Nickel manganese cobalt
LFP	Lithium ferro (iron) phosphate
NCA	Nickel cobalt aluminium
LCO	Lithium cobalt oxide
LMO	Lithium manganese oxide
LNMO	Lithium nickel manganese oxide
LTO	Lithium titanate
LiPF6	Lithium hexafluorophosphate
ACC	Advanced chemistry cell
PLI	Production Linked Incentive
IEC	International Electrotechnical Commission
ANSI	American National Standards Institute
kWh	Kilowatt-hour
GWh	Gigawatt-hour
EV	Electric vehicle
2W	Two Wheeler
3W	Three Wheeler

Executive Summary

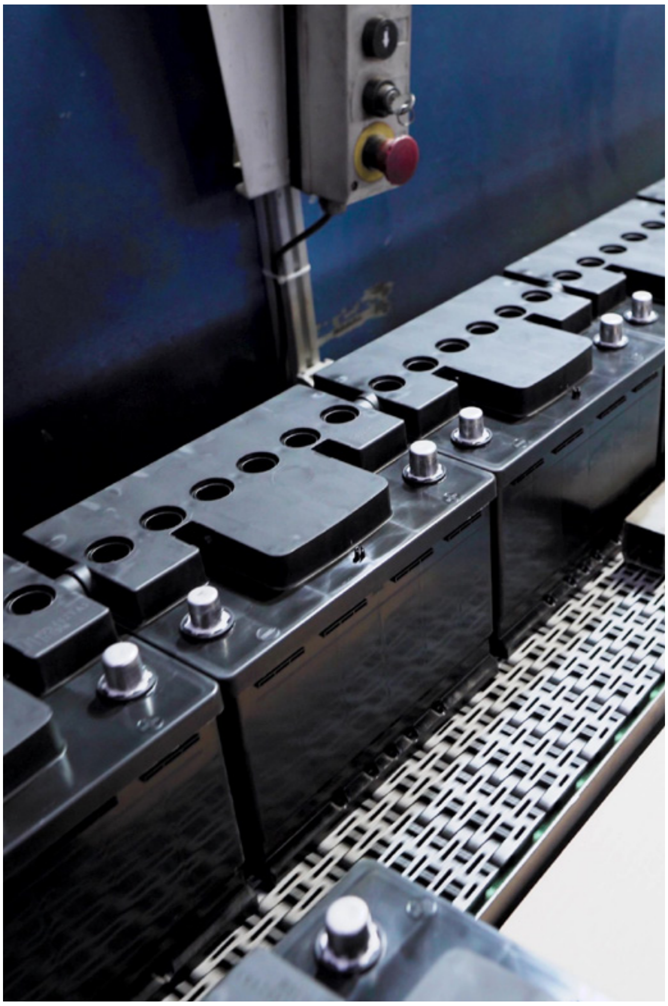
Executive Summary

The development of a domestic battery manufacturing ecosystem is crucial to India's ambitious push towards renewable energy and electric vehicles (EVs). The recent rollout of the solar photovoltaic (PV) and advanced chemistry cell (ACC) Production Linked Incentive (PLI) schemes worth $3.2 billion and $2.5 billion, respectively, will kick-start the domestic manufacturing of solar panels and advanced batteries that can drive India towards achieving the ambitious target of installing 500 GW of non-fossil fuel electricity capacity by 2030.[1]

Developing a localised advanced cell supply chain ecosystem will help India create a competitive advantage in the mobility, grid energy storage, and consumer electronics space, and insulate itself from any supply shocks that could put the entire battery ecosystem at risk. A robust domestic battery manufacturing hub that supports technological innovations could create better-performing batteries that can spur demand for electric vehicles across India. It can also support a stable and resilient electricity grid that can absorb increasing shares of renewable energy. In this way, batteries can facilitate some of the most dynamic and growing sectors of India's economy.

As battery technology and chemistry determine the range of services they can deliver, India needs to develop an array of technology options to ensure a robust battery ecosystem. Hence, the recent PLI scheme for ACC battery storage, launched by the Government of India (GoI), takes a technology-agnostic approach and offers financial incentives for battery manufacturers based on key technological factors such as higher energy density and cycle life.

Our first report in this series, titled, *Need for Advanced Chemistry Cell Energy Storage in India: Part I of III*, projected the market potential for energy storage in India across multiple critical sectors such as mobility, power, and consumer electronics. The report also outlined the need for domestic manufacturing of ACC battery storage by highlighting the opportunities it presents for India.



This report (part II of III) aims to further explore the domestic manufacturing opportunities for battery storage in India by focussing on battery chemistries. The report analyses existing, advanced, and upcoming battery technologies on multiple industry-standard performance metrics and projects battery chemistries that could go mainstream by 2030 and beyond. The key characteristics of various battery technologies, their merits and demerits, and their suitability for key applications are also highlighted in this report. Additionally, the report discusses the recently finalised PLI scheme on ACC battery storage by the GoI and its potential role in creating domestic economic value. Finally, the report highlights the value creation opportunities in building a domestic ecosystem for battery manufacturing in India.

About the Report

This is the second in a series of three reports designed with the objective of creating a shared understanding among stakeholders of the current status and future trends that are emerging in the advanced chemistry cell (ACC) battery sector and to build awareness of India's supportive programme on ACC battery storage, most importantly the Production Linked Incentive (PLI) scheme for cell manufacturing. NITI Aayog and RMI present a thorough assessment of the global electric mobility and stationary storage sectors through multiple lenses, including international best practices in policy design, international technology trends in advanced cell batteries, global and domestic market sizing, and an assessment of key risks across the value chain. This report looks at characteristics of different battery technologies and their applicability in the Indian context. It further introduces various considerations around enhancing value capture within India.

Introduction

Introduction

In the first report of this series, titled, *Need for Advanced Chemistry Cell Energy Storage in India: Part I of III*, India's annual demand for advanced chemistry batteries is projected to rise up to 260 gigawatt-hours (GWh) by 2030 across multiple sectors. This growth represents almost a hundredfold increase from existing domestic demand for batteries, which is close to 2.7 GWh. What underpins this massive growth potential is the accelerated adoption of electric vehicles (EVs) and rapid decarbonisation of the electricity grid, guided by ambitious government targets and supporting policies.

As the momentum on the PLI scheme accelerates—successful bidders were announced in March 2022—it is important to present a common understanding of battery characteristics, performance criteria, and the different chemistries available. Given that batteries can cater to a wide range of applications across the transport, power, and consumer electronics sectors, there is a need to develop a technology-agnostic ecosystem that promotes multiple battery chemistries to match the variety of anticipated demand sources.

Prior to the advent of lithium-ion batteries (LiBs)—conceptualised in the 1970s and commercialised in the 1990s—battery technology remained dominated by lead-acid batteries, which were invented in 1859. Lead-acid remains the most widely deployed battery technology. But it is also limited by relatively low energy and power density, and this restricts its use in newer applications such as EVs and energy storage systems.

Comparatively, LiBs benefit from high energy density. This allows for the design of much lighter systems, making LiBs ideal for EVs. High costs have presented early barriers, but higher penetration in EVs and energy storage applications—in addition to consumer electronics—has enabled economies of scale. Costs have dropped drastically, making lithium-ion the most dominant battery technology today. Although new chemistries are likely to enter the market, most industry experts agree that LiB technology will continue to have a strong market share for the next 5 to 10 years, given the large investments in LiB supply and technology.[2]

In the long term, newer battery chemistries have the potential to significantly shift cost and performance thresholds, leading to a larger market for energy storage by enabling new applications that previously were out of reach. Battery manufacturers are confident in the near-term market for LiBs, but even the large cell manufacturers see emerging technologies as a means of gaining long-term competitive advantage and have begun investing in alternative battery technologies.

Each battery chemistry will have distinct utilities in niche application areas; ultimately, however, the scale of adoption of a given battery technology will be based on its performance, its safety, companies' manufacturing volume and experience, the availability of materials, and, most importantly, cost considerations. India must also make careful assessments of how much of the integrated supply chain it will be able to capture in the short and long terms.

Battery Technologies and Considerations for India

Battery Technologies and Considerations for India

Performance improvements in lithium-ion technology and rapid declines in costs have driven an increase in adoption of EVs and grid-tied stationary energy storage. This uptake of LiBs has been critical for the initial transition towards a clean energy system, setting the electricity and transportation sectors on a path towards full decarbonisation. The success of lithium-ion technologies has also created a significant market opportunity for batteries to support multiple other end uses that previously have not been technically or economically feasible.

Advances in battery technologies—including advanced lithium-ion cathodes and anodes, lithium-sulphur batteries, solid-state batteries, metal-air batteries, flow batteries, and others now in various stages of development—could be crucial in advancing the next stage of energy transitions, and they should be encouraged and supported in the market.[i] These innovations have the potential to disrupt current assumptions about battery cost, safety, weight, and performance—specifically, assumptions that certain developments are challenging because they are unlikely to be achieved through incremental improvements in lithium-ion technologies. The innovations in battery technologies listed above can provide cheaper and safer alternatives for energy storage.

Different battery technologies may be preferable for different use cases, including long-duration storage (which will be critical for a 100% renewable energy grid), ground and maritime transportation, industrial applications, and even passenger and freight aviation. Despite signs of great promise, some of these emerging technologies face significant barriers before they achieve the technological readiness levels or manufacturing scale necessary to emerge as viable alternatives to existing lithium-ion technology. New battery technologies will require many stages of improvement at lab scale and in manufacturing processes before being ready for large-scale commercialisation.

LiBs, having emerged as the battery of choice for consumer electronics and now EVs, saw their prices decline 89% from 2010 to 2021. This was largely as a result of the hundredfold increase in production over the same period. This reduction in average battery pack cost from over $1,200/kWh to $132/kWh has enabled faster-than-expected adoption of EVs and increased growth in the stationary storage market.[3,ii] Although LiBs are the clear leader in the EV and stationary sectors today, a number of other emerging technologies will also participate in the future storage market. These technologies are covered in greater detail in the following pages and the Appendix.

Cell Parameters and Definitions

Battery cell performance and pack performance are key parameters that equipment manufacturers consider when building their supply chains.

Production of battery cells and packs in India must meet minimum application-specific performance metrics as defined by both domestic and export customers. Long-term competitiveness with global manufacturers requires that Indian manufacturers produce cells and packs that are on par with those of current suppliers around the world and that they will continue to do so. Performance metrics will be highly specific to the application of the cells and packs and are largely defined by the global market. Exhibit 1 provides a summary of several performance metrics that India must globally compete on in order to maintain a large fraction of the domestic market and capture a share of the export market. For EV applications, for example, Energy Density and Power Density are high priorities, while these metrics are lower priority for stationary storage applications. Other metrics that may impact consideration for batteries include cost, recyclability, safety, and performance in hot and cold conditions, though these are significant for determining best-fit applications.

Exhibit 1 Battery Performance Metrics and Best-Fit Applications

Metric	Definition	Applications				
		Electric 2W/3W	Passenger EVs	Commercial EVs	Stationary Storage	Consumer Electronics
Energy Density (Wh/kg)	Energy density is the battery's energy content in relation to its mass and is an important performance metric for cells used in EVs and consumer electronics, as weight is a key design criterion in both segments.	●	●	●	◑	◑
Power Density (W/kg)	Power density is the maximum available power per unit mass. It determines the battery weight required to achieve a given performance target.	●	●	●	◑	◕
Cycle Life	A battery cycle is defined here as discharging at minimum 80% of the nameplate energy capacity of the battery in one cycle. Cycle life is the number of equivalent cycles that a battery can undergo while maintaining 70–80% of the nameplate energy capacity.	◕	◕	◕	●	◑
Charge Rate (C-Rate)	A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour.	●	●	●	◑	◕

Other performance parameters include cost, recyclabilty, safety, performance in hot and cold conditions

● Higher priority ◑ Lower priority

Because it is not practical to define minimum performance criteria across all categories that apply to all battery applications, this report focuses on two technology parameters that have emerged as key criteria in analysing battery performance: cycle life and energy density. These parameters are good indicators of a battery's performance and overall cost-effectiveness in the market across the wide range of possible applications.

The suitability of batteries for end-use applications depends on their performance on the various metrics shown in Exhibit 1. This variability in performance drives the need for developing a diverse battery manufacturing ecosystem. It should be noted that there is no global industry-defined standard for a cycle used in cycle-life calculations. To ensure consistency across testing procedures of all battery chemistries, we define battery cycle and cycle life in Exhibit 1.

Technical Specifications and Performance of Various Battery Technologies

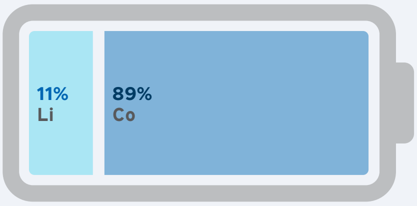
Commercial Lithium-Ion Batteries

Encompassing a suite of technologies, LiBs have emerged as the dominant market force because of their high energy density and rapidly decreasing costs. Though price and specifics vary among chemistries (and some batteries use multiple types of lithium-ion cells in concert to balance different advantages and disadvantages), the general chemistry, design, and characteristics for popular types are covered in Exhibits 2 and 3.[iii]

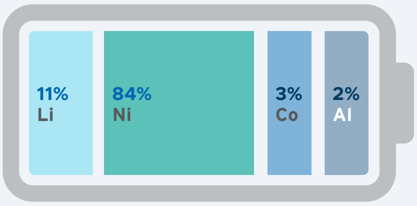
Exhibit 2 Lithium-Ion Battery Technical Specifications[4]

Cell Chemistry	Design and Manufacture	Characteristics
Anode: Typically carbon graphite **Cathode:** Lithium-ion cell types are generally recognised by the cathode material. Some of the most common lithium-ion variants are NMC, LFP, NCA, and LMO. **Electrolyte:** Mainstream electrolyte has been liquid carbonate-based organic solvents, mixed with lithium-ion salt of LiPF6 (high ionic conductivity over a wider temperature range).	**Architecture:** Can have effects on cycle life and energy densities: • Prismatic: Highest packing efficiency but complex wiring and more expensive • Cylindrical: Typically higher energy densities per unit than large-format cells, also longest calendar life • Pouch: High packing efficiency, but some concerns around swelling **Manufacturing Process:** Differs depending on architecture (most lithium-ion cells also contain a thermal management system)	• Cost Range: Pack prices are $120–$130/kWh for EVs, ~$152/kWh for stationary storage;[5] low-volume, high-power battery orders are significantly (2–4x) more expensive • Energy Density (by volume): 250–800 Wh/L • Specific Energy (by weight): 120–275 Wh/kg • Power Density: 300 W/kg • Nominal Voltage: 1.8–3.6 V (depending on cathode material) • Cycle Life: Approximately 1,500–6,000 cycles depending on chemistry • Safety: Varies widely between chemistries. Popular NMC types have poor performance; LFP and LTO are safer

Exhibit 3 Commercial Lithium-Ion Batteries

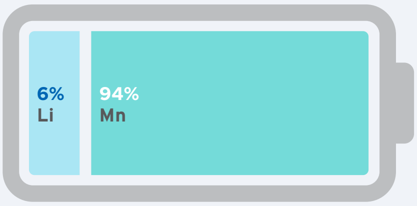
Cathode Metal Composition	Pros	Cons
Lithium cobalt oxide (LCO) 	• High energy density and moderate load capabilities • Acceptable cycle life	• High proportion of cobalt (increasingly cost-restrictive; issues in supply chain and sustainable mining concerns) • Poor heat resistance and safety

Applications	Major Developments
• Popular for consumer electronics (phones, laptops, and wearable products)	• DuPont has partnered with Steinerfilm and Polaris Battery Labs to use LCO cathodes to test innovations for other battery components, demonstrating 26% higher energy density.[7]

Cathode Metal Composition	Pros	Cons
Lithium nickel cobalt aluminium oxide (NCA) 	• High energy and power density • Good cycle life	• Poor thermal energy management and safety issues • High cost per kWh

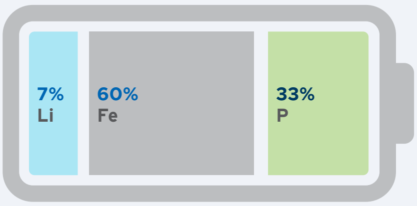
Applications	Major Developments
• Popular in EV powertrains, including Tesla	• Panasonic announced plans to start mass production of 4680 NCA cells for Tesla, which are five times as big as NCA cells currently used by Tesla, but up to 20% cheaper.[8]

Cathode Metal Composition	Pros	Cons
Lithium manganese oxide (LMO)	• Excellent power discharge and maximum load • Fast-charging capability • Good thermal stability and safety	• Low energy density • Low cycle life

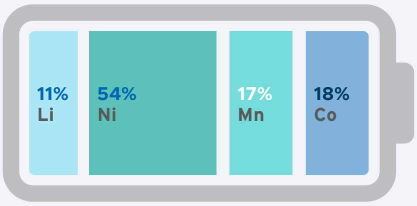


Applications	Major Developments
• Used in EV designs with a hybrid battery pack, in combination with NMC batteries—LMO's high power discharge allows better acceleration performance	• LMO batteries are used in a few EVs, such as the Nissan Leaf, because of their high reliability and relatively low cost.[9] But because of low cell durability compared with competing technologies, uptake has been limited.

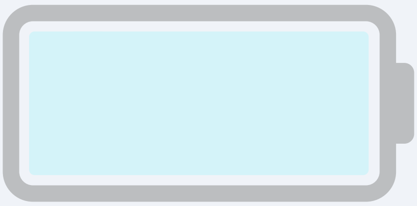
Cathode Metal Composition	Pros	Cons
Lithium ferro (iron) phosphate (LFP)	• Low cost • Thermally stable • Excellent cycle life, fast-charging capability • Uses easy-to-source minerals • Flat voltage discharge curve	• Lower energy density than NMC batteries



Applications	Major Developments
• Increasingly being considered as a replacement for NMC in low-/mid-range EVs (including electric buses) with improvements in pack-level energy density • Common use in stationary applications for grid-scale storage	• Reliance New Energy Ltd. announced plans to acquire Lithium Werks BV, an expert in LFP cell and module manufacturing.[10] • Tesla announced a transition from NCA batteries to LFP for its standard range models in 2021;[11] deployment for stationary applications is also expected in the future. • Contemporary Amperex Technology Co., Ltd. (CATL) and Build Your Dreams Co., Ltd. (BYD) announced the cell-to-pack (CTP) design for LFP batteries in 2020,[12] which allow energy density up to 140 Wh/kg.

Cathode Metal Composition	Pros	Cons
Lithium nickel manganese cobalt (NMC)  	• High energy density • Increasingly being optimised to achieve lower cobalt proportions, thus mitigating supply chain concerns and lowering costs	• Reliance on cobalt • Poor thermal performance and safety

Applications	Major Developments
• Current chemistry of choice for EVs	• Industry players (LG Chem, Samsung SDI, etc.) expect to move to high energy density NMC 811 from currently popular NMC 532/ NMC 611 as price premiums decline. • GODI India reported the first batch of domestically manufactured NMC 21700 cells in January 2022.[13]

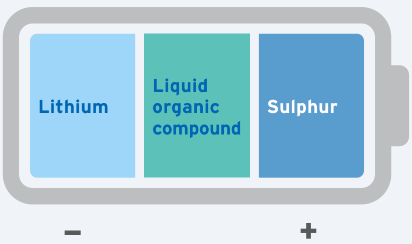
Anode Metal Composition	Pros	Cons
Lithium titanate oxide (LTO)[14] 	• Extremely long cycle life (~7,000 cycles) • Excellent thermal management and safety • Fast charge/discharge capabilities	• Low energy density • Higher costs

Applications	Major Developments
• Used in stationary grid storage • Used in specific applications, such as medical devices	• Leclanché, one of the world's leading energy storage solutions companies, has deployed 100 MWh of stationary storage projects with LTO batteries around the world.[15]

Advanced Lithium-Ion Batteries

LiBs are witnessing rapid growth in this decade spurred by the global transition in the mobility and power sector. As adoption of LiBs goes mainstream, a large number of startups and established battery manufacturers are developing advanced LiBs with improved performance and lower costs. These advanced LiBs have identified new manufacturing processes, cell design factors, and battery components to enhance the performance and efficiency of legacy LiBs. Advanced LiBs will play a key role in accelerating further uptake of LiBs globally. Leading advanced battery technologies are covered in Exhibit 4.

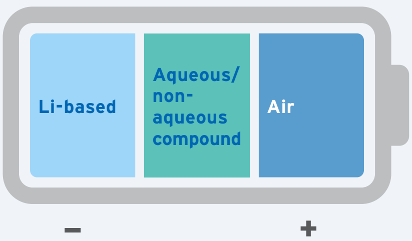
Exhibit 4 Advanced Lithium-Ion Batteries

Cell Schematic	Pros	Cons
Lithium sulphur  	• Higher specific energy and power discharge compared with conventional LiBs • High tolerance for extreme temperatures • Uses low-cost and easily disposable input material	• Low cycle life and longevity

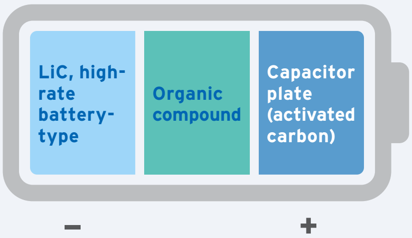
Applications	Major Developments
• Truck and bus electrification	• Industry expects LiS technology evolution for specialist, high-performance applications. • Research groups at Monash University and University of Michigan have reported advancements at laboratory scale in membrane/interlayer materials that can allow higher cycle life.[16]

Cell Schematic	Pros	Cons
Solid state 	• High thermal and impact safety because liquid electrolyte is replaced by a solid • Reduced dendrite growth issues extend service lifetime • High specific energy and low cost	• Cycle life highly dependent on specific anode-cathode mix (currently less than 1,000 cycles) • Not commercially viable currently; expected to reach mass market in 3–5 years

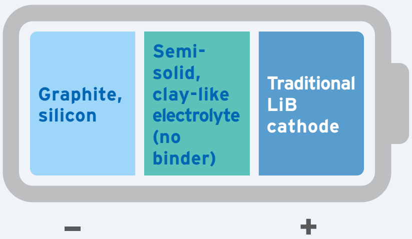
Applications	Major Developments
• Long-range EVs	• Samsung SDI announced the construction of a solid-state pilot line in South Korea; Nissan plans to mass-produce proprietary solid-state batteries by 2028 at $75/kWh pack targets.[17] • Solid Power is already producing 20 Ah solid-state batteries in low-volume batches.[18] • Volkswagen may be planning for EVs with solid-state batteries as soon as 2025, using QuantumScape's technology.[19]

Cell Schematic	Pros	Cons
Lithium air 	• Very high theoretical energy density • Uses abundant, low-cost materials for electrodes, offering lower bill of materials	• Technology still in R&D stage, currently limited by low efficiency and poor cycle life

Applications	Major Developments
• Residential storage, EVs	• Technology is still in R&D phase (advanced materials research)

Cell Schematic	Pros	Cons
Lithium carbon 	• Combines benefits of traditional LiBs with capacitors—good energy/power density and fast recharging • Promises low carbon footprint • Low cost, relatively abundant materials • Not susceptible to thermal runaway;[iv] does not need external cooling system	• Technology in very early stage, with limited number of makers

Applications	Major Developments
• EVs (especially 2-/3-wheelers) where fast charging can add value	• Allotrope Energy announced this technology for long-range and fast-charging use in last-mile delivery segment (electric 2-wheelers) in partnership with Mahle Powertrain.[20]

Cell Schematic	Pros	Cons
Semi-solid 	• Design eliminates the need for binder material, making the cell cheaper and lightweight • Storage capacity not limited by battery size (as in flow batteries) • Promises safer performance than incumbent battery technologies	• Technology not expected to be commercialised before 2025 • Currently faces issues with electrode separators, R&D in solid electrolyte material with sufficient electrical conductivity

Applications	Major Developments
• Can be tailored for specific applications (e.g., stationary storage, EVs)	• 24M announced the advanced semi-solid manufacturing process in 2015 and has since struck strategic partnerships with Kyocera (residential storage solutions) and Volkswagen, as well as Lucas TVS to set up production capacity in India.[21]

Anode Electrolyte Cathode

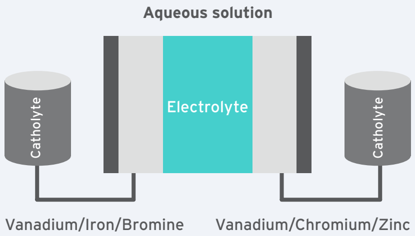
Other Emerging Technologies

Emerging technologies are those that manufacturers are investing in at commercial scale to fill the expected boom in battery demand through 2030. Though some of these technologies have existed for many years, recent advancements have improved performance and lowered cost to make them suitable for commercial deployment, and they represent a substantial innovation compared with lead-acid, nickel metal hydride, and other older battery technologies.

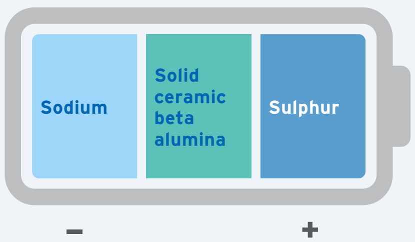
There is a need for developing other emerging technologies for India, as incumbent LiB chemistries rely heavily on scarce minerals such as lithium, cobalt, nickel, and graphite. India has negligible natural reserves of these materials and has minimal control over the supply chain. Heavy reliance on importations, of either minerals or cells, creates an energy security risk that could hinder successful economic development of both EVs and renewable energy. Efforts to develop domestic cell manufacturing capacity will require substantial investments in innovative technologies that either capitalise on resources abundant in India, minimise scarce resources, or enable successful implementation of circular economic principles through reuse and recycling.

Alternative and advanced cell chemistries will be vital for India's growing storage needs. These include technologies that maximise the use of resources abundant in India, such as sodium ion, aluminium air, liquid metals, and zinc hybrid (see Exhibit 5).

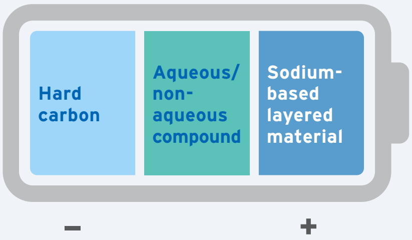
Exhibit 5 Other Emerging Technologies

Cell Schematic	Pros	Cons
Flow battery  	• Offers very long cycle life because anolyte and catholyte are stored in external tanks • High power and voltage delivery performance	• Low specific energy • Requires special housing for thermal safety • High system costs currently

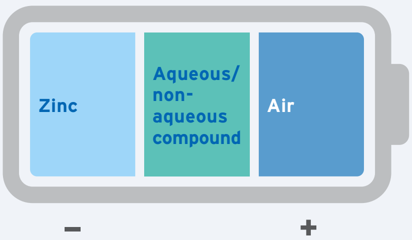
Applications	Major Developments
• Long-duration storage; typically used for stationary applications such as power backup (replacing diesel generators, transmission and distribution upgrades, etc.)	• ESS Inc. announced a deal in fall 2021 to supply 2 GWh of iron flow batteries to utilities through the US,[22] and has begun operations to sell iron flow batteries in Europe. • VFlow Technologies has announced two trial projects to use vanadium redox flow batteries to support EV charging in South Korea and Australia.[23]

Cell Schematic	Pros	Cons
Sodium sulphur  	• Very high cycle life • Good specific energy • Low input material costs; cost competitive with traditional LiBs • Uses environmentally benign materials	• High temperatures required for operation raise safety concerns and require special housing • Currently high system costs

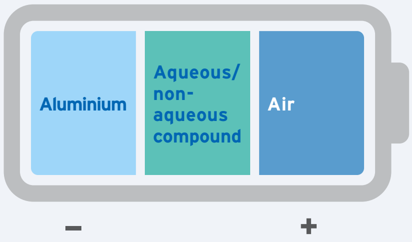
Applications	Major Developments
• Long-duration storage; grid support applications	• NGK Insulators already supplies commercial sodium-sulphur batteries for grid-scale storage; commissioned a long-duration storage test project in 2021 with BASF in Belgium.[24] • Material research for advanced electrolytes that inhibit dendrite growth is ongoing at University of Texas in Austin.[25]

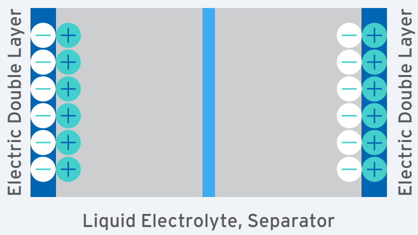
Cell Schematic	Pros	Cons
Sodium ion  	• Low material cost for sodium, more abundant and sustainably sourced • Allows easy and safe transport without loss of performance • Low tendency for dendrite growth on charging	• Currently in initial commercialisation phase, has not achieved scale • Relatively lower energy density and cycle life performance

Applications	Major Developments
• Grid-scale storage	• Reliance New Energy Solar announced acquisition of Faradion Ltd., a UK-based battery maker specialising in sodium-ion technology; it plans to use the technology for a domestic manufacturing plant in Gujarat.[26] • CATL announced first-gen sodium-ion battery in 2021 which can offer up to 160 Wh/kg energy density and fast charging; aims at target 200 Wh/kg by 2023.[27]

Cell Schematic	Pros	Cons
Zinc air  	• High theoretical energy density • Higher safety performance compared with incumbent LiBs • Low-cost materials for the electrodes allow lower overall manufacturing cost	• Technology has not reached mass market penetration; currently expensive to manufacture rechargeable zinc-air batteries • India has limited zinc reserves

Applications	Major Developments
• Small consumer electronics • Potential use in long-duration storage	• Technology still in R&D phase (advanced materials research)

<table>
<tr><th>Cell Schematic</th><th>Pros</th><th>Cons</th></tr>
<tr><td>Aluminium air
</td><td>• High theoretical energy density, lightweight
• Easily recyclable cell raw material
• Not susceptible to thermal runaway
• India has abundant aluminium reserves</td><td>• Technology still in early R&D stage
• Typically nonrechargeable, so battery replacement stations need to be built out if the technology achieves commercialisation</td></tr>
<tr><th>Applications</th><th colspan="2">Major Developments</th></tr>
<tr><td>• Long-range EVs and unmanned air vehicles (UAVs)</td><td colspan="2">• Technology still in R&D phase (advanced materials research)</td></tr>
</table>

<table>
<tr><th>Cell Schematic</th><th>Pros</th><th>Cons</th></tr>
<tr><td>Supercapacitors
</td><td>• Very high cycle life
• Good specific energy
• Low input material costs; cost competitive with traditional LiBs
• Uses environmentally benign materials</td><td>• High temperatures required for operation raise safety concerns and require special housing
• Currently high system costs</td></tr>
<tr><th>Applications</th><th colspan="2">Major Developments</th></tr>
<tr><td>• Fast-response grid support applications
• Medical devices and consumer electronics</td><td colspan="2">• Researchers at companies are developing different materials, such as various carbon materials, mixed-metal oxides, and conducting polymers for supercapacitor electrodes. Advances in carbon-based materials, namely graphene, can increase the energy density to nearly the level of batteries.[28]</td></tr>
</table>

Anode | Electrolyte | Cathode

It is important for cell and pack manufacturers to understand the specific needs of their market and adapt as global technology and applications change over time, moving in the direction of higher-performing and lower-cost advanced batteries.

Using the technology metrics recommended in this report allows for market forces to raise the minimum threshold of battery performance required to meet domestic demand and also compete in global markets.

Box 1: Advanced Lead-Acid Batteries

Lead-acid batteries have been the most prevalent storage technology across the globe over the past few decades. They are used in applications such as automotive starter batteries and grid-scale storage. Despite the head start and maturity of the technology, issues with charging rate and cell degradation (leading to low cycle life) make these batteries unfavourable for use in EVs and grid energy storage. Recent advances aim to address these issues and make lead acid competitive with other commercially available chemistries.

Key focus areas for improving the performance of lead-acid batteries are increasing energy density using high-energy carbon electrodes, using advanced electrolytes to address acid settling issues (which reduce battery service life), and even developing hybrid capacitor-pair electrodes that can increase the power capacity. One of the key performance targets globally is to increase charging performance by five times, which could make these advanced lead-acid batteries attractive for use in micro-hybrid EVs and Uninterruptible Power Supply (UPS) applications.[29]

Battery Technology Roadmap and Applications

The technology landscape for ACC batteries is evolving rapidly; multiple emerging chemistries are heading towards commercialisation this decade. This transition has significant implications for the existing battery ecosystem, as several commercial mainstream battery technologies might become obsolete and lose market share to emerging technologies that offer better economic value and improved performance.

The matrix in Exhibit 6 lays out the existing battery technology roadmap on two important performance parameters: cycle life and energy density. The matrix seems to advance in a regular fashion—moving from top left to bottom right, batteries become more advanced, with higher cycle life and greater specific energy. The battery technology landscape projected to 2030 is guided by expert interviews and technology assessments; it shows when today's emerging technologies can achieve their expected potential performance and ramp up their manufacturing capabilities at a commercial scale.

Exhibit 6 Current and Expected Performance Characteristics of Commercial Batteries

Technology Landscape in 2022

		Energy Density (Wh/kg)				
		≥ 50	≥ 125	≥ 200	≥ 275	≥ 350
Cycle Life	≥ 1,000	Lead Acid	LMO	LCO	NCA, NMC 622, 811	
	≥ 2,000		LFP, Sodium-Ion	NMC 111, 532		
	≥ 4,000		LTO			
	≥ 10,000	Advanced Redox				

Expected Technology Landscape in 2030

		Energy Density (Wh/kg)				
		≥ 50	≥ 125	≥ 200	≥ 275	≥ 350
Cycle Life	≥ 1,000	Lead Acid	LMO	LCO	NMC, NCA	Solid State, Al-Air, Li-Air
	≥ 2,000			LFP, Sodium-Ion		Lithium-Sulphur
	≥ 4,000				Sodium-Sulphur	
	≥ 10,000	Advanced Redox	Lithium-Carbon, LTO		Semi-Solid	Zn-Air

A similar matrix has been adopted in the recently announced ACC PLI scheme by the GoI, as indicated in Exhibit 7. In this matrix, advanced battery technologies that fall in the categories shaded in blue are eligible to receive financial incentives, as these technologies are still at a nascent stage and in need of support to scale up their manufacturing. Batteries that fall in the categories shaded in white are not expected to receive a subsidy, as they would not qualify as 'advanced'. These battery chemistries are already manufactured at scale and are profitable. The intention of the matrix in the context of the PLI scheme is to incentivise the industry to move towards batteries of higher energy density and cycle life and, in the process, move the industry towards global technological leadership.

Exhibit 7 Subsidy Matrix from the ACC PLI Scheme from the GoI

Energy Density (Wh/Kg)						
Rs. Per kWh		**≥ 50**	**≥ 125**	**≥ 200**	**≥ 275**	**≥ 350**
Cycle Life	≥ 1,000	–	–	–	A	A*(1.2)
	≥ 2,000	–	–	A	A*(1.2)	A*(1.2^2)
	≥ 4,000	–	A	A*(1.2)	A*(1.2^2)	A*(1.2^3)
	≥ 10,000	A	A*(1.2)	A*(1.2^2)	A*(1.2^3)	A*(1.2^4)

Note: It is expressly clarified that the ACCs manufactured shall have a minimum technical specification with respect to energy density and cycle life as provided in the shaded regions.

A = amount of subsidy indicated in the financial bid

Though many of the batteries subsidised in this matrix (for example, a 350 Wh/kg, 10,000-cycle battery) are not currently viable, the ACC PLI scheme aims to provide encouragement for commercialisation of batteries currently in R&D and to push towards batteries with greater specifications than what is currently available in the market. Many of these technologies have not been brought to scale, but their early-stage economics for constructing a 5 GWh manufacturing facility might improve with a subsidy incentive. In this way, India will be pushing towards the future of battery manufacturing. Some of these advanced batteries may, in the long term, prove to be cheaper than existing ones. By utilising alternative mineral blends, manufacturing techniques, and stable chemistries, these batteries are expected to provide greater performance at lower cost. Beyond that, a higher energy density and greater cycle life also promote better material efficiency, as lesser battery material will be required for storing the same quantum of energy while lasting longer.

These batteries will have uses across a wide swath of applications; some key markets are summarised in Exhibit 8. Different sets of battery specifications are more viable depending on the use case. For example, a battery used to provide stationary storage for a power grid must be able to endure many cycles before replacement, but its energy density is almost irrelevant because it will not be used in any mobile application. Simultaneously, a vehicle would have little need for a 10,000-cycle battery (which would likely outlast the vehicle itself), but energy density is a key consideration in not having the battery outweigh the rest of the vehicle. In general, the market will determine which features are most relevant for specific use cases and how much different manufacturers are willing to pay to gain higher performance in certain areas.

Exhibit 8 Expected Use Cases for Battery Technologies

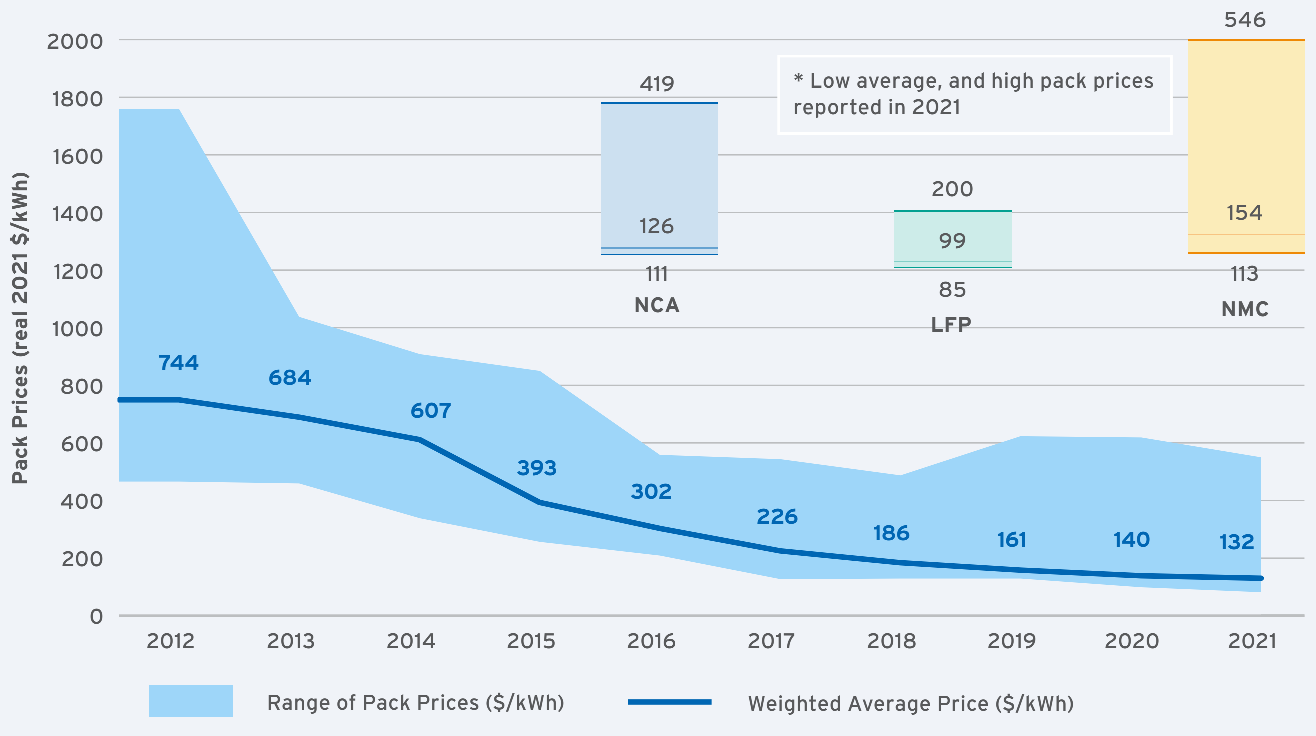
Specific Energy (Wh/kg)						
Expected Applications		**≥ 50**	**≥ 125**	**≥ 200**	**≥ 275**	**≥ 350**
Cycle Life	≥ 1,000	Backup Power	2W/3W EVs	Consumer electronics		
	≥ 2,000	Rooftop Photovoltaic (PV)	Consumer Electronics	4W EVs High-Performance 2W/3W EVs Buses Consumer Electronics		
	≥ 4,000	Microgrids	Medical Devices	High-Performance EVs Electric Planes Drones		
	≥ 10,000	Frequency Regulation Renewable Integration				

Battery Pricing Analysis

Advanced battery prices have decreased by more than 89% since 2010, thanks to a massive ramp-up in global production capacity (economies of scale) and industry- and government-funded R&D in battery materials and chemistry. At the same time, prices of key mineral components have been volatile as chemistries shift and demand adjusts (see Exhibit 11 for recent trends in battery metal prices).

It is important to note, however, that battery prices cover a wide range, depending on technology and manufacturer (see Exhibit 9). Batteries will continue to have a broad range of costs, due to such factors as material costs and manufacturing scale. Breakthroughs in technologies such as solid-state batteries are expected to lower overall market costs, as are changes in minerals used and mineral pricing. For example, a shift to NMC 811 chemistry would reduce the amount of expensive cobalt used in battery manufacturing. As a side effect, cobalt demand would drop, and cobalt mineral prices might drop as well.

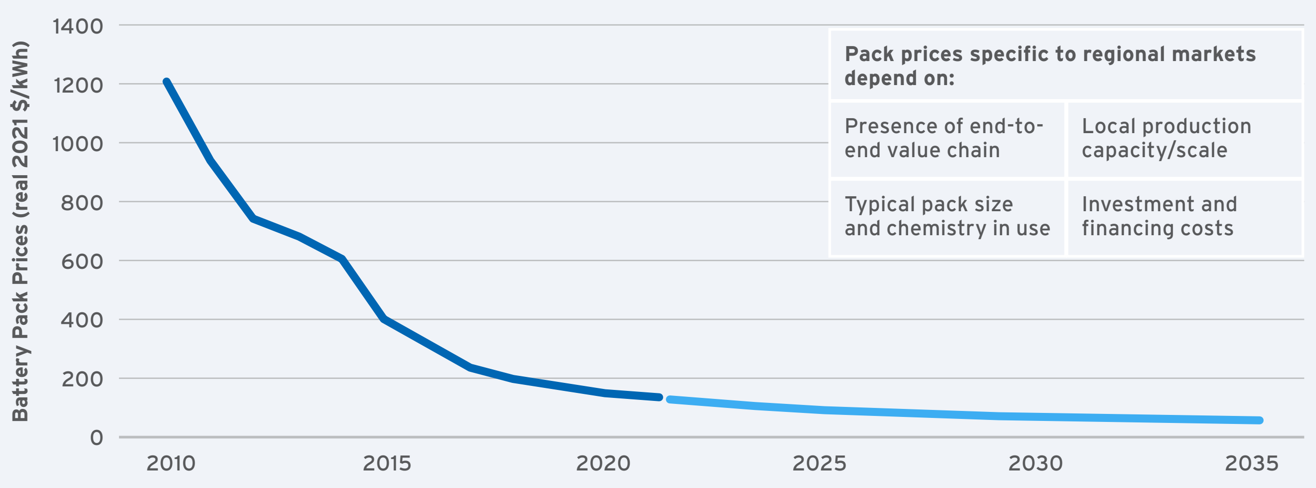
Exhibit 9 Battery Pack Price Range over Time[30]



Note: NMC here refers to all chemistry variants of the NMC battery type currently in use.

Global battery prices are expected to reach $59/kWh by 2030, representing an average year-on-year decline of 8.7% (CAGR) between 2019 and 2030 (see Exhibit 10).[31] These are weighted values from cell makers and nations with existing large production capacity and a certain degree of vertical integration, such as in China. Currently, battery pack prices are 40%–60% higher globally than they are in China.[32] India can also be expected to see higher pack prices, at least in the short run, due to its relatively smaller manufacturing base and reliance on imports for raw materials.

Exhibit 10 Battery Pack Price Range over Time[33]

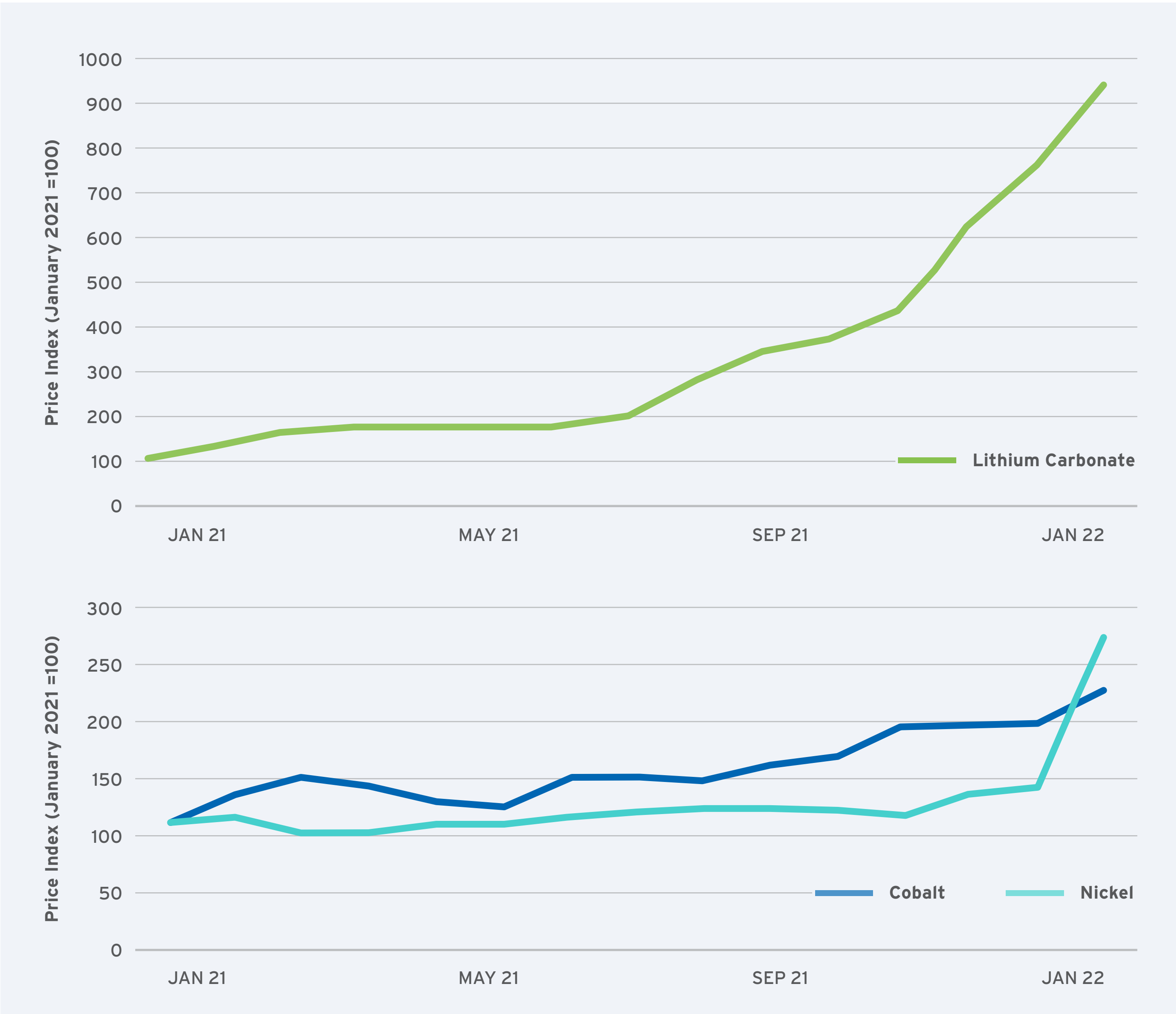


Mineral prices are the primary driver behind battery pricing, so a shift in either chemistry or mineral pricing has wide-ranging effects on the market. Many solid-state battery manufacturers anticipate prices under $50/kWh when their technology approaches commercial status, whereas most NMC manufacturers see prices of under $80/kWh as difficult to reach because of the limits of required mineral pricing.[34] These batteries have different specifications, price points, and uses—the storage market will likely be filled with products occupying different niches and price points.

Factors That Can Dictate Future Battery Prices

A recent surge in metal prices (such as for copper, nickel, cobalt, and lithium), attributed to a global supply crunch, has started to affect the near-term cost of batteries. As seen in Exhibit 11, lithium carbonate prices and nickel prices have increased to nearly 900% and over 220%, respectively, and cobalt prices are up by more than 250% over the price level in January 2021. The average battery pack price is expected to rise by 2% over current prices owing to the spike in metal costs.[35] This is the first such reversal in cost decline since 2010. Because raw materials make up a large share of the overall cost of a battery, the higher costs for battery manufacturers are passed downstream to end consumers, which can potentially affect the adoption of electric vehicles and hurt the economics of coupling battery storage with renewable energy assets.

Exhibit 11 Price Volatility for Key Battery Metals, January 2021–Present[36]



The precipitous decline in the cost of LiBs over the past decade was a result of huge improvements in battery chemistry, the use of advanced materials, and the realisation of economies of scale. Barring material price spikes, the future price trajectory of batteries will depend on the following factors:

Performance Improvements

Higher power and energy density can shrink the size and quantum of batteries needed, which can improve the unit economics and performance of consumer electronics and electric vehicles.

Improved battery life can lead to lower degradation and fewer replacements, which can improve the economics of coupling batteries with renewable energy assets and minimize the overall levelised cost of electricity offered by these assets.

Material Efficiency

Given the growing demand for batteries, the requirement for key metals such as lithium, cobalt, nickel, and copper continues to grow. Battery prices are exposed to price volatilities associated with rare earth metals, many of which are concentrated in only a few countries.

Battery technologies that minimize the use of rare earth metals and utilize abundantly available metals (such as sodium and aluminium) can help shrink battery prices and minimize future cost uncertainties associated with rare metals supply shocks.

Unlocking Second Life of Batteries

Batteries reach the end of their life when their performance falls below 70% or 80% of the initial nameplate storage capacity and they are no longer capable of meeting the end-use application.

Although the battery can no longer meet its original performance requirements, the battery still has life remaining, and it can be repurposed for a second-life application. Unlocking the second-life batteries for stationary storage applications can enable the maximum value extraction of batteries before their eventual end-of-life recycling or disposal.

Temperature and Safety Considerations

LiB fires and accidents, both at manufacturing sites and in the field, have emerged along with the growth of the market and increased focus on NMC technologies (which have had the most frequent temperature control problems). South Korean manufacturers have experienced more than 28 fires at storage facilities since 2017, and all major airlines have prohibited power banks from checked baggage after thermal runaway incidents witnessed with mobile phones.[37]

Major EV makers have also experienced troubles with battery-related fires; for example, General Motors issued a full recall of its Chevrolet Bolt model in 2021, incurring nearly $2 billion in costs (of which the majority, about $1.9 billion, was borne by pack supplier LG Energy Solution).[38] LG faced a similar issue in the Indian market recently, when Hyundai Motors was forced to recall nearly 76,000 sold EVs in response to battery fires.[39]

LiB fires are associated with flammable organic electrolyte coupled with high specific energy of the batteries. Apart from active and passive thermal management, the battery manufacturer can increase safety levels through high-quality manufacturing processes that minimise imperfections and contaminants that often lead to thermal runaway. In many cases, cell manufacturers will supply cells only to approved pack assemblers that are using an approved safety circuit and that have a track record of safe pack manufacturing. Ultimately, the accountability for safe cell and pack manufacturing falls on the auto original equipment manufacturers and consumer electronics companies that integrate packs into their products. These stakeholders will be responsible for the damages associated with a product recall. India can ensure that safe batteries enter the market by enforcing safety standards and holding manufacturers accountable for fire or other dangerous incidents.

Thermal runaway has long been an issue with LiBs across a range of applications; it typically requires complex active thermal management systems to minimise the risk of violent energy release events. Global manufacturers are investing in R&D efforts to improve the safety of lithium-ion technologies, and many of the problems have been addressed via quality control across the supply chain and use of active thermal management within battery packs. Numerous global standards exist to test the heat resistance of battery packs, and these should be enforced in India.

For example, International Electrotechnical Commission Standard 62133 requires batteries to be tested in increments of 5 Celsius degrees until thermal runaway or other catastrophic failure.[40] India has already introduced the AIS 156 standards for EV battery testing, which is among the most stringent standards globally and includes thermal shock tests, fire resistance, external short-circuit tests, and hydrogen emissions checks.[41] India can use this standard and other existing global standards to ensure that manufactured products meet market conditions and address safety concerns.

Box 2: Temperature Impact on Testing

Cell temperature is a main contributor to battery degradation,[42] and this is particularly relevant in India given the high environmental temperature ranges. At high temperatures, the active chemicals in a battery begin to break down. This can cause a range of problems in LiB performance. The majority of these issues have been recorded with NMC batteries, which are prevalent on the EV market. However, temperature likely affects LFP or other LiB types as well. These effects include:

- Even when stored and not subject to use, an NMC battery stored for one year at 40°C will drop to 65% of its full capacity.[43]
- Temperatures above 35°C can reduce the range of EVs with NMC batteries by up to 4%.[44]
- The time and electricity required to charge a battery is higher in extreme heat conditions (45°C and above) because of reduced battery performance.[45]

- Low temperatures (0°C and below) reduce the power and energy capabilities of battery cells. The capacity of an LiB at –20°C is roughly 60% of its capacity at 25°C.

Despite this extreme temperature influence, most battery cycle life is listed at room temperature. Whereas battery testing standards from IEC and ANSI (such as IEC 61960–1:2000 or ANSI C18.3M) do require testing at higher temperatures for performance and safety, the standard for battery cycle life reporting is in the 20°C–25°C performance range. This is good for manufacturers, as they can display the operation of their batteries under peak conditions, but it may not be optimal for India. Hence, establishing Indian standards for cycle life reporting should be crucial. This may involve either listing temperature at two levels (for example, cycle life at 20°C and 40°C) or choosing one relevant temperature. This will ensure that a battery manufacturer lists its product cycle life in a manner relevant to the operating conditions in India, rather than in pure laboratory conditions.

Vehicle manufacturers or other users might choose to add cooling systems or other temperature control equipment if the technology's strengths overcome the added costs. Battery thermal management may be needed for EVs with extended range to keep the cells in the desired temperature range, minimise cell-to-cell temperature variations, prevent the battery from going above or below acceptable limits, and maximise useful energy from cells and pack.

Recyclability

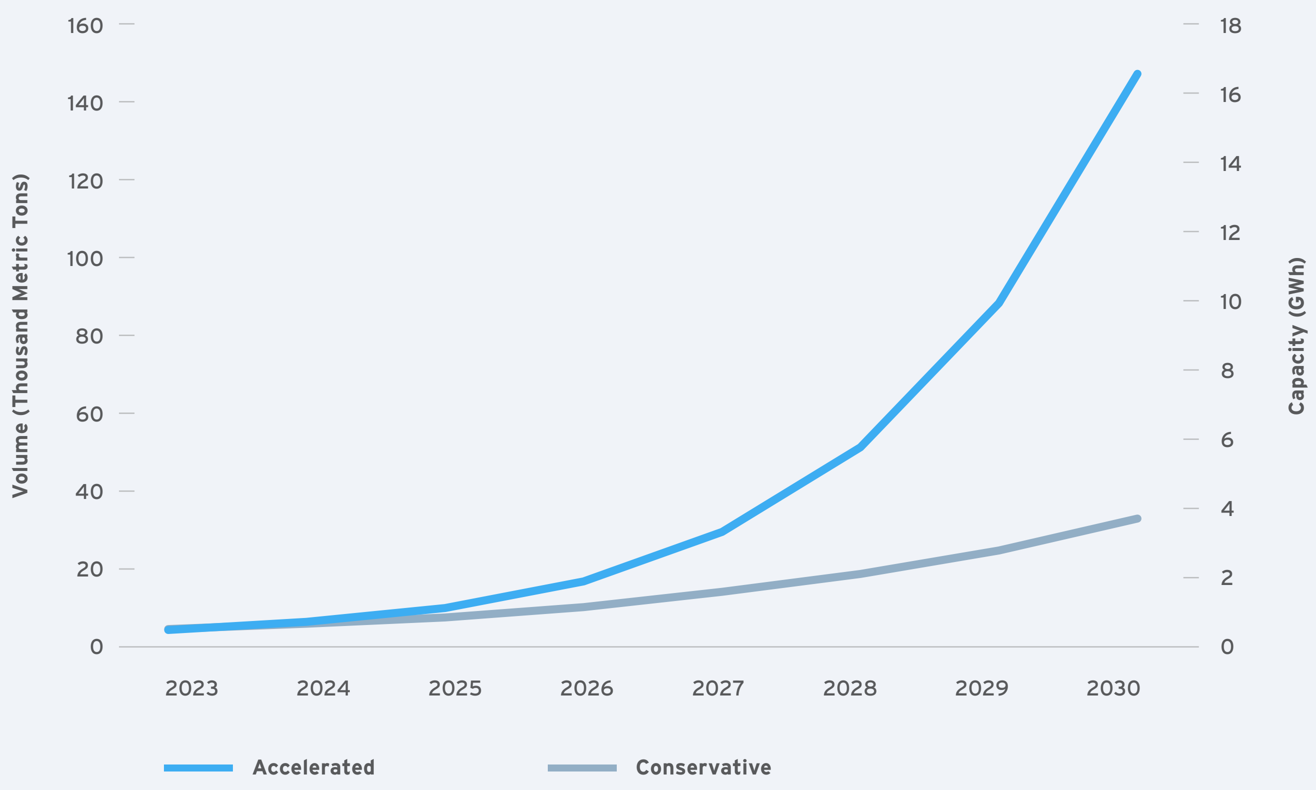
Battery recycling is a critical technology area for India owing to the domestic shortage of certain materials for today's lithium batteries. To ensure a level of resilience, India can develop capabilities to reuse the majority of its battery materials, thereby limiting imports of expensive, price-volatile ingredients. Battery recycling will support India in end-to-end manufacturing of batteries (ensuring less waste, avoiding environmental pollution, and reducing costs) while also developing a domestic reserve of important minerals. The first generation of battery imports can be retained as a domestic resource, as the cells imported could have a second use in future generations of Indian batteries. Prior to being recycled, they can serve a profitable 'afterlife' in the secondary market of stationary applications, for which they are well suited even after losing a fifth of their capacity (which loss makes them less fit for mobile uses).[46]

Recycling of batteries has become a worldwide concern; the great variety of chemistries among LiBs has made mass scaling of battery recycling difficult, and diverse new technologies are poised to enter the market. The United States and China have recently created centres to study recycling of batteries, as well as prizes for breakthroughs in recycling technology.[47] However, no country has a strong policy yet given the nascent status of the field.

Annual global demand for batteries is expected to surpass 2,000 GWh by 2030—perhaps surpass it substantially, if current accelerating trends continue—signalling that thousands of GWh of batteries will need disposal at their end of life. As batteries shift towards lower-cost materials, the economic feasibility of recycling to obtain cobalt and other valuable minerals may disappear. Recycling, therefore, must become an environmental requirement in order to retain supplies of valuable minerals and avoid a disposal and environmental leakage crisis. Given this need for recycling, India has begun drafting a policy for LiBs from electric vehicles. It will establish an extended producer responsibility programme covering battery stakeholders, including manufacturers, producers, and importers. Covered entities will be required to form a producer responsibility organisation and submit a product management plan to be authorised by the regulating authority.

By 2030, approximately 38 GWh cumulatively of LiBs will be reaching the end of their usable life from the transportation sector in India (see Exhibit 12).[48] EV batteries reach end of life at 70–80% of nameplate capacity but still hold inherent value for other uses, as well as the values of the materials that could be recovered. Reuse policies could effectively mitigate the need for new, more expensive batteries in the stationary storage system, potentially meeting 5% of the batteries required to meet the 2030 target of 500 GW of non-fossil fuel installed capacity. Should an effective battery recycling policy be established, recycled EV LiBs could provide between 5% and 20% of the minerals required to meet domestic manufacturing demand by 2030. This includes high-value materials with little to no domestic reserves and volatile market prices, such as lithium, nickel, cobalt, and graphite.

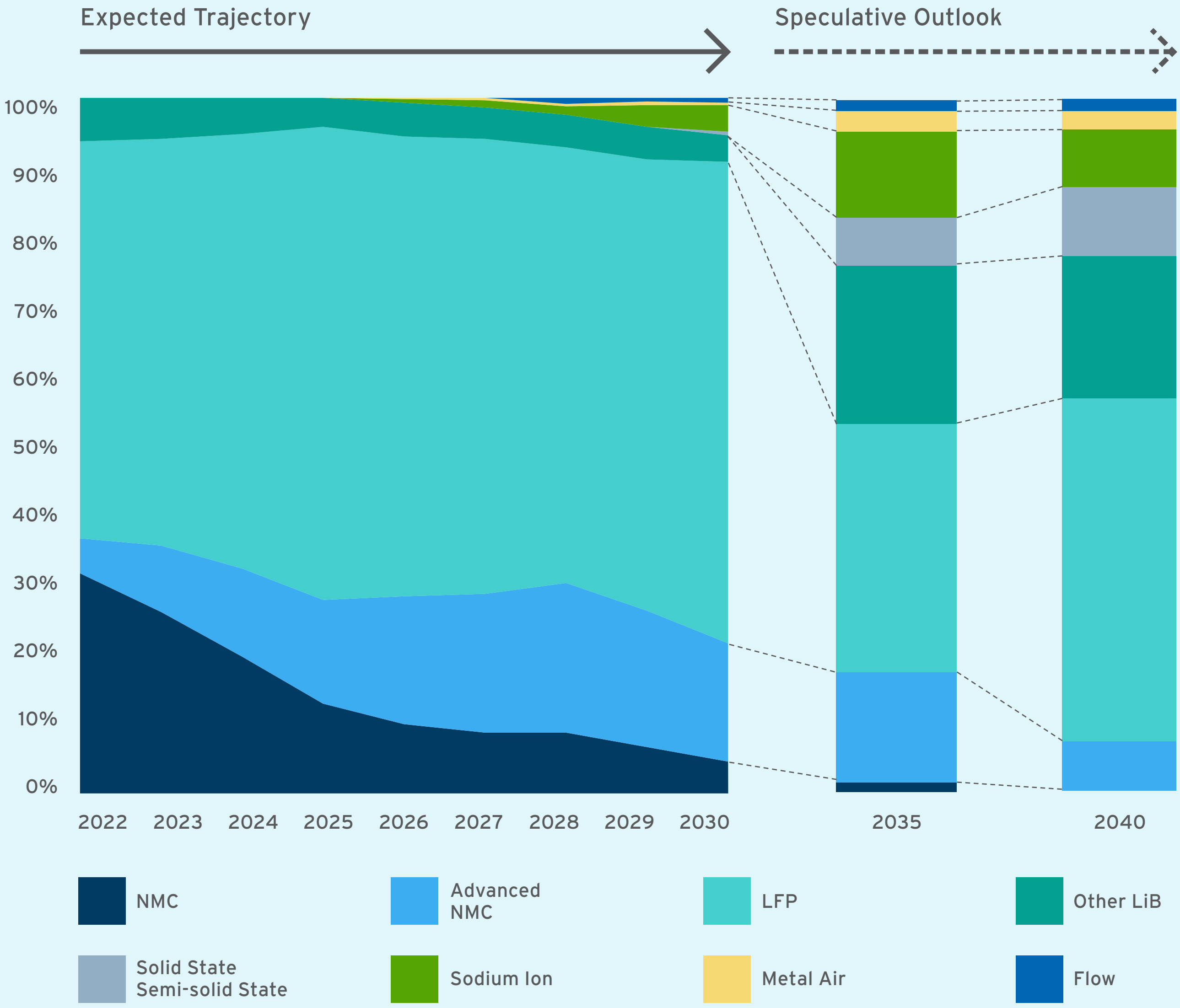
Exhibit 12 Outlook for Annual EV LiBs Retirement



Box 3: How Battery Chemistries Might Evolve in India

Assessing battery technologies that can dominate in the long term is a speculative exercise given the evolving situation on performance, cost, and raw material constraints. Whereas the near-term outlook to 2030 can be ascertained with a high degree of confidence, the level of uncertainty rises as the outlook extends into the long term (see Exhibit 13). A few predictions can be made, however: continued dominance of LFP, growth in less cobalt-intensive NMC, and gradual movement towards higher-performance LiBs and non-LiB chemistries.

Exhibit 13 Expected Evolution of Battery Chemistry Mix in India



- '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 955, NMC 442, lithium- and manganese-rich NMC (LMR-NMC), nickel manganese cobalt aluminium (NMCA), and cobalt free (NMx).
- 'LFP' refers to lithium ferro (iron) phosphate.
- 'Other LiB' refers to chemistries containing oxide (LNO, LMO, LNMO, and LCO), as well as advanced lithium chemistries such as lithium sulphur and lithium carbon.
- 'Solid state/semi-solid' refers to chemistries using solid-state or semi-solid electrolytes.
- 'Sodium ion' refers to batteries using sodium ions as the charge carriers.
- 'Metal air' includes both zinc and aluminium air batteries.
- 'Flow' includes iron flow batteries, vanadium redox flow batteries, and zinc-bromine flow batteries.

Of note: LFP batteries have a higher degree of penetration in India than they do globally. Other common chemistries, such as NCA, are absent in India. Views that informed innovative chemistries application in EVs emphasis are energy density, supply chain control, transactions made by major manufacturers, and need for supportive infrastructure. Conventional NMC chemistries are anticipated to be phased out in India because of high requirement for scarce minerals of which India has insufficient natural reserves, and replaced with advanced NMC and other innovative chemistries as they reach commercialisation.

Battery energy storage systems (BESS) demand projections are based on RMI analysis through 2030 and an International Energy Agency accelerated case through 2040. RMI's BESS analysis projects that capacity growth will meet the 500 GW installed non-fossil fuel capacity target by 2030. The BESS chemistry mix prioritises price per installed watt-hour with capacity for innovative chemistries such as flow batteries expected to enter the market a few years after entering other geographies. BESS chemistry mix also accounts for potential second-life utilisation from EV batteries that have reached the end of their usable life for EV applications. Second-life utilisation accounts for chemistries from high-capacity vehicle categories, including passenger and commercial four-wheel vehicles, as well as electric buses.

This projection encompasses both EV and BESS demand. EV demand projections are based on RMI's internal analysis, broken down into two categories: passenger and freight vehicles. Both categories include seven vehicle types. Demand projections are based on anticipated economic growth, cost declines, efficiency improvements, and supportive policy and infrastructure environments. Battery chemistry mix projections for vehicles are based on stakeholder interviews and industry expertise, using Bloomberg New Energy Finance (BNEF) global mix projections adjusted for India's market.

Creating Value in India

Creating Value in India

In the years ahead, energy-related sectors, including electricity, transportation, and associated manufacturing, are likely to be disrupted by ongoing technological advances, new environmental policies, and rapid shifts in competitive economics and business models. India has witnessed similar disruptions in the telecom and solar industries but has been unable to capture the opportunity to become a world leader. The battery market is still nascent, but it is growing and technology is rapidly evolving, suggesting that India could emerge as a global manufacturing hub for advanced energy storage technologies in the coming decade.

The recent PLI scheme for ACC batteries can help the country reach this goal. It provides flexibility in the choice of battery technologies in order to benefit from the immense advances taking place in the technology landscape (rather than focussing exclusively on current technology); this flexibility also helps map local capabilities with various parts of the global value chain. The opportunity is perishable, and the explosive growth in research, commercialisation, and manufacturing suggests that India would benefit from acting with some urgency if it is to position itself as a global player.

Box 4: Lessons from China and South Korea

Creating a successful domestic ecosystem for battery manufacturing requires government support and planning for both the supply and demand ends of the value chain. In the early 2000s, China identified its growing oil dependence and projected vehicle demand and kicked off strategic planning for a shift to new energy vehicles (NEVs).[v] Inclusion of EV technologies, auto drivetrains, and batteries in national roadmaps as early as 2001 guided early investments; between 2001 and 2005, nearly $135 million had been provided in funding to stimulate R&D in plug-in hybrids by Dongfeng, BYD, and other companies, and city-based pilot accelerators for EVs. An initial focus on research and innovation, as well as a comprehensive study of the economics required to motivate a shift to EVs, informed these pilot demonstration programmes. By 2016, China had offered nearly $1.9 billion in subsidies to stimulate EV penetration across various segments and $214 million specifically to fund R&D in battery technologies.[49]

Policies supporting commercialisation of EVs also spurred innovation in the battery industry, because subsidy programmes incentivised higher performance; nearly 10 years of strong subsidy support and pilot programmes for EVs drove the average battery pack capacity higher (from 33 kWh in 2013 to 44 kWh in 2019), contributing to lower average pack prices as domestic firms ramped up production.[50] Long-term supply of battery material was identified as a strategic issue in the national plan, which led to an aggressive push to secure cathode metals from Angola, Chile, and the Democratic Republic of the Congo. This clear strategic vision and alignment in technology, policy, and markets have given China competitive advantage in battery production with a high degree of material security.

South Korea had a similar head start in the rechargeable batteries market, driven by the strong investments in industry R&D for electronics and semiconductors; however, even as local firms such as LG Energy Solution lead the market in battery production, continued import dependence on China for raw materials has become a pressing issue. South Korean manufacturers imported nearly 60%

of their critical battery materials in 2020, spurring makers such as LG Energy Solution and SK Innovation to start exploring secondary supply through recycling.[51]

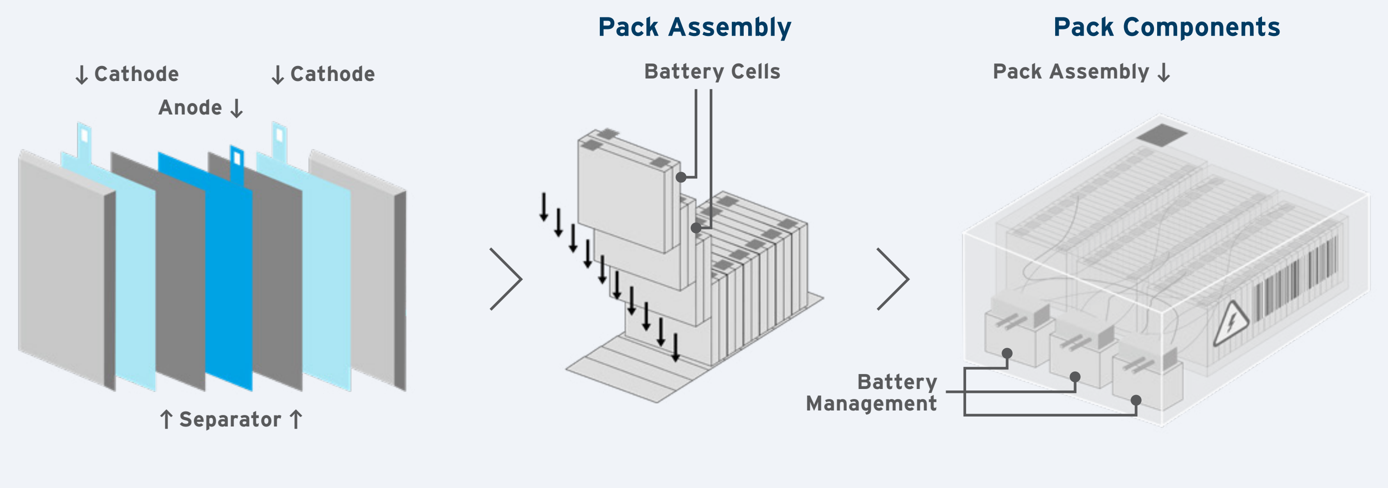
India has the potential to capture domestic value quickly by ramping up local module and pack assembly capability; however, competitiveness in the longer run will require a simultaneous focus on industry R&D investments in next-generation batteries. Even as global innovation efforts serve as a guide for India, leapfrogging towards emerging chemistries (such as sodium ion and metal air) that are expected to gain market share in the future could make India an attractive global manufacturing hub.

An Integrated Manufacturing Process

A modern EV battery has many components beyond its lithium-ion cells. The battery cells (materials plus manufacturing) represent close to 70% of a battery pack's total value, and the cells' assembly into a battery pack ready to insert into a vehicle represents around 30% of the total value.[52] Battery pack manufacturing is already under way in India, and is already a profitable endeavour. In Gujarat, the Suzuki Motor Company is investing $530 million in a production facility for battery packs for the Indian market. This joint venture among Suzuki, Denso, and Toshiba showcases the value of foreign partnerships in bringing manufacturing and intellectual property to India. Other companies and partnerships, including Reliance and Suzuki, have announced multibillion-dollar investments towards domestic battery manufacturing over the next decade.[54] Facilities are growing in order to produce some components for LiBs, such as graphite-grade binder pitch for lithium anodes or separators for battery packs. As India looks to incentivise growth and increase value capture within the country, it should encourage development in new areas, such as cell manufacturing of emerging battery chemistries, in addition to its battery pack manufacturing, which is already profitable and growing.

Aside from true flow or 'redox' batteries, almost all modern and planned batteries have a similar structure and can be broken down into several major components (see Exhibit 14). In the future, more advanced batteries may alter this structure, but most batteries can be subdivided into components detailed below.

Exhibit 14 Battery Component Details

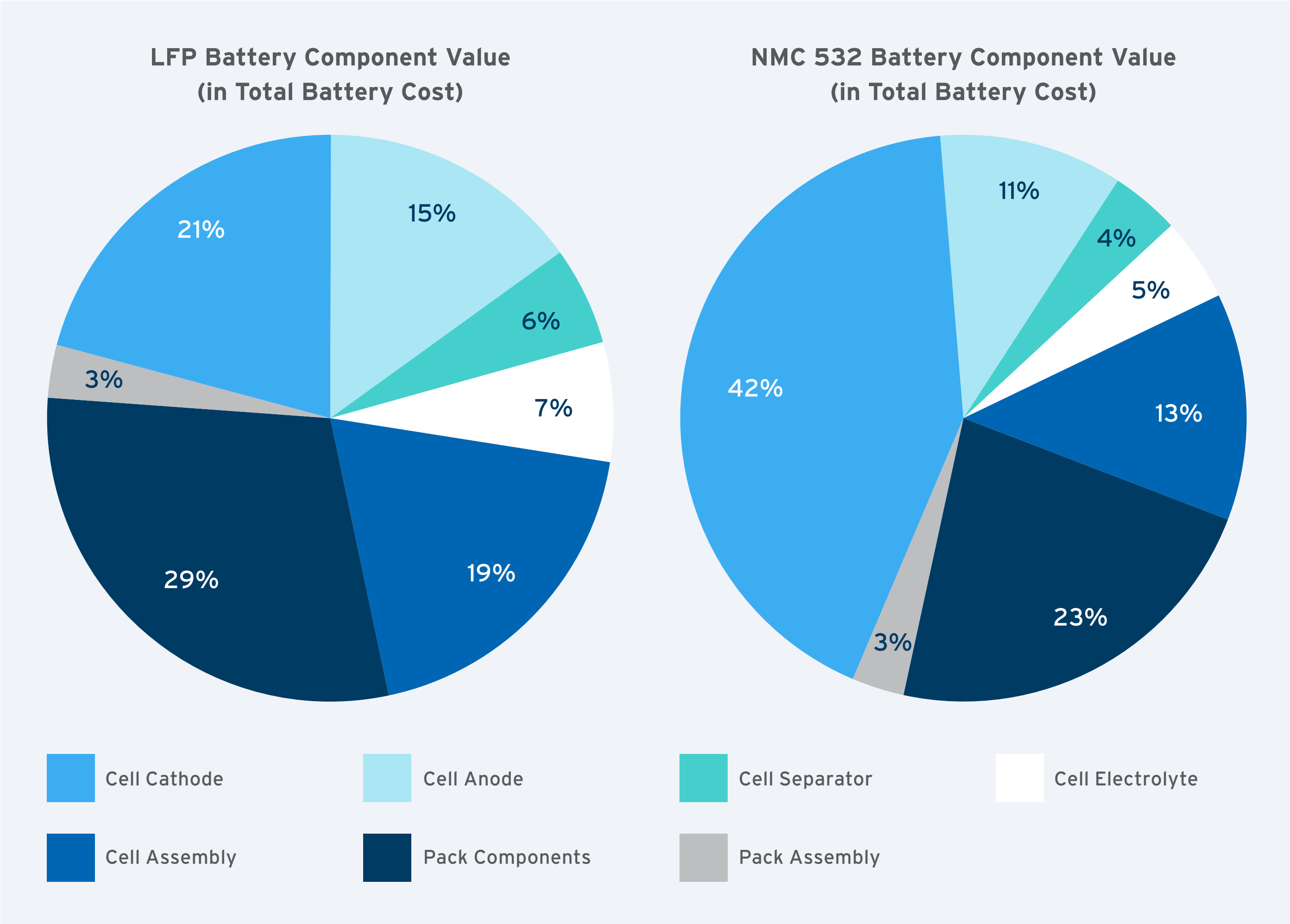


Battery Cell	Pack Assembly	Pack Components
Cell cathode: The positive electrode of a battery accepts electrons during discharge.	**Pack assembly:** A number of cells are combined in a larger housing in order to provide charging and discharging potential to a device and integrate with the device's electrical needs.	**Pack components:** Monitoring and control equipment within a pack assembly adjusts electricity flow or provides interconnectivity with other systems.
Cell anode: The negative electrode of a battery releases electrons during discharge.		
Cell separator: The separator separates the anode from the cathode, forcing electrons to move through the electrical circuit.		
Cell electrolyte: The electrolyte makes ion flow possible.		

The value contribution of different battery components for manufacturing batteries in India is shown in Exhibit 15. Although this graphic provides an understanding of value breakdown, it is neither exhaustive nor universal. It should be noted that integrated battery value can generally be divided (at sale, as opposed to during manufacture) into battery pack and battery cell. India has the resources and expertise to build battery packs and cells and is already building the battery packs. The value breakdowns between NMC and LFP batteries vary owing to the difference in chemistries and raw materials that go into building the cell and the pack, as shown in Exhibit 15.

The value contributions are prone to change as a result of fluctuations in raw material prices shown in Exhibit 11. For example, the value of cathodes is significantly higher in NMC batteries than in LFP batteries because of the recent surge in global prices of nickel, manganese, and cobalt. The spike in raw material costs leads to higher battery costs, which can affect the economics of end-use applications. Hence, battery chemistries that rely on indigenous raw materials allow maximum domestic value capture and are also better insulated from any future supply or cost shocks.

Exhibit 15 LFP and NMC Battery Component Value (in Total Battery Cost[55]



Most next-generation, high-density batteries will use lithium, which is unavailable in India. Therefore, supply chain challenges and resource constraints will persist for the country's ACC domestic manufacturing ecosystem. Because raw materials represent much of batteries' manufacturing cost, access to robust supply networks will be critical.

Measuring Potential Value Capture for Cells in India

Given the current viability of pack manufacturing, the focus of discussions of value capture needs to be specific to cell manufacturing. By fostering domestic cell manufacturing capacity, India is poised to capture over 90% of LFPs' cell value, owing to the greater use of domestically available minerals such as iron oxide, phosphate, and graphite (see Exhibit 16). The remaining 10% of value is attributed to the lithium in the cathode, which India cannot capture because of lack of domestic reserves. This value breakdown varies significantly between LFP and NMC batteries.

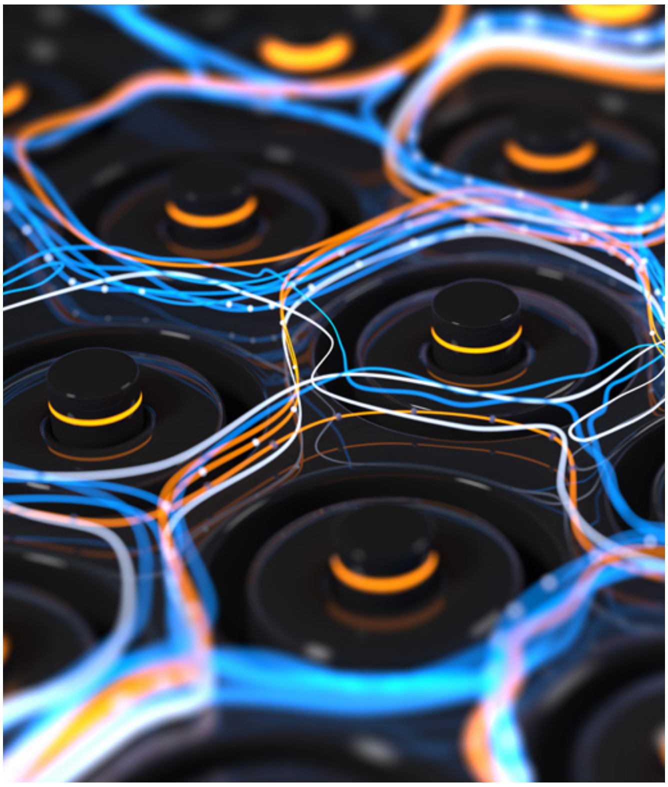
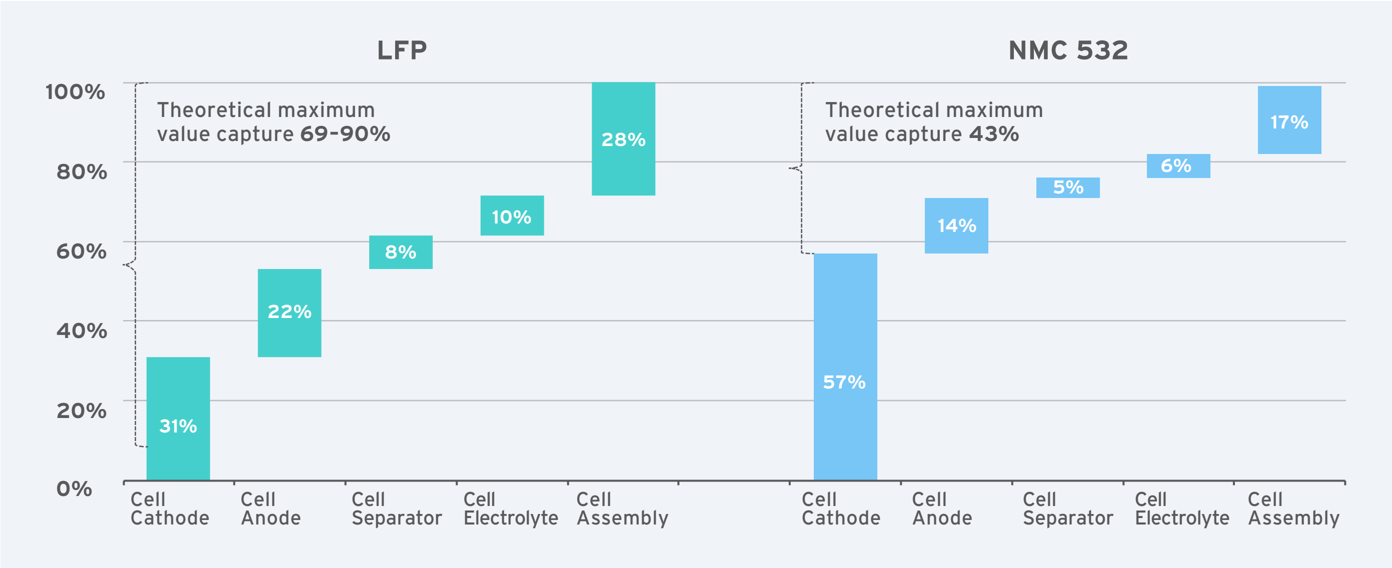


Exhibit 16 NMC and LFP Cell-Only Value Breakdown[56]



NMC batteries have a very expensive cathode, owing to heavy reliance on cobalt and nickel, both of which must be imported because of the lack of domestic reserves. The dependence on imports shrinks the domestic value capture of NMC batteries in India. Given current raw material prices, about 40% of NMC batteries' value capture is possible in India. Any downwards trajectory of material prices will also result in higher potential for domestic value capture.

The Government of India addressed value capture in its recently announced ACC PLI scheme. The scheme stipulates a minimum domestic value creation of 60% within five years. This approach can favour movement towards material efficiency and alternative chemistries that use a higher percentage of domestically available minerals.

Risks Along the Value Chain

As is the case with any new technology, numerous risks are associated with setting up battery manufacturing plants in India. Establishing the entire value chain in India presents a challenge, given the rapidly evolving battery chemistries and the learning curve and investment risks linked with adapting to new technology and manufacturing processes. It is imperative to recognise these risks in advance and devise an optimal strategy to mitigate them in developing a favourable ecosystem for battery manufacturing.

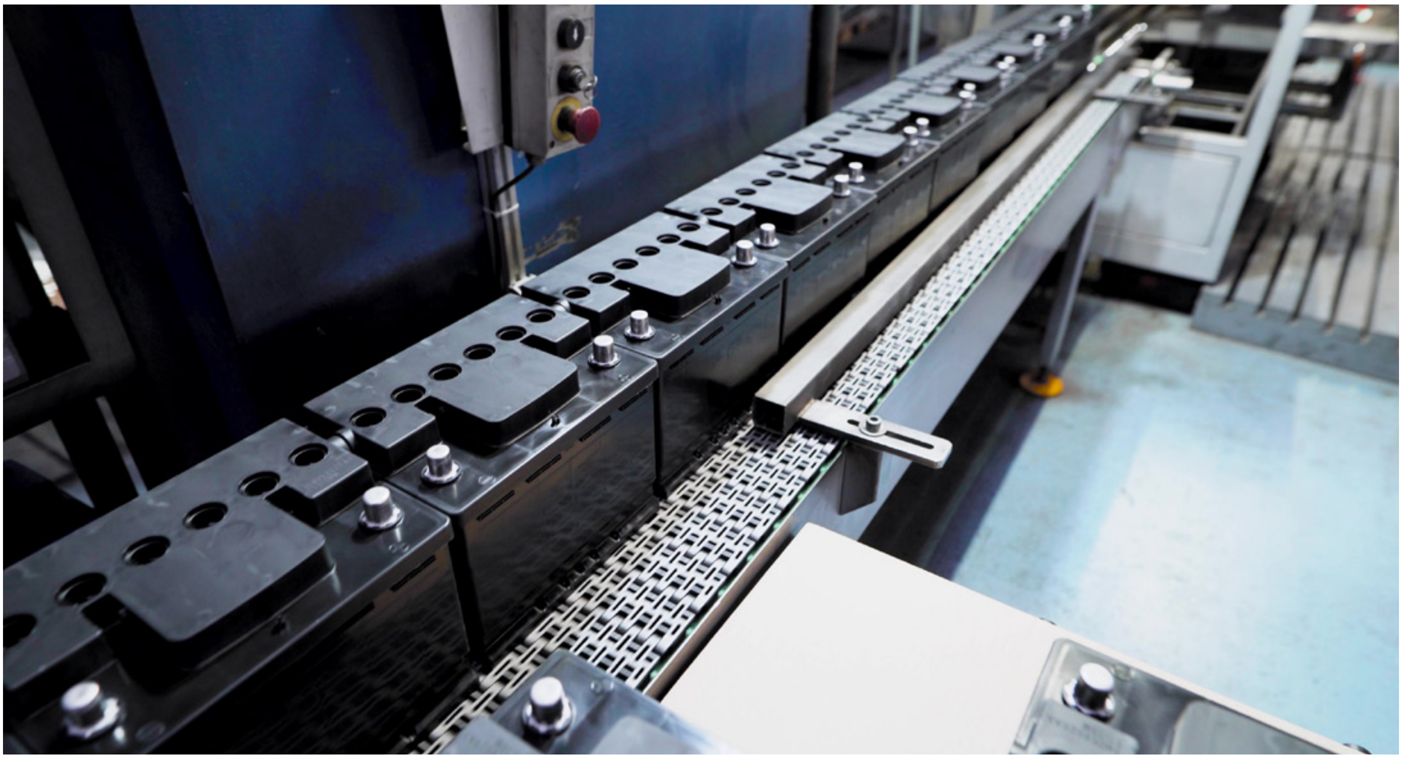
Risks are posed by the supply chain, policy and regulatory frameworks, technology transfer, financing and market availability. Raw materials will be a major barrier to secure domestic manufacturing growth, as India will rely heavily on imports for key materials such as lithium and cobalt. The nascent state of the industry will also present key risks. Financial institutions are likely to impose a risk premium on their investments, making low-cost financing a barrier for smaller domestic players. Lack of technical expertise and knowledge pertaining to the sector, especially when it comes to hiring skilled labour for plant operations and maintenance, will be a key operational risk. Any unfavourable change in policy and regulatory frameworks can drastically affect the viability of a project, financial returns, and investor confidence in future projects.

Developing India's battery manufacturing industry requires a phased approach, one that integrates a larger fraction of the value chain over time, as local demand grows and as local technical expertise and capacity evolve to meet demand. This will require a coordinated and strategic approach to attract supply and stimulate demand. Such an approach will increase investor and manufacturer confidence in the marketplace and overcome many of the risks associated with developing the industry domestically.

A deeper discussion of these potential risks is one of the focuses of the third report of this series.

Conclusion

Conclusion

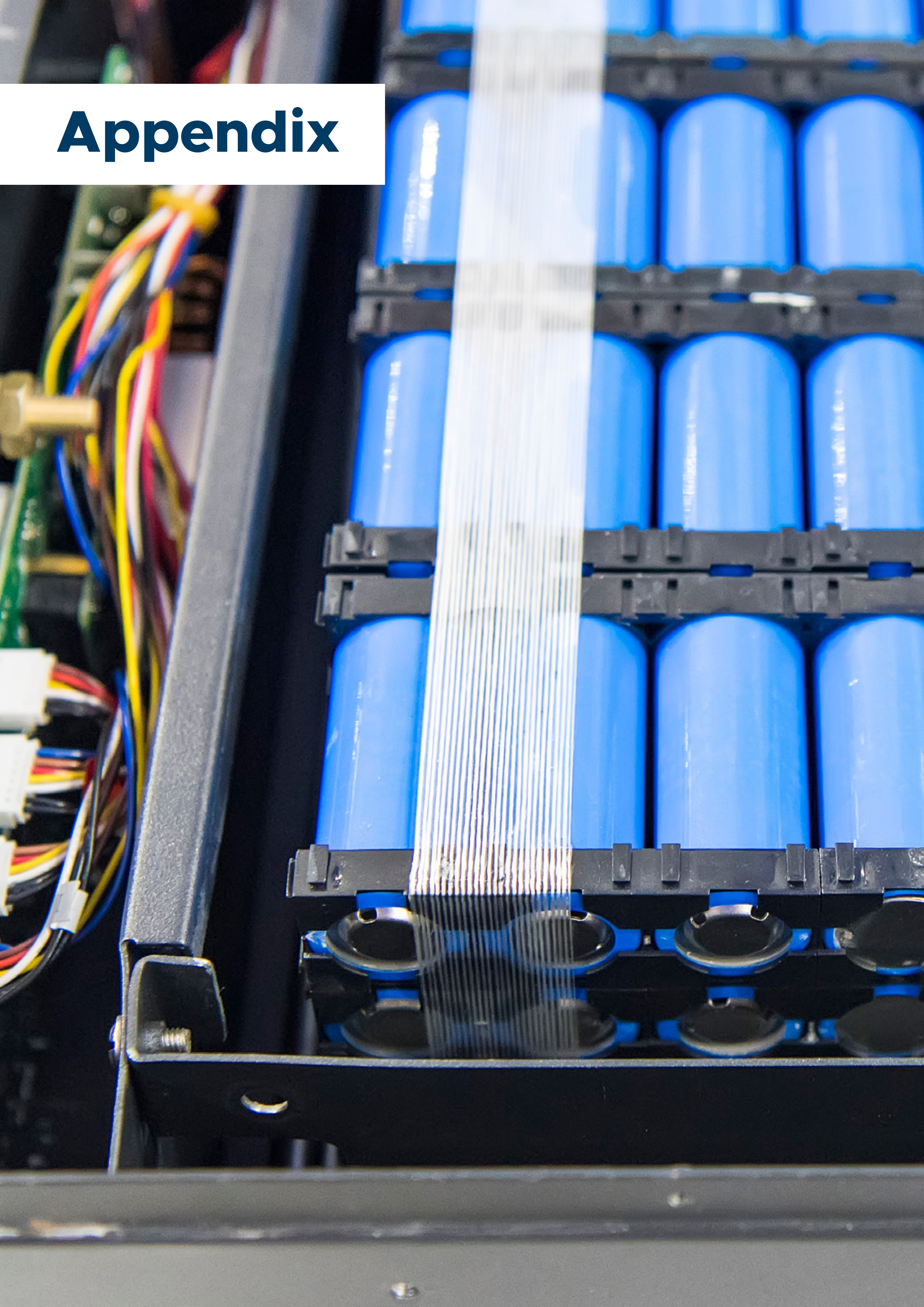


Battery manufacturing represents one of the largest economic opportunities of the 21st century. For India to achieve its ambitious targets of 500 GW of non-fossil fuel energy by 2030 and also to have EVs make up 30% of its new vehicle sales by 2030, a robust domestic battery ecosystem will play a vital role. These targets will spur the demand for ACC battery technologies and create significant growth from some of the largest sectors, such as transport and power.

India's participation in the global race to create advanced battery manufacturing hubs has been almost nonexistent so far, owing to tepid domestic demand and a lack of the rare metal reserves that are key ingredients for LiB chemistries. But advanced battery technologies are maturing and moving away from rare metals while making rapid strides towards higher performance and improved affordability. This gives India the perfect opportunity to establish a battery manufacturing ecosystem on the foundation of new-age technologies that leverage abundantly available indigenous materials such as sodium and aluminium. Promoting the domestic manufacturing of ACC batteries also provides India with the opportunity to reduce its dependence on imports to meet the future demands of the advanced energy economy. The recent ACC manufacturing PLI scheme can kick-start investments for creating domestic battery manufacturing hubs, create new jobs, and foster economic growth. These hubs will play a vital role in advancing battery technologies across various sectors, which could also very well dictate the adoption of EVs and stationary energy storage across the country. Because the PLI scheme incentivises the manufacture of more advanced battery technologies and high domestic value creation, India stands to benefit significantly from its rollout.

It is important to note that the PLI scheme is just the first step. India needs to be at the forefront of advanced development. The growth in the battery market will bring many opportunities and risks in the future; hence, having supportive, transparent, and consistent government frameworks at national, state, and local levels will increase corporate willingness to bear these risks. India's decisive actions can help realise its bold ambitions by strategically supporting growth in supply and demand for energy storage technologies, creating lasting benefits for the country and the world.

Appendix



Appendix

Exhibit A1 Advantages and Disadvantages of Major Battery Types

Technology	Description	Advantages	Disadvantages
Lithium-Ion	Lithium-ion has emerged as the battery of choice for electronics. Lithium-ion refers to a suite of battery technologies with a lithium anode, including lithium iron phosphate (LFP), nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA), etc.	Increased demand and technological improvements have led to cost reductions, making lithium-ion chemistries extremely common worldwide for applications in electronics, vehicles, and stationary storage.	Chinese manufacturers increasingly dominate the global supply chain. Cost reductions and performance improvements are slowing down. There are additional safety concerns in high-temperature environments within India as well as supply chain constraints associated with raw materials.
Advanced Lithium-Ion	Efforts to improve safety and specific energy for lithium-ion batteries are under way; improvements are focused on shifting to low-/no-cobalt cathodes, silicon anodes, or lithium anodes. Some actors are pursuing means to reduce cobalt content in the cathodes to reduce costs and address supply chain concerns, whereas others are focussing on improving anodes, as the traditional graphite anode already operates close to theoretical capacity.	Reductions in the use of cobalt and graphite reduce the costs and improve the economics of lithium-ion batteries, likely allowing continued cost reductions for lithium-ion battery types or improvements in power output or specific energy. These changes to battery chemistry can be inserted into existing manufacturing facilities during retrofits, making facilities more fungible for future use. These chemistries typically make batteries less heat sensitive and improve their viability in high-temperature conditions.	Advanced lithium-ion battery chemistries are still in prototype phases, and they are more costly than standard NMC, LFP, or other modern chemistries. Some of these new chemistries have negative impacts on cycle life. In general, these changes to chemistry would result in improvements to lithium-ion batteries, which could then remain competitive compared with emerging next-generation battery technologies.

Metal-Air	Metal-air batteries are promising thanks to their high specific energy potential and low costs resulting from their use of atmospheric oxygen as a cathode. Their low charging efficiency, low power rating, and low cycle life do not make them ideal batteries for EV use, but their low and falling cost will make them contenders in specific markets (including, potentially, two-wheelers). They may be used in combination with high-power battery for EVs.	The costs are low and falling, and they may soon be the cheapest batteries in the market. This may overcome their short lifetime and help them find applications as EV range extenders or in off-grid batteries. They have excellent environmental resistance, which is an advantage in India over LiB types.	Using oxygen as a cathode limits stability and lifetime, so these batteries lose their capacity quickly (less than 1,000 cycles in the most promising types, only 300 in current versions). They demonstrate a low charging efficiency of roughly 60% and a lower power output, making them less suitable for EVs. Their short cycle life will mandate a much lower cost if they are to be competitive with higher-power, longer-lifetime batteries. Development of non-zinc anodes may require a number of years of development.

Advanced Lithium-Ion Battery

Many improvements in LiB technology have begun to enter the market, and are approaching commercial manufacturing prices. Some combination of these technologies is expected to be applied to LiB manufacturing in the coming years, offering an improvement in performance, safety, and cost that will likely keep lithium-ion as a dominant battery technology through 2030. The three major expected changes are covered below.

Exhibit A2 Chemistry and Characteristics of Advanced Lithium-Ion Batteries

Advance	Cell Chemistry	Design and Manufacture	Characteristics
Low/No Cobalt	Cobalt-heavy cathodes are being replaced by new chemistries with little to no cobalt, e.g., cobalt-free lithium nickel manganese oxide or enhanced LNO.	Low- or no-cobalt initiatives are pursuing designs and manufacturing plans that are aligned with existing processes for lithium-ion cells.	Reduced cobalt use eases supply chain constraints and reduces use of one of the costliest elements in modern LiBs. Maintaining specific energy is a primary barrier to overcome.

Silicon Anode	This innovation replaces graphite anodes with silicon anodes. Silicon potentially has poor cycle life due to volumetric expansion.	These silicon anodes can be dropped seamlessly into the existing commercial battery manufacturing process, so minimal extra investment to the production process is required.	Silicon anodes have a lower weight and higher energy density than their graphite counterparts. Further, they are naturally abundant and environmentally friendly. Silicon anodes, although light, can swell when charged, which affects cycle life. Volumetric expansion issues continue to improve through nanomaterial design. Techniques include silicon particle size reduction. Or using silicon graphite composites graphene to improve anode characteristics.
Lithium Metal Anode	Metallic lithium offers advantages over aqueous lithium in the form of low equivalent weight and correspondingly higher specific energy and volumetric energy capacities.	The needed anode production process is simpler than for current LiBs and easy to insert in manufacturing. Subverting the volatility of lithium-metal anodes has been a goal in manufacturing; this is close to a solid-state battery and can lead to more homogeneous Li deposition.	Lithium metal is expected to have cost volatility concerns similar to those of other forms of lithium. Additional costs may be associated with the processing to thin foil. Lithium-metal anodes are therefore not currently cost competitive with lithium-ion cell chemistries. These batteries have significantly higher specific energy and energy density while being lower in weight. Lithium-metal anodes most likely require electrolyte innovations (solid-state) to avoid problematic dendrite formation.

Metal-Air Battery
Metal-air batteries have been commercially available for a long time, but recent innovations have dramatically reduced the costs of one type (zinc) to make it viable for storage applications. These batteries are very safe and inexpensive but have poor lifetime and power output.

Exhibit A3 Chemistry and Characteristics of Metal-Air Batteries

Cell Chemistry	Design and Manufacture	Characteristics
Anode: Zinc (most developed product to date). Magnesium, aluminium, and lithium also demonstrate feasibility but are not yet well developed. **Cathode:** Oxygen from air is reduced using a catalyst inside a nanoporous carbon network, immersed in electrolyte. **Electrolyte:** KOH + other alkaline electrolytes	**Architecture:** Cells are larger than lithium-ion counterparts and are designed around the optimisation of the bifunctional air electrode (cathode). Standard cathode design: Teflon film + current collector + gas diffusion layer + catalyst layer. **Manufacturing process:** Zinc requires high-purity manufacturing processes and continual improvements to minimise self-discharge.	**Cost range:** \$100–\$400/kWh **Energy density:** 500–1,000 Wh/L **Specific energy:** 180–200 Wh/kg **Specific power:** 90–200 W/kg **Nominal voltage:** 1.4–1.65 V (Zn anode) **Cycle life:** 300–1,000 cycles depending on chemistry **Safety:** Zn-air is relatively safe and environment-friendly.

Lithium-Sulphur Battery

Incorporation of sulphur into the cathode allows a greater storage density of lithium, while utilising an inexpensive construction material. Lithium-sulphur batteries have very high specific power and specific energy. These batteries have had issues with volume expansion of the sulphur cathode and the necessity of extra mass in the conducting agent, but have shown significant progress and are considered a potential successor to modern LiBs.

Exhibit A4 Chemistry and Characteristics of Lithium-Sulphur Batteries

Cell Chemistry	Design and Manufacture	Characteristics
Anode: Lithium metal anode (the commercial success of this technology requires perfecting the lithium metal component) **Cathode:** Sulphur-based **Electrolyte:** Currently being addressed, as there is high solubility of sulphur in common lithium battery electrolytes, leading to low cycle life and high discharge rates.	**Architecture:** Standard pouch cell **Manufacturing process:** Some solid electrolytes may be able to be dropped into existing lithium-ion cell production processes, whereas others require new methods of establishing a high surface area contact. Another area for manufacturing improvement is super thin Li-metal foil production	**Cost range:** $250/kWh **Energy density:** 240–425 Wh/L **Specific energy:** 300–400 Wh/kg **Specific power:** Experimentally estimated at 300–2,500 W/kg **Nominal voltage:** 2.15–3.8 V **Cycle life:** 50–500 cycles **Safety:** Solid-state lithium membranes enable higher safety ratings

Solid-State Battery

Incorporation of solid-state electrolytes in ambient-temperature batteries was originally motivated by concerns over the safety of LiBs. Since the 2000s, solid electrolytes have been used in emerging lithium batteries with gaseous (i.e., lithium air) or liquid cathodes. The primary goal for the further development of all-solid-state LiBs is to achieve higher cycling and safety performance in comparison with traditional LiBs while maintaining similar or higher power and energy densities.

Exhibit A5 Chemistry and Characteristics of Solid-State Batteries

Cell Chemistry	Design and Manufacture	Characteristics
Anode: Lithium metal is the primary target for most solid-state batteries and is the rationale for higher achievable energy density and specific energy. However, solid-state technology could be incorporated into other anode technologies. **Cathode:** Can be made with existing cathodes, but the cathodes could also use more innovative low- or no-cobalt chemistries, which are under development. **Electrolyte:** The distinguishing factor of the all-solid-state battery is the solid electrolyte. Some companies are also pursuing dual solid and liquid electrolytes.	**Architecture:** Solid-state innovators are exploring ways to incorporate the technology into existing architectures. Packs with solid-state batteries will not need significant safety equipment, which can greatly improve the energy density. **Manufacturing process:** Some solid electrolytes may be able to be dropped into existing lithium-ion cell production processes (primarily organic solid-state), whereas others have required new methods of establishing a high contact, pressurised area between the solid electrolyte and active material (versus liquid electrolytes, which naturally permeate the active material surface). Manufacturing scale and compatibility remain a significant challenge.	**Cost range:** N/A **Energy density:** 250–1,200 Wh/L **Specific energy:** 150–500 Wh/kg **Specific power:** Unknown **Nominal voltage:** 1.8–3.8 V **Cycle life:** 50–1,000 (extremely variable) **Safety:** Lab testing has shown improvements in safety over conventional LiBs.

Sodium-Sulphur Batteries

Sodium-sulphur (NaS) batteries are the established commercialised high-temperature battery. Although they have showed promise in long-term storage, a 2011 fire in Japan raised concerns about the high-operation temperatures.[57] Safer molten chemistries and lower temperature operations for existing chemistries could provide more cost-effective long-duration grid storage.

Exhibit A6 Chemistry and Characteristics of Sodium-Sulphur Batteries

Cell Chemistry	Design and Manufacture	Characteristics
Anode: The negative electrode, historically sodium, gives up electrons to the external circuit. While charging, the negative electrode is electrochemically reduced. **Cathode:** The cathode, historically sulphur, accepts electrons from the external circuit. On charge, the positive electrode is oxidised and gives up electrons. **Electrolyte:** High-temperature NaS batteries have used a solid electrolyte membrane (Beta-alumina solid electrolyte, or BASE membrane), which allows for transfer of sodium ions between the negative and positive electrodes.	**Architecture:** Cells are made in a cylindrical configuration with the molten cathode inside the sulphur solution, which is then enclosed in a steel case that is coated with chromium or molybdenum to protect from corrosion. **Manufacturing process:** The battery relies on the ceramic membrane manufacturing skills of the primary producer. Almost all practical sodium-sulphur cells are based on electrolytes formed as closed tubes. The reliability of the electrolyte tube is the key to the success of the sodium-sulphur battery, and a great deal of effort is being made to develop dependable units. Unsurprisingly, many of the details of the electrolyte formation process are industrial secrets. One of the most difficult technical problems in the history of this system has been the development of seals to isolate the cell compartments from one another and from the external environment.	**Cost range:** \$420–\$1,000/kWh **Energy density:** 140–367 Wh/L **Specific energy:** 150–240 Wh/kg **Specific power:** 120–160 W/kg **Nominal voltage:** 2 V **Cycle life:** 1,500–4,500 **Safety:** This is a huge area of improvement since the 2011 fire in Japan.

Flow Battery

A flow battery stores the energy as electrolytes and not as electrodes. These electrolytes are stored outside in two separate tanks instead of inside the core. One tank stores the positive electrolyte (catholyte) and the other stores the negative electrolyte (anolyte). Oxidation/reduction reactions take place on either side of a membrane, through which an ion passes. Redox flow batteries need to continue to bring down cost, which is primarily dependent on membrane cost, pumping, and anolyte-catholyte material costs. Some companies have pivoted from the best understood chemistry, vanadium, towards lower-cost options. Other companies have looked to simplify the system costs. A significant barrier with this technology is its high cost, low specific energy, and low portability (liquid electrolyte). This makes it a potential future technology for grid storage but, barring major technology advances, not for any mobile purposes.

Exhibit A7 Chemistry and Characteristics of Flow Batteries

Cell Chemistry	Design and Manufacture	Characteristics
Anolyte: Many redox chemistry combinations can be used. Some of the most common anode ions are vanadium, iron, zinc, sodium, and copper. **Catholyte:** Many redox chemistry combinations can be used. Some of the most common cathode redox ions are vanadium, bromine, and iron.	**Architecture:** Large containers, such as those for shipping, are often used to hold the electrolytes and the power stack. Electrolytes can be added and scaled volumetrically with the same electron transfer capability in the power stack, leading to improved long-duration economics. **Manufacturing process:** Nafion or Nafion derivative membranes are commonly available.	**Cost range:** On-market: $266–$353/kWh; Advanced chemistries: $150–$2,500/kWh **Energy density:** <200 Wh/L **Specific energy:** 10–50 Wh/kg **Specific power:** 0.5–2 W/kg **Nominal voltage:** 1–2.2 V **Cycle life:** Up to 40 years of daily storage; >10,000 cycles **Safety:** Primarily composed of water; nonflammable

Sodium-Ion Battery
Sodium-ion batteries are considered to be a viable alternative to their currently available lithium-ion counterparts because of the relative abundance and lower cost of sodium. Although their performance in energy density terms is only now beginning to match that of commercial LFP batteries, these are very promising from a lifetime operational cost perspective and can change the status quo of battery chemistry for stationary applications where weight and volume limitations don't exist. Sodium-ion batteries have so far achieved only low-volume manufacturing capacity; improving technical performance by economies of scale is required to achieve commercialisation.

Exhibit A8 Chemistry and Characteristics of Sodium-Ion Batteries

Cell Chemistry	Design and Manufacture	Characteristics
Chemistry is similar to LiBs, replacing the Li ions with Na ions as charge carriers. **Anode:** Typically hard carbon and metal oxide compounds (compared with graphite in LiBs), which can intercalate the larger Na+ ions. **Cathode:** Composed of sodium containing layered material such as transition metal oxides, ceramic oxides, Prussian blue analogues, etc. **Electrolyte:** Can be aqueous or non-aqueous, such as sodium hexafluorophosphate (NaPF6), or sodium bis(trifluoomethylsulfonyl) mide (NaTFSI) in carbonate-based solvents; allows migration of Na+ ions during charge and discharge cycles. Electrolyte needs high electrochemical stability to allow for longer cell cycle life.	**Architecture:** Prototypes have been manufactured in cylindrical and pouch configurations. **Manufacturing process:** Production process is similar to that of LiBs, so existing facilities can be repurposed to produce sodium-ion batteries; the current challenge is to optimise the choice of functional anode and electrolyte materials for better energy density and cycle life at par with other commercial battery chemistries.	**Cost range:** \$240–\$270/kWh (initial commercialisation) **Specific energy:** 160–265 Wh/kg **Specific power:** 1,000–2,000+ W/kg **Cycle life:** 2,000–5,000 **Safety:** Nonflammable properties of electrolytes allow higher safety ratings

Supercapacitors
Supercapacitors store energy as a static charge, as opposed to an electrochemical reaction in batteries. A voltage differential applied between the plates of a capacitor builds up a charge, which can be released at high current for short durations. This results in high power capacity and good recharging capability, making supercapacitors useful in power applications such as transportation, especially for regenerative braking. Supercapacitors have a cycle life far exceeding that of commercial LiBs and also provide higher round-trip efficiency. Most current applications of this technology are limited to hybrid projects in which supercapacitors are coupled with batteries to extend their life.

Exhibit A9 Chemistry and Characteristics of Supercapacitors

Cell Chemistry	Design and Manufacture	Characteristics
Electric double-layer capacitors (EDLCs) consist of activated carbon electrodes immersed in electrolyte, where ion absorption occurs during charging. Capacitance (and thus the discharging capability) depends on the electrolyte in use. **Electrode:** Carbon materials, mixed metal oxides, and conducting polymers, with aluminium current collectors **Electrolyte:** Typically organic and ionic salts	**Architecture:** The most common structures are cylindrical (wound electrodes) and square (stacked electrodes); pouch and chip type EDLCs can be used for electronics.	**Cost range:** ~$10,000/kWh **Specific energy:** ~10 Wh/kg **Specific power:** >2,000–10,000 W/kg **Cycle life:** 500,000–1,000,000 **Safety:** Typically safer than LiBs since overcharging cannot occur; however, it is advised not to charge beyond specified voltage since dielectric can fail.

Exhibit A10 Summary of Commercial and Advanced Battery Technologies

Battery Technology	2021 Cost ($/kWh)	2030 Cost Estimate ($/kWh)	Energy Density (Wh/L) By volume	Energy Density (Wh/kg) By weight	2021 Cycle Life	Overall Assessment
Lithium-Ion	132	59	186-720	120-275	1,000-5,000	Industry standard with diminishing returns
Advanced Lithium-Ion	250	70	350-900	325-640	1,000-6,000	Could continue lithium-ion dominance into future
Zinc-Air	100	50	500-1,000	300-400	500-10,000	Good cost and performance but low lifetime and power; niche uses
Lithium-Sulphur	250	110	240-425	300-400	~100	Excellent for high-power applications
Solid-State	N/A	80	400-1,200	200-450	100-1,000	Significant research and manufacturing hurdles, but heavy potential
Flow Batteries	300	40-200	<200	10-50	Very long: 12,000-14,000	Excellent for long-term grid storage with further development

Exhibit A11 Summary of Emerging Battery Technologies

Battery Technology	Energy Density (Wh/kg)	Cycle Life	Overall Assessment
Sodium-Ion	140–160	2,000–5,000	Excellent performance in high-power and low-temperature applications
Lithium-Carbon	20–60	100,000–1,000,000	Allows good power density and fast charging, useful for mobility applications
Semi-Solid	275–350	1,000	Can allow cost advantages in manufacturing; lightweight and reliable
Aluminium Air	300–350	1,500	Can allow major advantages in energy density and material recyclability if commercialised; useful for long-range EVs

Methodology for Mapping Battery Technology

For 2021:

1. Energy density for commercial LiB chemistries such as NMC, NCA, LFP, LTO, LMO, and LCO has been compiled from announced data from international cell makers (such as CATL, Panasonic, and BYD), BNEF surveys, reports from the National Renewable Energy Laboratory and Pacific Northwest National Laboratory, and other sources.

2. NMC and NCA batteries offer higher specific energy than other LiBs, whereas LFP batteries offer higher cycle life (>2,000). The upper range of energy density from LiBs is close to 270 Wh/kg.

3. Lead-acid batteries are commercially mature. They offer low energy density at cycle life <1,000. Commercial flow batteries (vanadium RFBs are the most common) offer low specific energy but very high cycle life.

4. Niche chemistries such as lithium-sulphur and solid-state that have clearly announced commercialisation roadmaps have been included under 'emerging technologies' (they currently have no or low-volume commercial production).

For 2030:

1. LiBs commercialised today are expected to evolve into next-generation variants, as advanced anode materials, electrolytes, etc., receive continued R&D focus for performance improvements. However, since credible data is not available for specific chemistries, these have been placed in similar brackets as in 2021.

2. Emerging chemistries such as sodium-sulphur, solid-state, metal-air, and hybrids are mapped according to announced plans of commercialisation and expected range of specific energy and cycle life. Initial commercialisation by 2025–27 can be expected to feature performance on the lower end; however, by 2030 these chemistries could mature and become mainstream.

3. Supercapacitors have not been mapped because they are still in R&D and most expected use cases combine them with a commercial battery in a hybrid product.

Definitions

i. Per the Ministry of Heavy Industries and Public Enterprises (MoHIPE) notification, advanced batteries are defined as new-generation batteries such as lithium polymer, lithium iron phosphate, lithium cobalt oxide, lithium titanate, lithium nickel manganese cobalt oxide, lithium manganese oxide, metal hydride, zinc air, sodium air, nickel zinc, lithium air, and other similar chemistry under development or use.

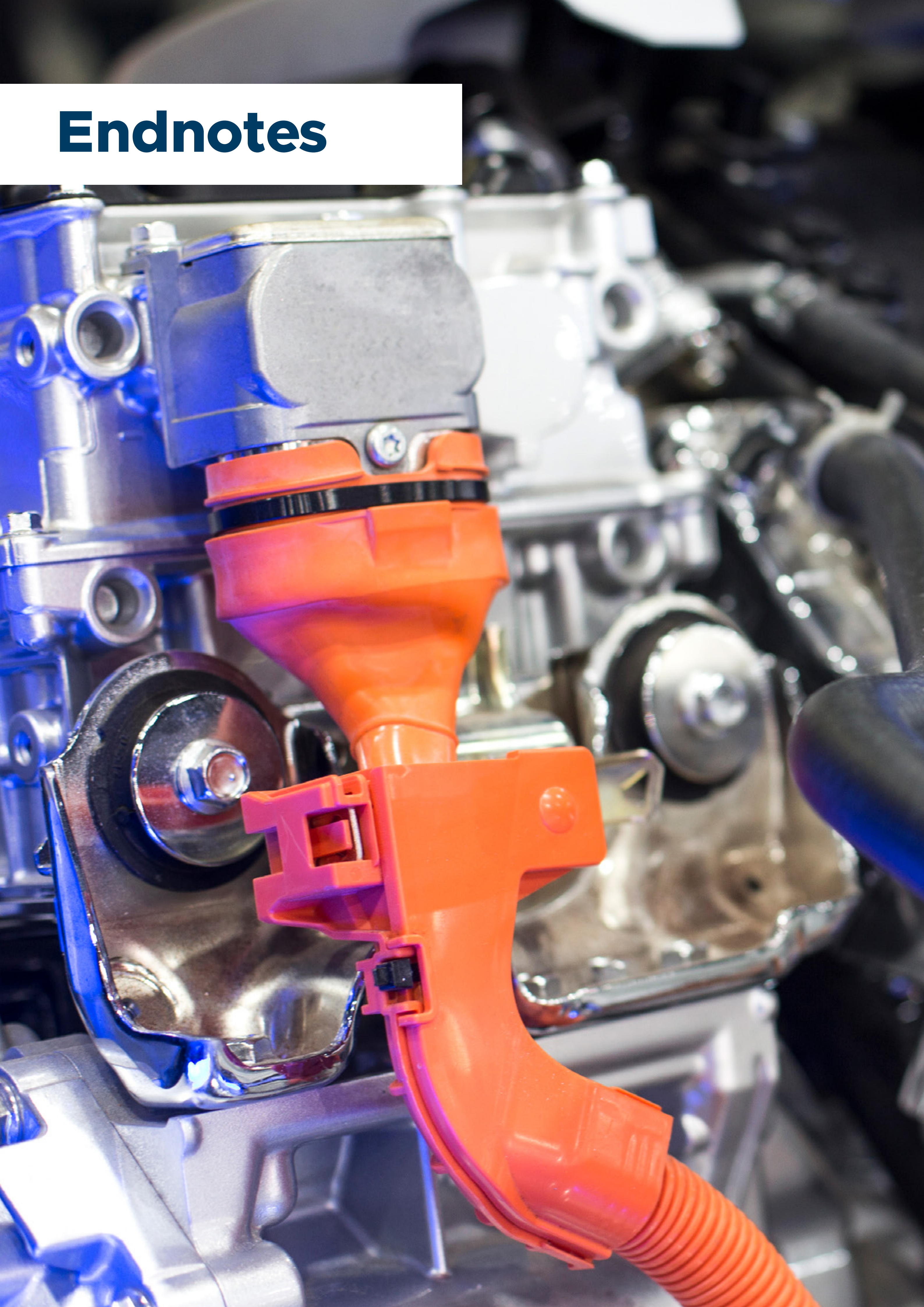
ii. All dollar amounts referred to in this report are in US currency.

iii. Unless otherwise stated, these tables on cell chemistry, characteristics, design, and manufacture are derived from confidential interviews with experts at major international battery manufacturing companies.

iv. Thermal runaway occurs when cell damage due to mechanical or electrical causes results in an uncontrolled temperature rise beyond safe limits, leading to venting of flammable gasses and, in extreme cases, fire and explosion.

v. New energy vehicles (NEVs) refers to battery electric vehicles (BEVs), plug-in hybrids (PHEVs), and fuel cell vehicles (FCVs), as included in various Chinese national five-year plans and industrial development plans.

Endnotes



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