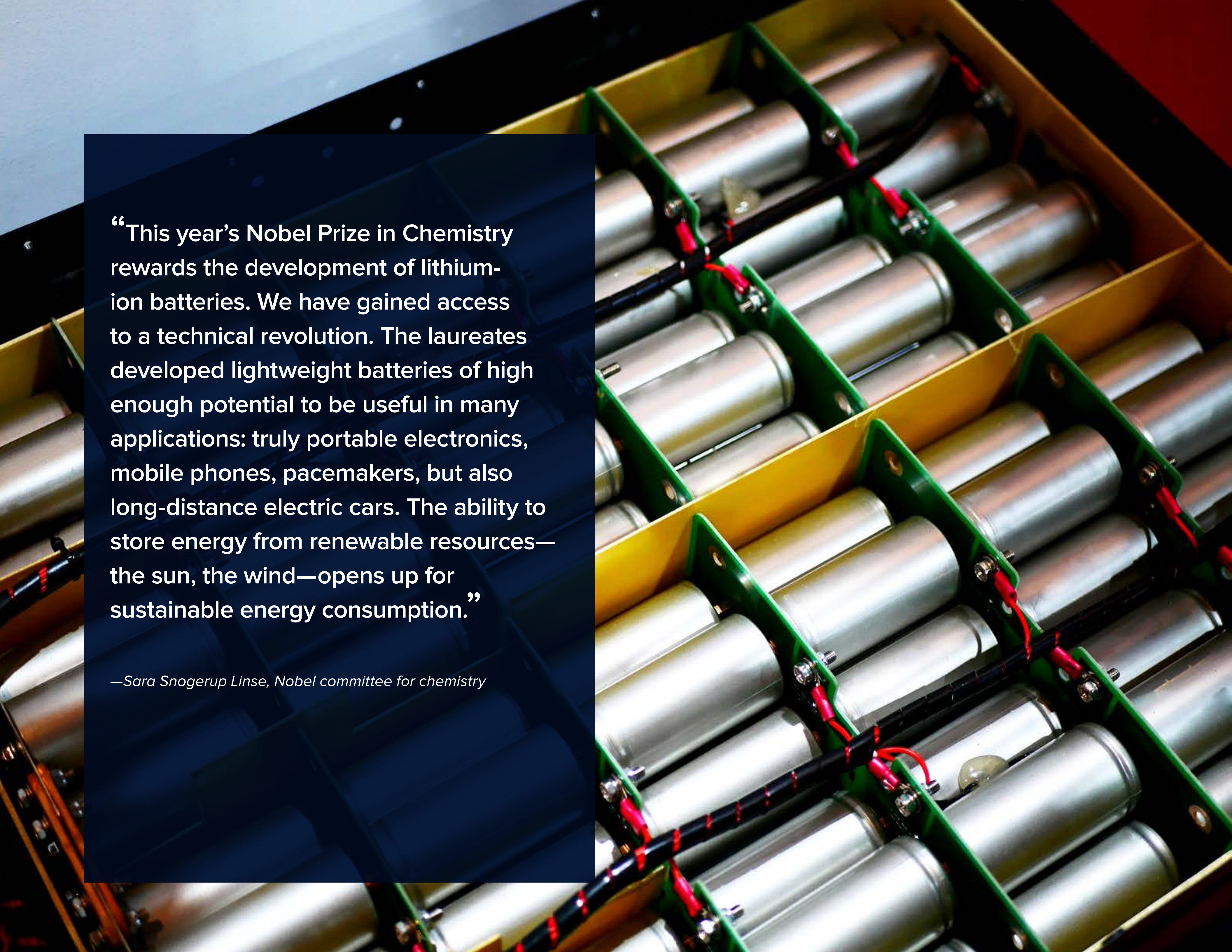
BREAKTHROUGH BATTERIES

Powering the Era of Clean Electrification

BY CHARLIE BLOCH, JAMES NEWCOMB, SAMHITA SHILEDAR, AND MADELINE TYSON



"This year's Nobel Prize in Chemistry rewards the development of lithium-ion batteries. We have gained access to a technical revolution. The laureates developed lightweight batteries of high enough potential to be useful in many applications: truly portable electronics, mobile phones, pacemakers, but also long-distance electric cars. The ability to store energy from renewable resources—the sun, the wind—opens up for sustainable energy consumption."

—Sara Snogerup Linse, Nobel committee for chemistry

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ABOUT ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; the San Francisco Bay Area; Washington, D.C.; and Beijing.

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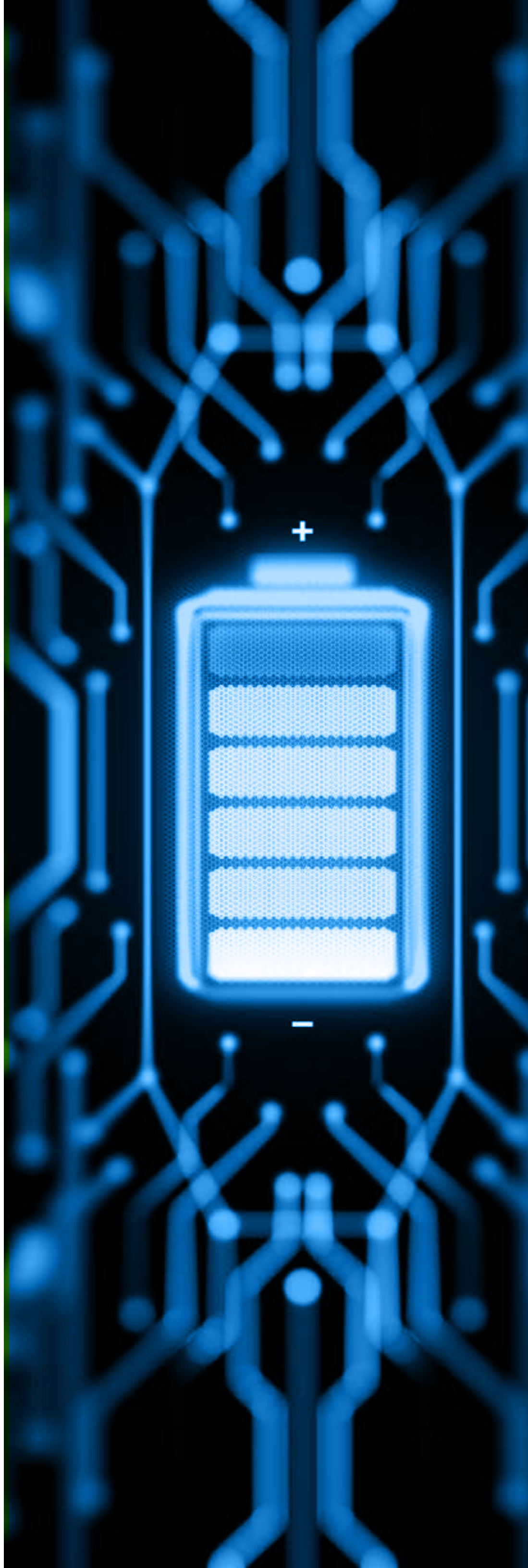
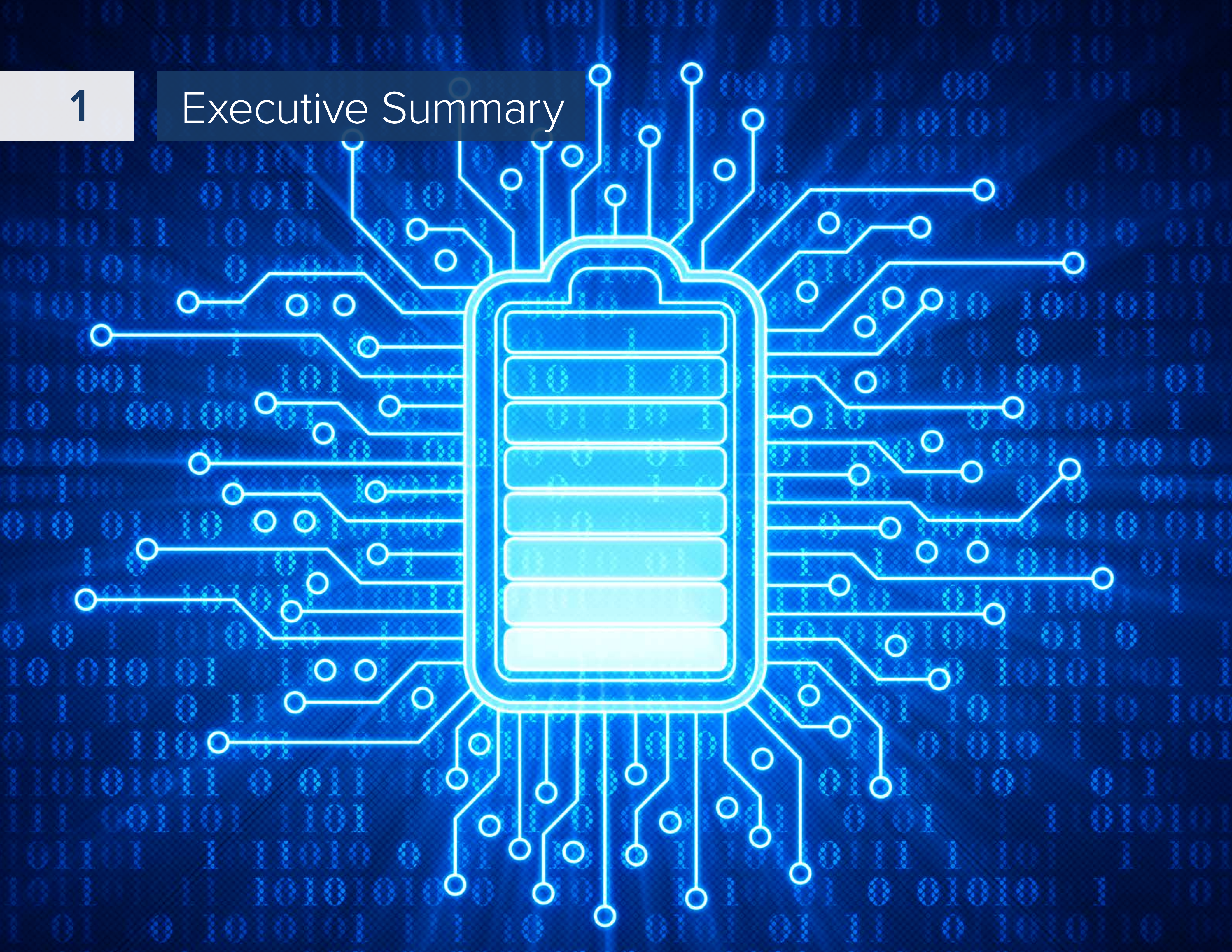


1 Executive Summary



Executive Summary

Advanced battery technologies are poised to dramatically change our lives, sooner than many market actors realize.

Recent rapid improvements in lithium-ion (Li-ion) battery costs and performance, coupled with growing demand for electric vehicles (EVs) and increased renewable energy generation, have unleashed massive investments in the advanced battery technology ecosystem. These investments will push both Li-ion and new battery technologies across competitive thresholds for new applications more quickly than anticipated. This, in turn, will reduce the costs of decarbonization in key sectors and speed the global energy transition beyond the expectations of mainstream global energy models. Self-reinforcing feedback loops linking favorable public policies, additional research and development (R&D) funding, new manufacturing capacity, and subsequent learning-curve and economy-of-scale effects will lead to continued cost declines and exponential demand growth.

Total manufacturing investment, both previous and planned until 2023, represents around $150 billion dollars, or close to $20 for every person in the world.[i]

Through 2025, advances in technology and manufacturing will keep Li-ion batteries at the forefront of electrochemical energy storage markets.

Emerging innovations will improve all aspects of Li-ion battery performance, with costs projected to approach $87/kWh by 2025.[1] These rapid improvements and cost declines will make battery-based applications cost competitive with both stationary and mobile applications in the near term (Exhibit ES1). For example, these changes are already contributing to cancellations of planned natural gas power generation. The need for these new natural gas plants can be offset through clean energy portfolios (CEPs) of energy storage, efficiency, renewable energy, and demand response.[2] Natural gas plants that move forward are at high risk of becoming stranded assets, and as early as 2021, some existing power plants could be more expensive to continue operating than least-cost CEP alternatives, depending on gas prices. On the electric mobility front, low-cost Li-ion batteries will contribute to a rapid scale-up of demand for smaller (e.g., two- and three-wheeled) EVs in fast-growing markets like India by 2023, as upfront capital costs drop below those for internal combustion engine vehicles. A similar shift, due to capital cost competitiveness, will occur for personal and commercial EVs in the US market after 2025.

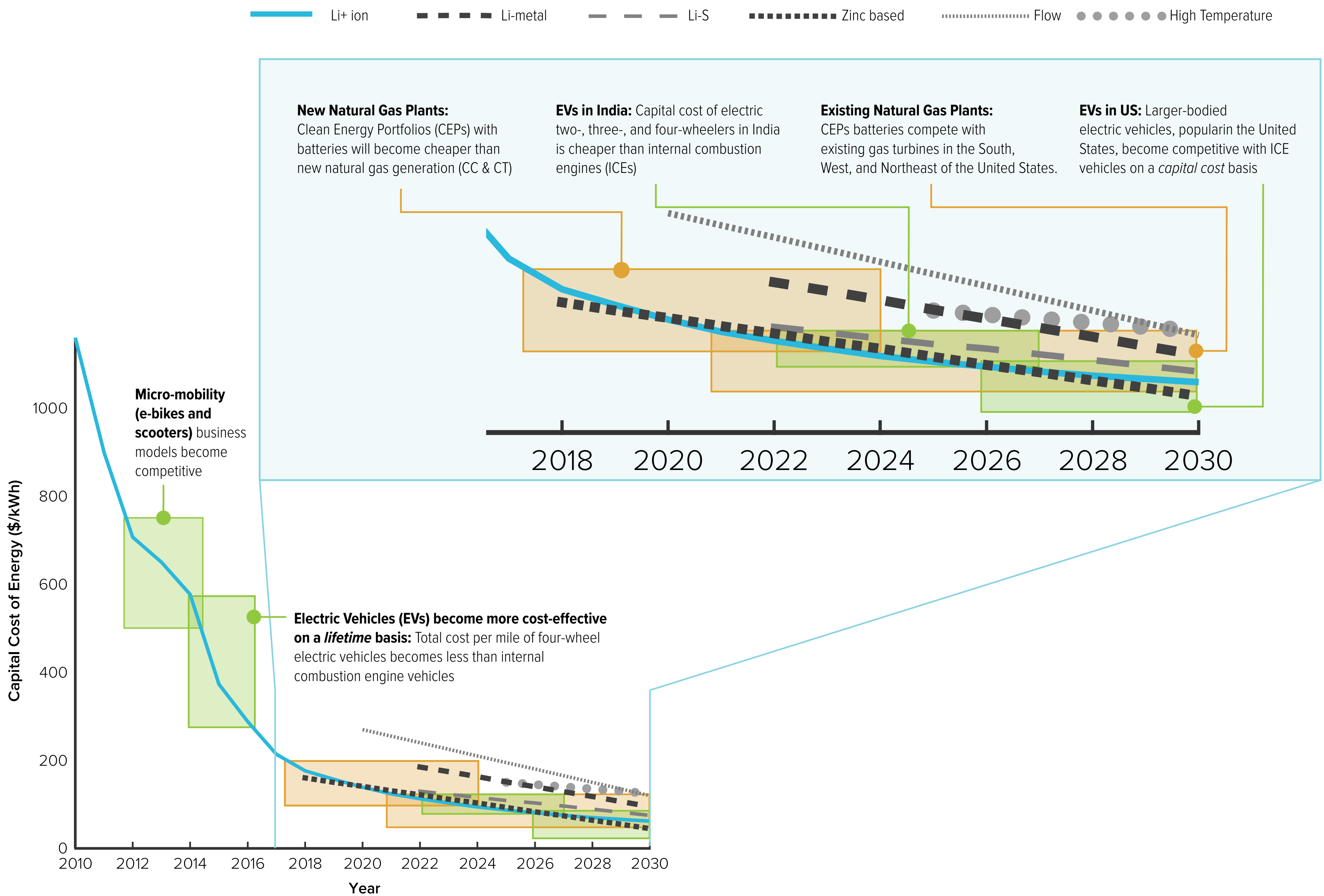
Diversifying applications will create opportunities for new battery chemistries to compete with Li-ion.

- Solid-state batteries such as rechargeable zinc alkaline, Li-metal, and Li-sulfur will help electrify heavier mobility applications.
- Low-cost and long-duration batteries such as zinc-based, flow, and high-temperature technologies will be well suited to provide grid balancing in a high-renewable and EV future.
- High-power batteries, which are best compared on a $/kW basis, are well positioned to enable high penetration and fast charging of EVs.

[i] Based on BNEF battery manufacturing capacity data.

EXHIBIT ES1

Competitive Thresholds for Advanced Battery Technologies to Displace Incumbent Technologies



But markets for advanced battery technology will not be a winner-take-all opportunity for Li-ion batteries.

Despite the anticipated trajectory for Li-ion cost and performance, technology limitations and tradeoffs will likely persist. Unlike the market development pathway for solar photovoltaic (PV) technology, battery R&D and manufacturing investment continue to pursue a wide range of chemistries, configurations, and battery types with performance attributes that are better suited to specific use cases. Solid-state technology, in particular, is poised to massively disrupt the storage industry by unlocking new opportunities for cheap, safe, and high-performing batteries, including non-lithium-based chemistries.

Emerging, large market opportunities for such alternative battery technologies that are at or are nearing commercial readiness will reinforce diversification of the increasing investment, regulatory, and policy support for transportation electrification and stationary energy storage.

As early as 2025, and no later than 2030, RMI expects non-Li-ion battery technologies to have made significant commercialization steps through demonstration and early-stage deployments in long-duration energy storage, electrification of heavy transport (e.g., heavy freight and short-duration aviation), and battery-integrated approaches to EV fast-charging infrastructure.

Battery technology ecosystem actors should think comprehensively and strategically about a near-term future in which diverse technologies support an increasingly wide range of battery applications.

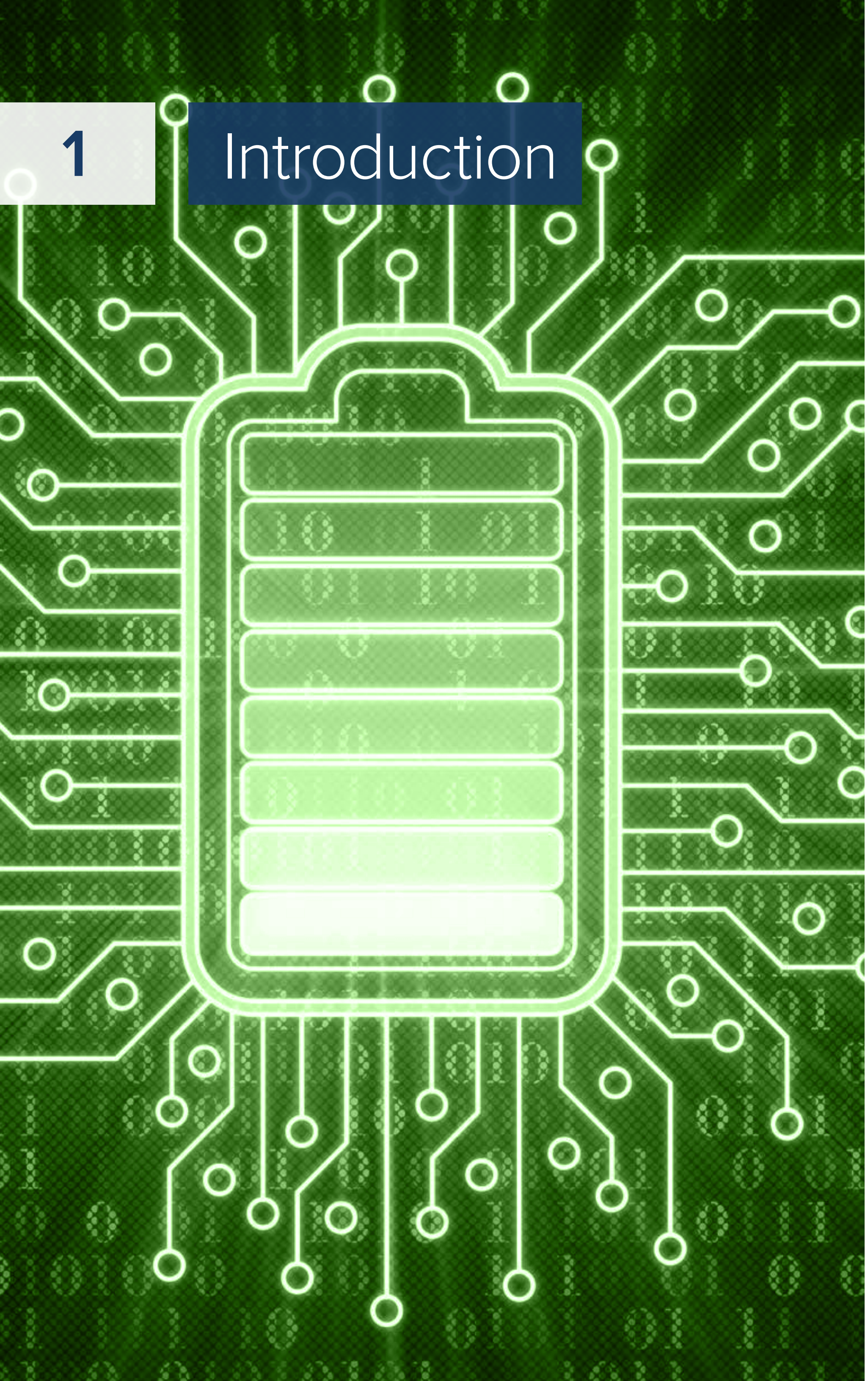
Capturing the massive economic opportunity underlying the shift to controls- and battery-based energy systems requires that planners, policymakers, regulators, and investors take an ecosystem approach to developing these markets. Regions that fail to develop such ecosystems will sacrifice economic gains to their global trading partners. As Li-ion battery costs and performance continue steadily improving, ecosystem actors may be tempted to assume the long-term dominance of Li-ion batteries across applications. However, market actors should consider how to capitalize on near-term economic opportunities from Li-ion without sacrificing progress or truncating opportunities for nascent applications where new technologies are better suited.

Regulators and policymakers must look ahead to understand just how quickly lower-cost batteries will accelerate the transition to zero-carbon grids and open new pathways for mobility electrification.

The rate of change in the battery space, measured in terms of both falling prices and diversifying performance attributes of new technologies, is outpacing the adaptive capacity of the electricity sector to integrate new solutions. Dramatically lower storage costs will disrupt conventional assumptions about optimal grid architectures and open a rapidly widening array of opportunities for delivering energy services. Utilities and their regulators must build scenarios based on forward price curves to assess the possible implications of falling prices for batteries and renewable power in order to minimize the risks of investing in assets that could soon be stranded. The synergies now emerging from the smart combination of renewable supply, storage, and demand flexibility will require new methods of planning and analysis as well as revamping traditional utility business models.

In the mobility sector, alternative battery technologies will open up new market opportunities for longer-range EVs and electric heavy transport, as well as provide new options for the cost-effective build-out of DC fast-charging infrastructure.

1 Introduction



Massive investments in battery manufacturing and steady advances in technology have set in motion a seismic shift in how we will power our lives and organize energy systems as early as 2030.

Over the past 10 years, a global ecosystem has emerged to provide a foundation for rapid innovation and scaling of these new technologies (Exhibit 1). This ecosystem includes:

- **Large and Diverse Private Investments:** Venture capital investments in energy storage technology companies exceeded $1.4 billion in the first half of 2019 alone and have continued to increase.[3] This money flows increasingly from acquisitions as well as non-traditional sources, including venture capital funds targeting risky and early-stage technologies (e.g., Breakthrough Energy Ventures), consortia of utilities targeting later-stage commercialization (e.g., Energy Impact Partners), and a growing number of incubators and accelerators.[4]

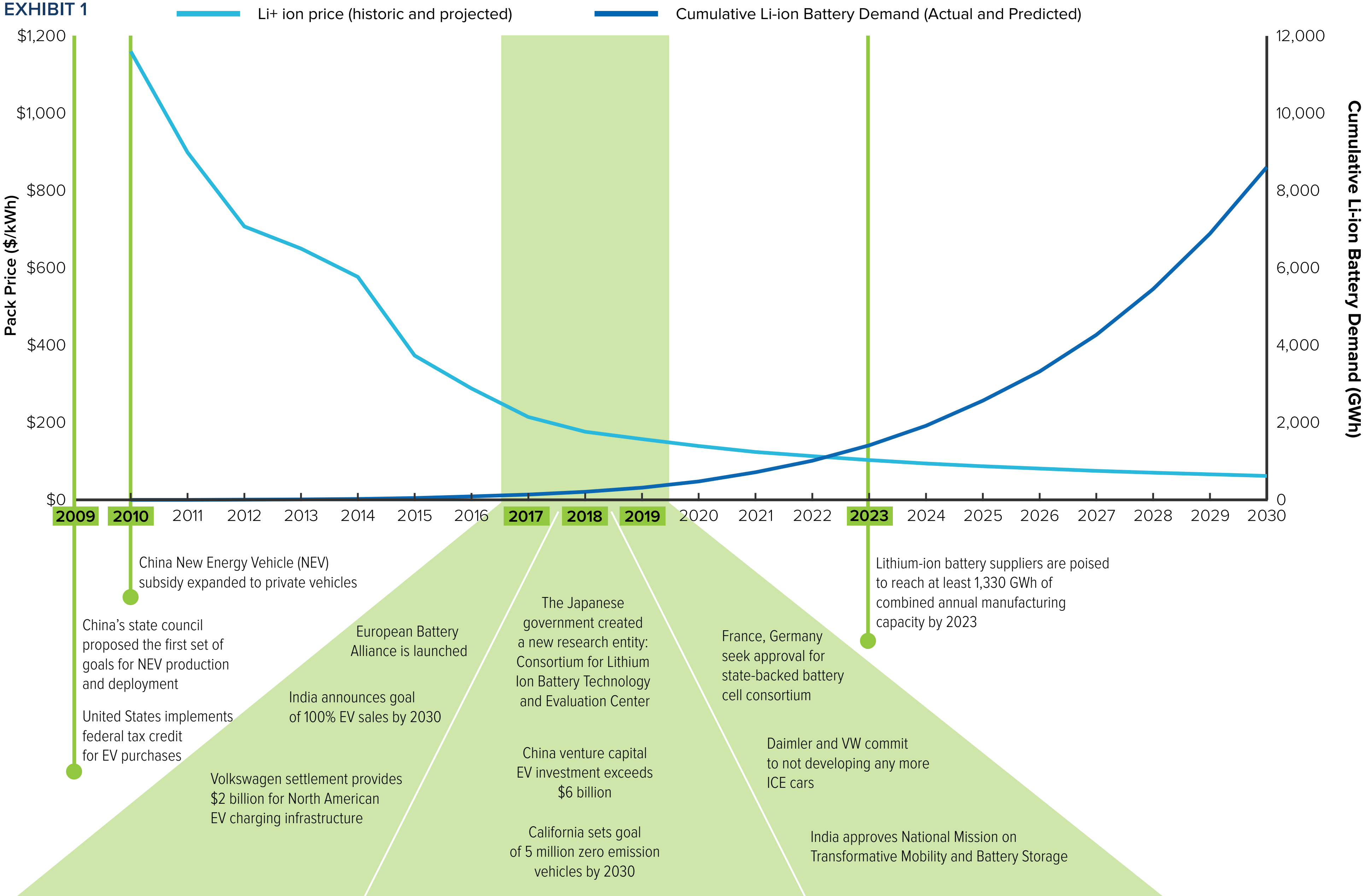
- **Ambitious Government Support:** Government support for early-stage research and development (R&D) continues to drive new innovations. As countries and major cities set ambitious goals for electric vehicle (EV) adoption, programs to support domestic battery manufacturing have followed.[5]

- **Strategic Alliances:** A diverse array of players—vehicle OEMs, oil and gas majors, and battery manufacturers—are forming strategic alliances with companies working on alternative battery technologies in efforts to gain a competitive edge.

- **Diversifying Global Manufacturing Investment:** These incentives and the anticipated exponential growth in EV adoption have led to massive investments in lithium-ion (Li-ion) battery manufacturing capacity, which is expected to more than triple to 1.3 TWh by 2023.[6] More than half of this capacity is in China, but countries in Europe and other parts of Asia have announced their own investments in an effort to compete, many with new lithium battery chemistries.

EXHIBIT 1

Summary Timeline of Li-ion Battery Market Development for EVs



Investment in research and development (R&D) will continue to unlock better performance, while faster adoption in both mobile and stationary applications will create self-reinforcing feedback loops for demand growth and price decreases.

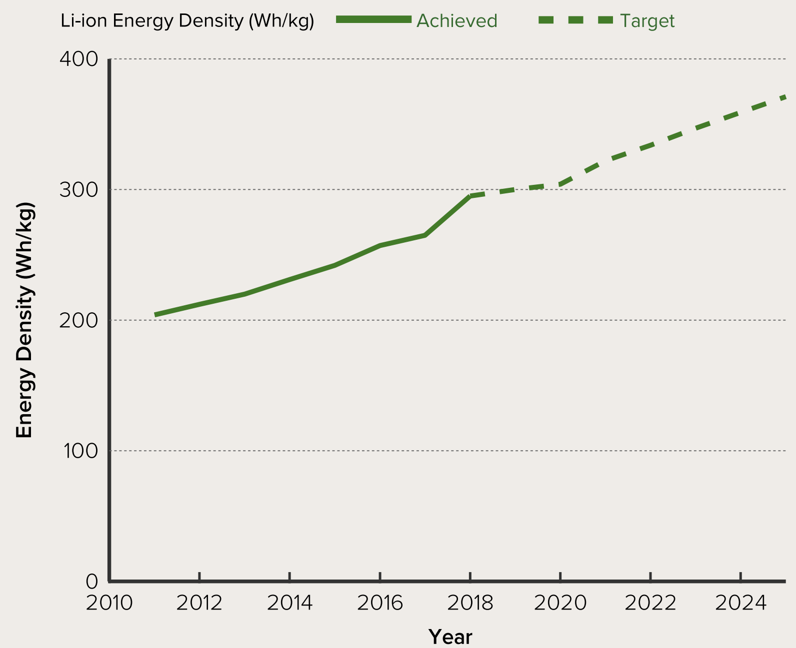
The combined outputs of these ecosystem elements have compounding effects, leading to a far faster rate of innovation and disruption than most analysts have expected. The resulting nonlinear increase in the value proposition of battery technology across multiple applications reinforces the cycle of demand creation and investment.

Performance Multipliers

Historic and continuing investments in Li-ion technologies are leading to batteries that perform better against multiple attributes, especially energy density and cycle life (Exhibit 2).[7] The resulting improvements in EV range, price, and model availability will foster rapid, near-term acceleration of consumer adoption. As illustrated in Exhibit 3, such improvements have multiplicative and self-reinforcing effects—as the prices decrease, batteries are simultaneously becoming longer lasting, lighter, and safer, leading to rapid increases in value for customers. As early adoption shifts to exponential growth, additional investment and enabling policies reinforce the cycle of innovation. Newer innovations approaching commercialization, such as solid-state technology, could unlock even more dramatic cost reductions and step changes in performance.

EXHIBIT 2

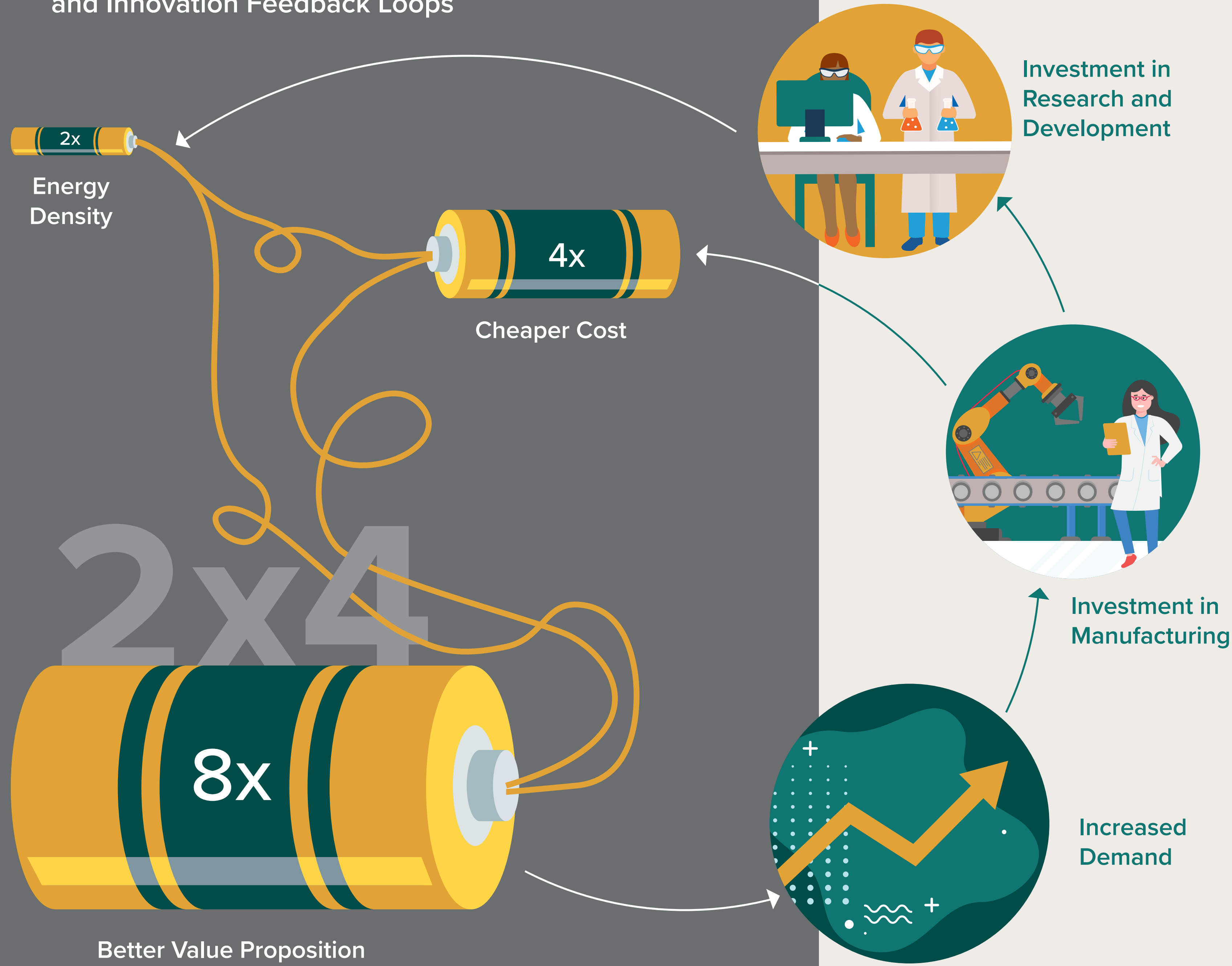
Energy Density Is One Example of a Continual Performance Improvement That Has Compounding Effects on the Value Proposition of Advanced Battery Technologies



Source: Data from BNEF

EXHIBIT 3

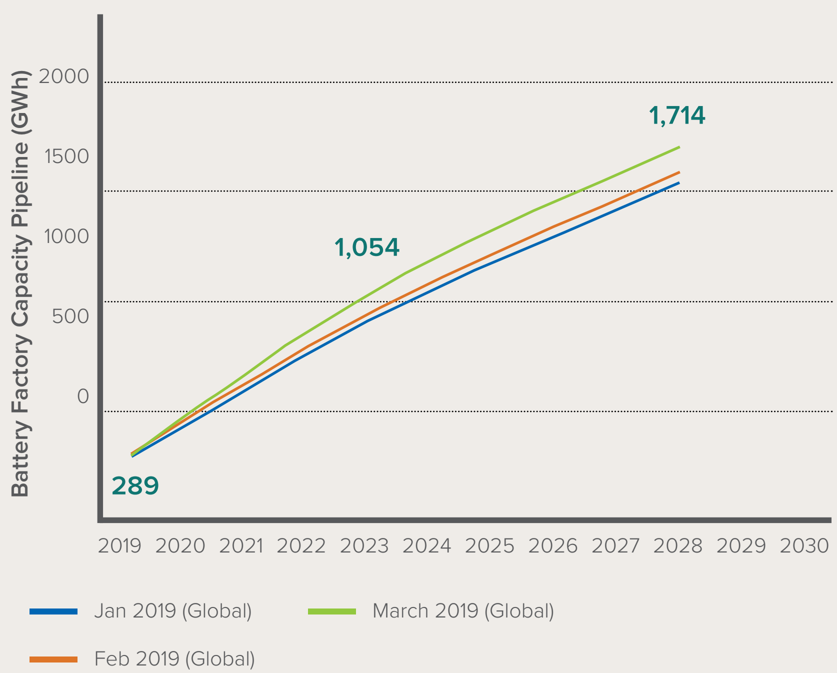
Cost and Performance Improvements Drive Investment and Innovation Feedback Loops



Dramatic scaling effects: Ambitious governmental EV adoption targets and significant growth in adoption rates have sent signals to manufacturers and capital markets that have encouraged investments in the Li-ion supply chain. In early 2019, updates to announced battery manufacturing capacity increased substantially on a monthly basis, suggesting that investors were responding to perceived market growth opportunities (Exhibit 4).[8,9] As this new production capacity comes online, price declines driven by economies of scale, manufacturing technology and process improvements, and industrial and unit design will continue. Battery pack prices have fallen by an average annual rate of 21% since 2010, or at an 18% learning rate with every doubling in production (Exhibit 5).[10] Analysts expect the capital cost for new planned manufacturing capacity (on a per-gigawatt hour [GWh] basis) to drop by more than half from 2018 to 2023.[11]

EXHIBIT 4

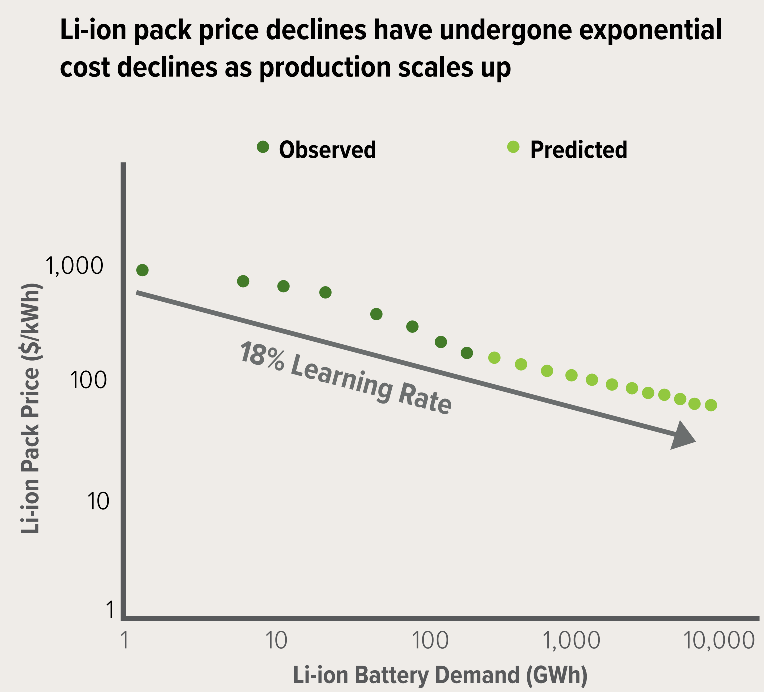
2019 Q1 Growth in Global Battery Factory Capacity Pipeline (GWh)



Source: Benchmark Mineral Intelligence

EXHIBIT 5

Historic and Projected Li-ion Pack Price Declines against Production



Source: Data from BNEF

These investments will push both Li-ion and new battery technologies to cross competitive thresholds for new applications more quickly than anticipated.

Li-ion battery chemistries began to scale, differentiate, and proliferate with cell phones and laptops. Now, as the battery market continues to grow, the number of competitive use cases will similarly expand beyond light-duty EVs. As illustrated in Exhibit 6, energy storage will contribute to the replacement of natural gas plants and gain a foothold in other new market segments, including heavy trucking and short-range aviation. As this transition occurs, legacy infrastructure across the fossil fuel value chain risks becoming stranded, including gas pipelines and internal combustion engine (ICE) manufacturing plants.[12]

Diversifying applications will create opportunities for new battery chemistries to compete with Li-ion.

- Solid-state batteries such as rechargeable zinc alkaline, Li-metal, and Li-sulfur will help electrify heavier mobility applications.
- Low-cost and long-duration batteries such as zinc-based, flow, and high-temperature technologies will be well suited to provide grid balancing in a high-renewable and EV future.
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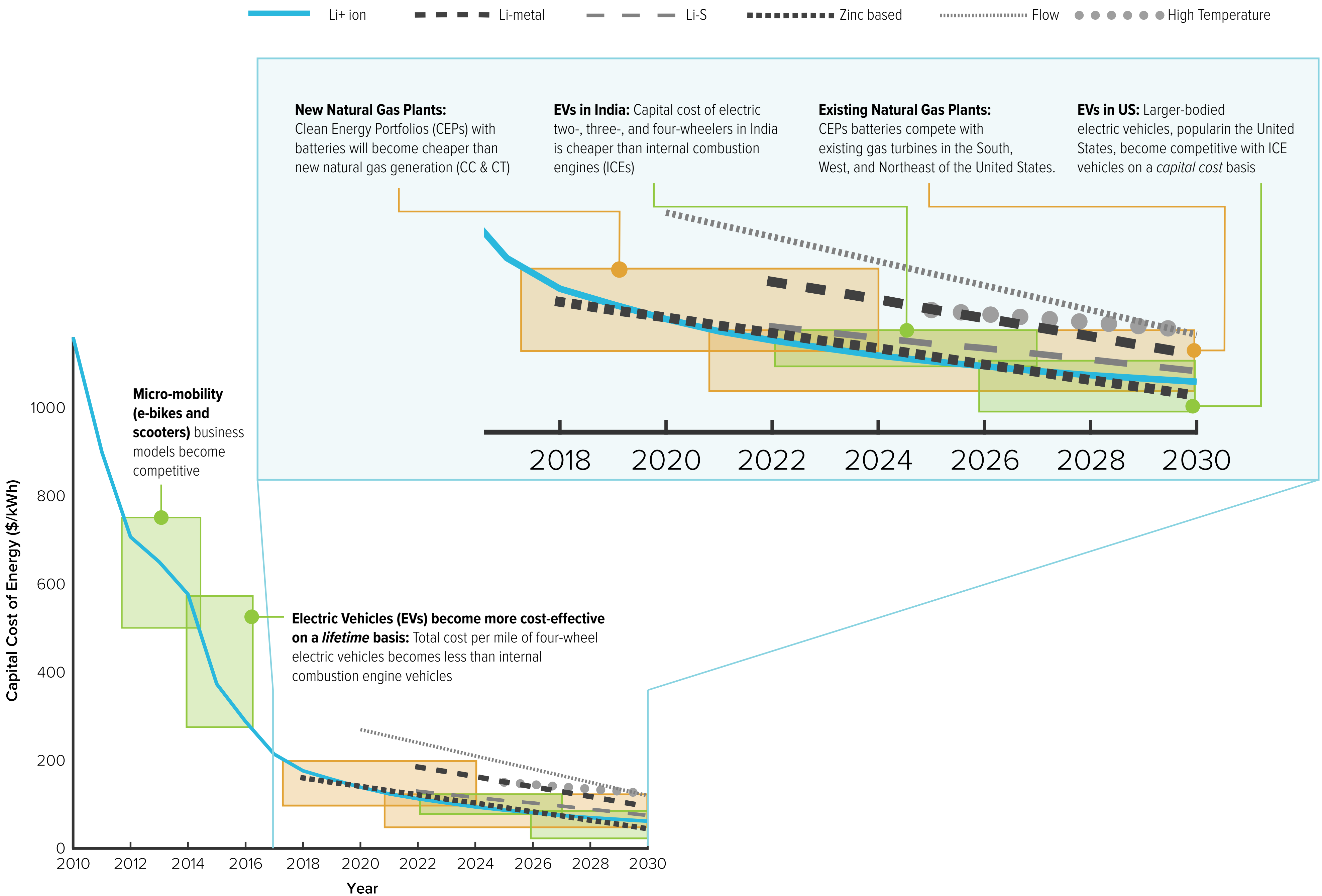
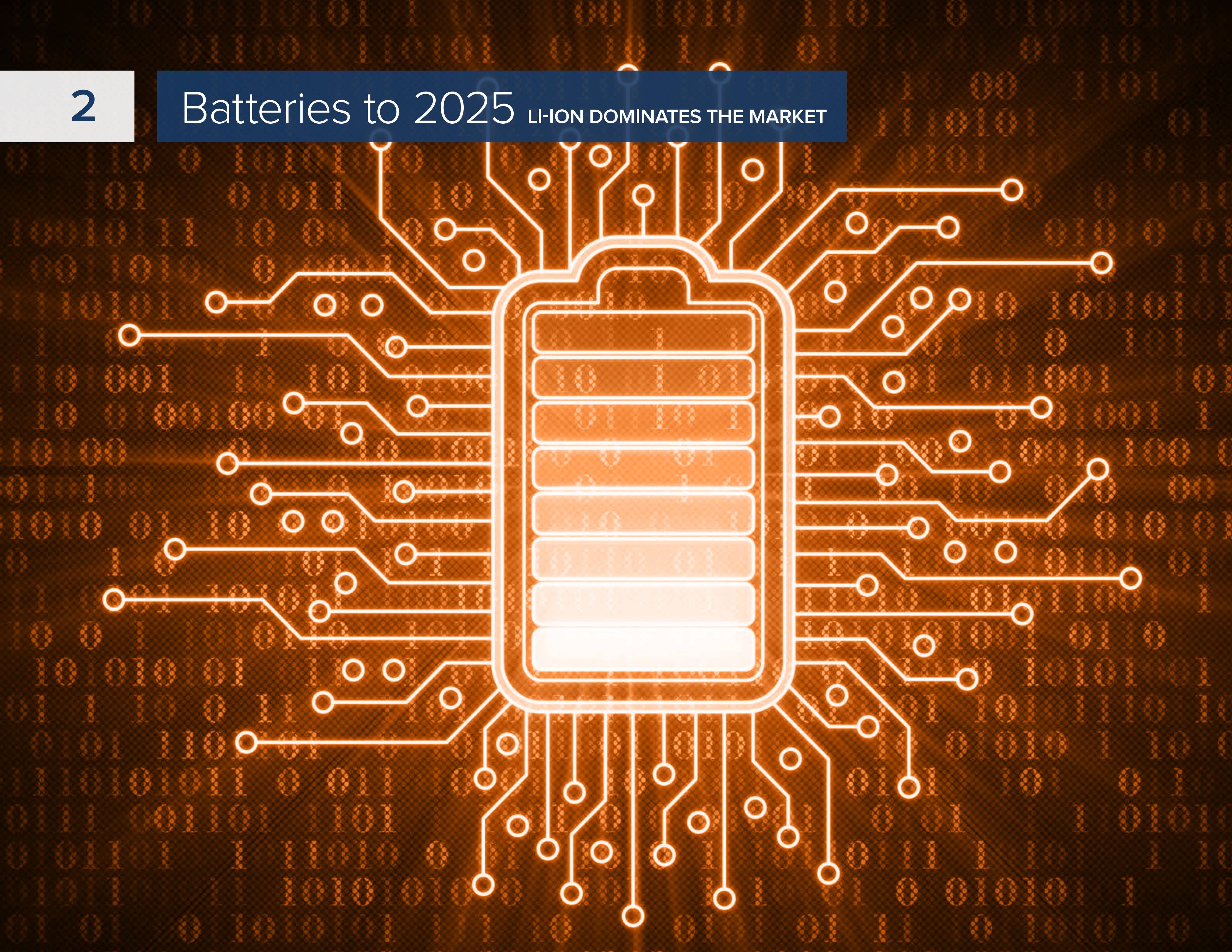
EXHIBIT 6

Competitive Thresholds for Advanced Battery Technologies to Displace Incumbent Technologies



2 Batteries to 2025 LI-ION DOMINATES THE MARKET



CONTINUED DIVERSIFICATION OF LI-ION TECHNOLOGIES

Li-ion batteries' scaling pathway is unlike that for silicon photovoltaic cells; investment continues to differentiate among chemistries with performance attributes that are best suited to specific use cases.

As investment in Li-ion grows, companies are pursuing different battery chemistry compositions with widely varying performance attributes (Exhibit 7). The number of battery types will likely continue to diverge in terms of the types of anodes, cathodes, separators, and electrolytes used. These various approaches are pursuing improvements across several areas:

- **Specific Energy:** Competition between EV manufacturers will continue to fuel the search for more space- and weight-efficient batteries. Li-nickel manganese cobalt oxide (NMC) and Li-nickel cobalt aluminum (NCA) chemistries have the most effort directed toward increasing energy density at an affordable cost.

- **Cycle Life:** Fast charging and temperature strain have big impacts on Li-ion battery cycle life. Li-iron phosphate (LFP) and Li-titanate (LTO) have good cycle life but are not the main focus of current manufacturing additions, as this cycle life comes at the expense of specific energy and cost.[13] These two chemistries will retain market share and may grow in the future.

- **Safety:** Todays Li-ion batteries are vulnerable to cooling and controls failures due to their use of highly flammable electrolytes. The required thermal management systems and controls add around 1%–5% to total pack costs, and decrease round trip efficiency. Project developers, investors, policymakers, and regulators should gain familiarity with differences in manufacturer quality to minimize risk.

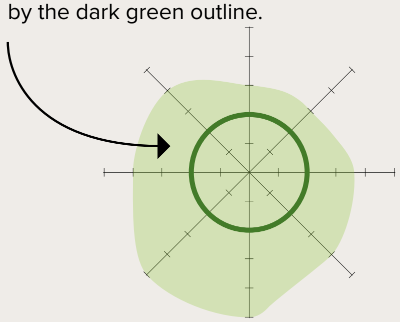
- **Cost:** Battery packaging costs represent around 19%–34% of the total pack price.[14] Continual manufacturing improvements are expected to reduce packaging costs by 10%–15%.[15] Cathode improvements represent one key area for cost reduction, especially decreasing cobalt content (e.g., moving from NMC 111 to NMC 811.)[ii] This requires significant R&D and carries similar technological risks to other new battery chemistries.

[ii] NMC 111 refers to the ratio of nickel, manganese, and cobalt. 811 has 8 parts nickel for every part manganese and cobalt. Other combinations, like NMC 532, have also been successful.

EXHIBIT 7

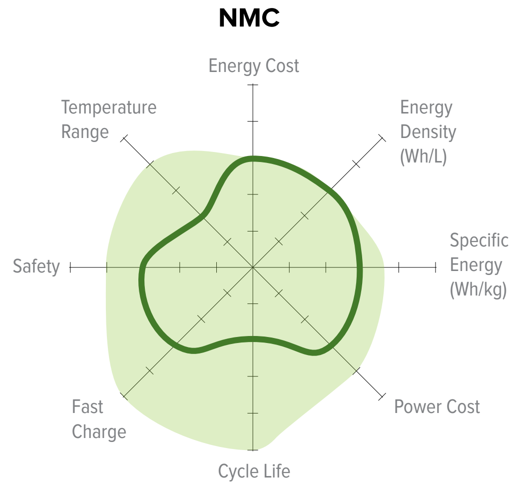
Relative Performance Characteristics of Selected Li-ion Chemistries

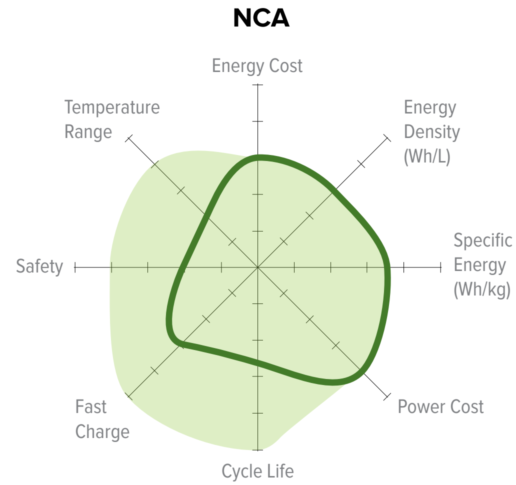
How each battery type currently performs on each metric is represented by the dark green outline.

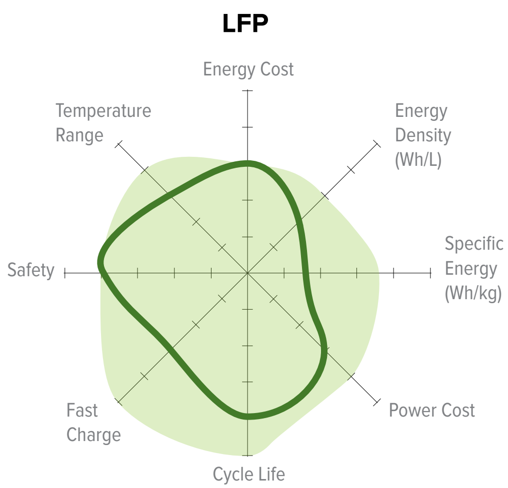


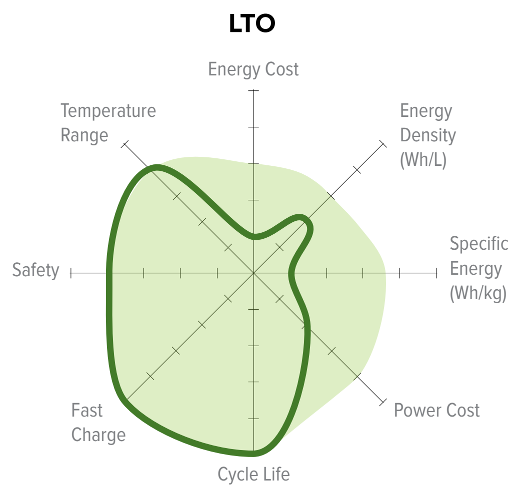
The highest theoretically achievable level for each metric of the Li-ion chemistries here is represented by the green-shaded area.

Existing Li-ion Chemistries









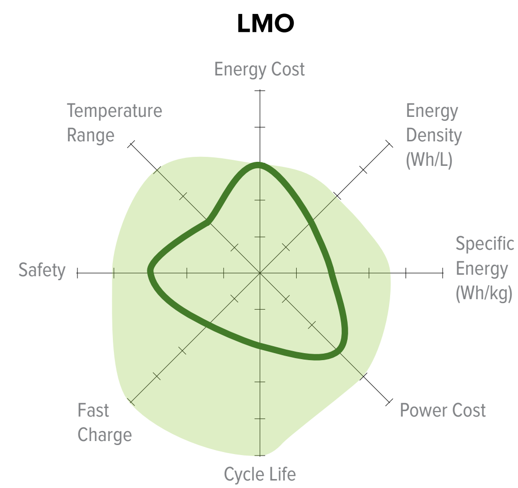


EXHIBIT 8

The Varying Characteristics of Li-ion Chemistries Contribute to the Diversification and Specialization of Use Cases and Integrators

	Primary Use Cases	Representative Manufacturers
NMC	Power tools, electric vehicles	CATL, Sanyo, Panasonic, Samsung, LG Chem, SK Innovation
NCA	Electric vehicles	Tesla/Panasonic
LFP	Electric buses, grid storage	BYD, K2, Lishen, Saft, GS Yuasa, A123, Valence, BAK
LTO	Personal electronics, UPS, some electric vehicles	Altairnano, Toshiba, Yabo
LMO (Li-manganese oxide)	Power tools, some electric vehicles (often combined with NMC)	Hitachi, Samsung, LG Chem, Toshiba, NEC

Resulting innovations could improve all aspects of Li-ion battery performance, but tradeoffs persist.

Automotive companies, start-ups, national research labs, and universities are heavily invested in improving Li-ion batteries. Exhibit 8 illustrates common target applications of these technologies along with several companies manufacturing them. Exhibit 9 shows some of the key opportunities for improving Li-ion batteries against each performance attribute that a host of companies are pursuing. While a future Li-ion chemistry may perform better across all metrics, battery research into different compositions historically results in tradeoffs between performance characteristics. As a result, different batteries will be better suited to diverging applications based on their unique performance qualities.

For example, NMC innovators are trying to realize a low-cobalt cathode (NMC 811); however, since cobalt acts as a battery stabilizer, low-cobalt chemistries tend to sacrifice stability and cycle life in exchange for cost and range improvements.

EXHIBIT 9

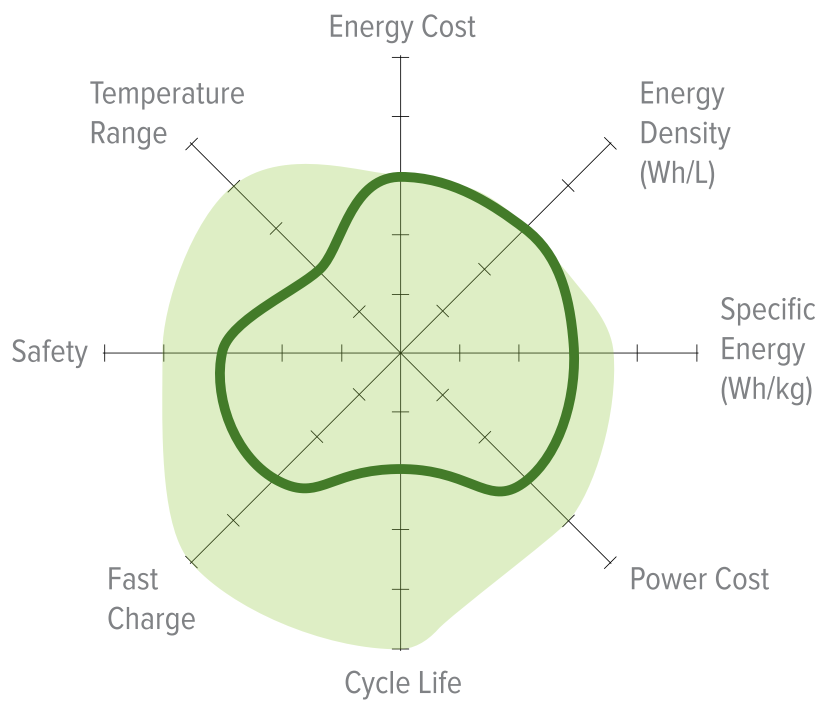
Future Advancement Pathways for Li-ion Battery Performance

ENERGY COST
Lower material costs will come primarily from reducing cobalt and systems costs in solid-state batteries

TEMPERATURE RANGE
Solid-state electrolytes represent one of the most likely solutions to improve performance in hot and cold environments

SAFETY
Solid-state electrolytes could significantly improve safety by replacing flammable electrolytes

FAST CHARGE
Improved electrolytes (solid state and liquid), cathodes, and anodes are needed to realize affordable and safe fast charging



SPECIFIC ENERGY (WH/L) / ENERGY DENSITY (WH/KG)
Silicon anodes are one of the main innovation pathways for improving energy density

POWER COST:
Most product improvement plans are focused on increasing cell voltage, which often comes at the expense of cycle life

CYCLE LIFE
Cycle life has some of the most difficult trade-offs with other improvement traits, although progress continues

DISRUPTIVE IMPACTS OF FALLING COSTS AND IMPROVING PERFORMANCE

Falling battery costs will change the economics of wholesale power markets, potentially stranding investments in new natural gas-fired power generation plants across the globe, even in cold climates.

In the United States alone, utilities have proposed $70 billion of natural gas plants in the next decade. Increasingly, however, new natural gas power plants are being outbid by competitive solar- or wind-plus-storage projects. Recent analysis by RMI on clean energy portfolios (CEPs) shows that this trend is likely to accelerate (Exhibit 10).[16] CEPs are optimized, least-cost combinations of wind and solar generation, energy efficiency, demand response, and energy storage that provide services matching those provided by natural gas plants. While battery storage is a higher-cost flexibility resource relative to demand flexibility (e.g., energy efficiency and demand response), a level playing field for those resources to compete on the grid can create an overall more efficient and less expensive system. The projected cost of CEPs has fallen 80% over the last ten years, driving expectations of rapid ongoing growth in grid-tied storage installations in the United States. Current trends show that battery installations will double from 2018 to 2019, with more than 600 MW of storage in development.[17]

While most of these low-cost procurements have occurred in resource-rich (solar or wind) environments, the falling cost of storage is driving competitiveness of CEPs in more markets. RMI modeled CEPs optimized to directly replace planned gas combined cycle (CC) and combustion turbines (CT) in the United States. This study included follow-on analysis to test two different battery scenarios—incremental and disruptive—to understand how battery innovations and improvements would affect the competitiveness of

EXHIBIT 10

Modeled Savings From a Clean Energy Portfolio Versus Currently Planned Natural Gas Plants (Grid-Storage Scenarios)

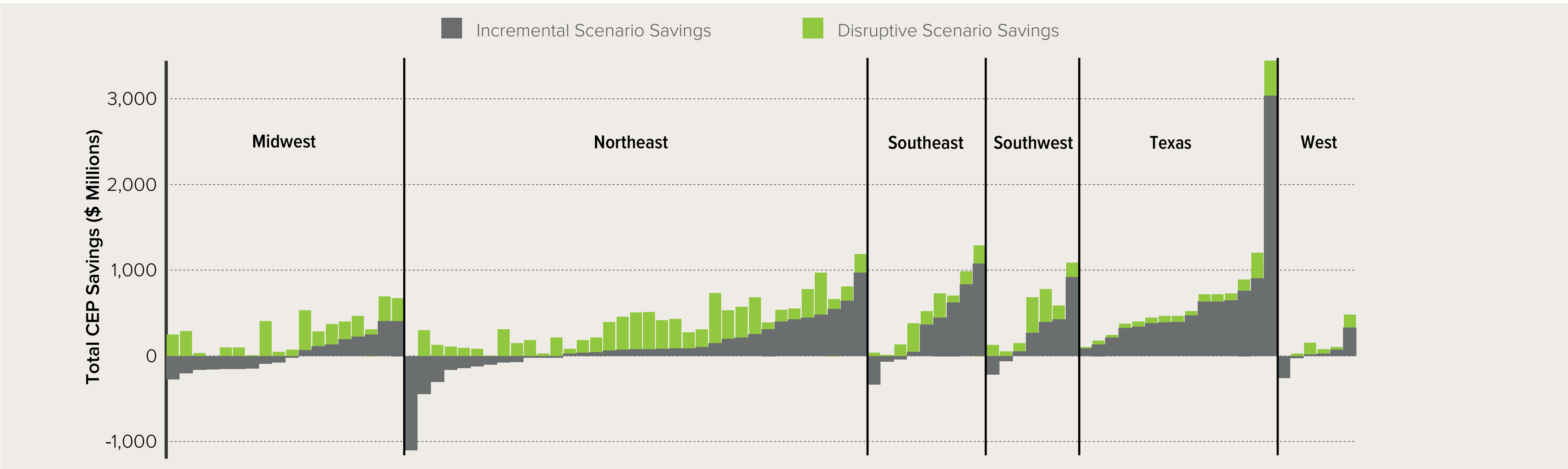
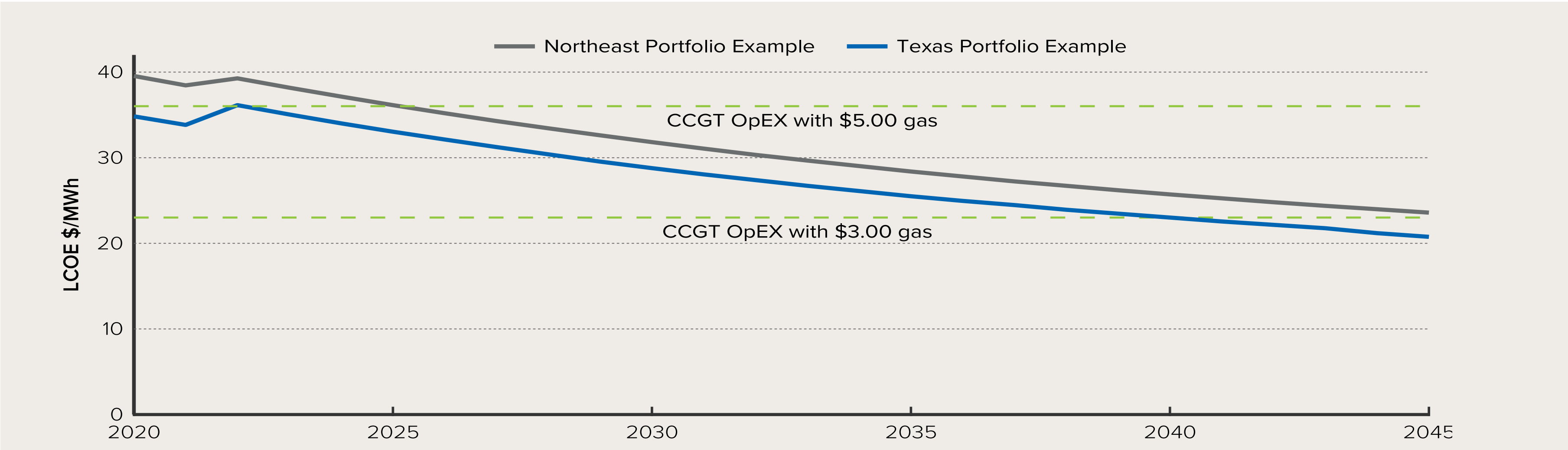


EXHIBIT 11

Comparison of CCGT OpEx Versus Clean Portfolio LCOE in Disruptive Battery Scenario



CEPs. The incremental scenario represents the price trajectory for Li-ion batteries inclusive of continuous cathode and anode improvements. The disruptive scenario represents a price trajectory in which low-cost materials for grid storage, such as zinc- or sulfur-based batteries, gain greater market share due to improvements and scaling.

The disruptive scenario results suggest that CEPs with significantly better batteries could unlock substantially larger lifetime savings compared with those achieved in the incremental scenario when compared to currently planned gas plants. These battery improvements are especially critical in colder climates, which face significant variability in renewable supply that cannot be met with demand response and energy efficiency alone. Keeping procurement open to the most cost-effective solution, including non-lithium alternatives, will be critical for realizing the value of these innovations and saving rate-payers money.

Falling costs of batteries and renewable power supply will make CEPs cheap enough to strand existing natural gas plants.

Under the disruptive battery scenario, continuing cost declines will make CEPs competitive with the operating costs (OpEx) of existing combined cycle gas plants within ten years over a range of natural gas prices (Exhibit 11). This has important implications for plant owners and operators as well as the upstream gas industry. Modeling these solutions suggests that such CEPs will begin to compete after 2025, depending on gas prices. In reality, however, they will likely compete earlier for portions of those gas plants' loads, since batteries at multiple scales can contribute to managing and flattening demand and generation profiles. While this approach provides a useful illustration of breakthrough batteries' disruption potential, precisely replicating a gas turbine's profile captures only one aspect of batteries' value, as they can participate in multiple, stacked markets, and may take on different operational profiles than a gas turbine.

By 2023, lower capital costs will contribute to a scale-up of EV adoption in markets like India that utilize smaller EVs.

Many EVs are already cost-effective on a total cost of ownership (TCO) basis, but the higher capital costs of EVs compared with internal combustion engine vehicles remain a major adoption barrier.[18] Markets like India that use smaller and lighter EVs are expected to become competitive well before markets where larger vehicles dominate. Exhibit 12 shows that four-wheeled EVs will become competitive on a capital cost basis in India around 2023 (due in part to increasing emissions regulations on ICE vehicles). Electric vehicles using advanced Li-ion batteries in the United States may not cross capital cost thresholds until 2030 (Exhibit 13).

Investors, policymakers, and market players should consider that:

- Urban and smaller-vehicle markets are important first markets for scaling electric mobility.
- Alternative business models and strategies like mobility as a service that can leverage disruptive innovations related to autonomous driving may be needed to rapidly electrify markets that have a strong consumer preference for large vehicles.
- Battery innovations and improvements, including beyond Li-ion chemistries, will be important for personally owned, heavier EVs.

EXHIBIT 12

Capital Cost (INR) of Private Cars in India

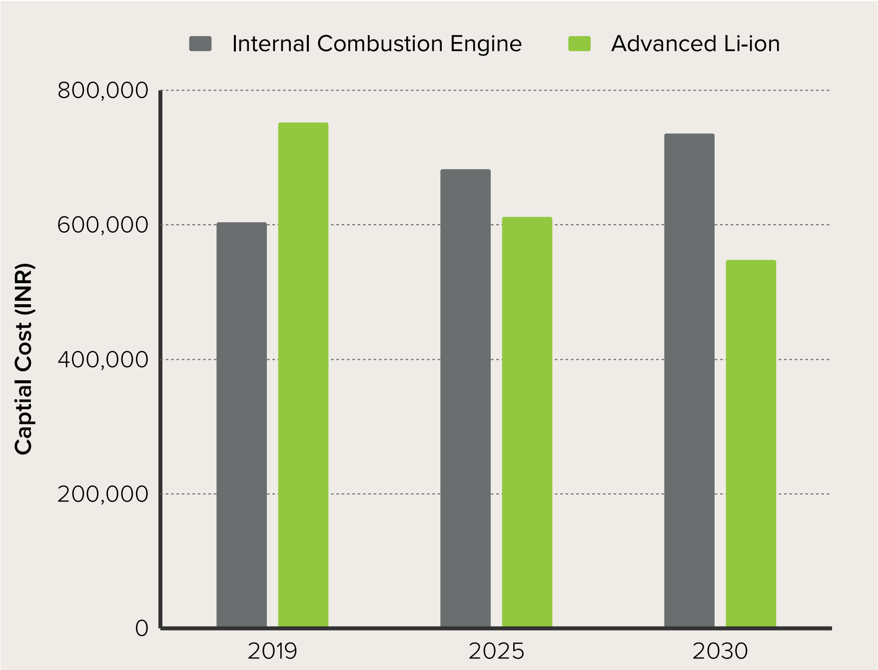
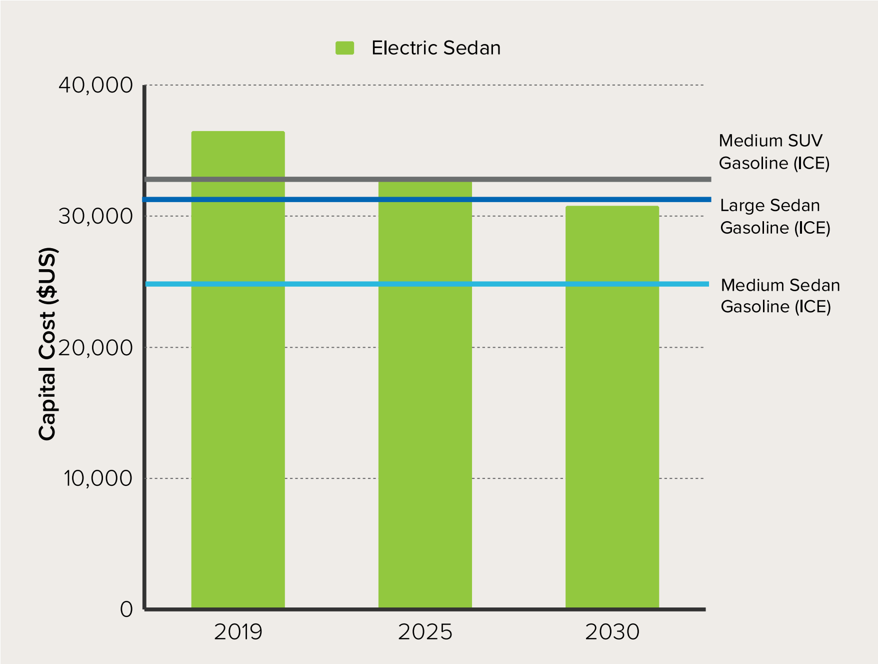


EXHIBIT 13

Capital Cost ($) of Vehicles in the United States



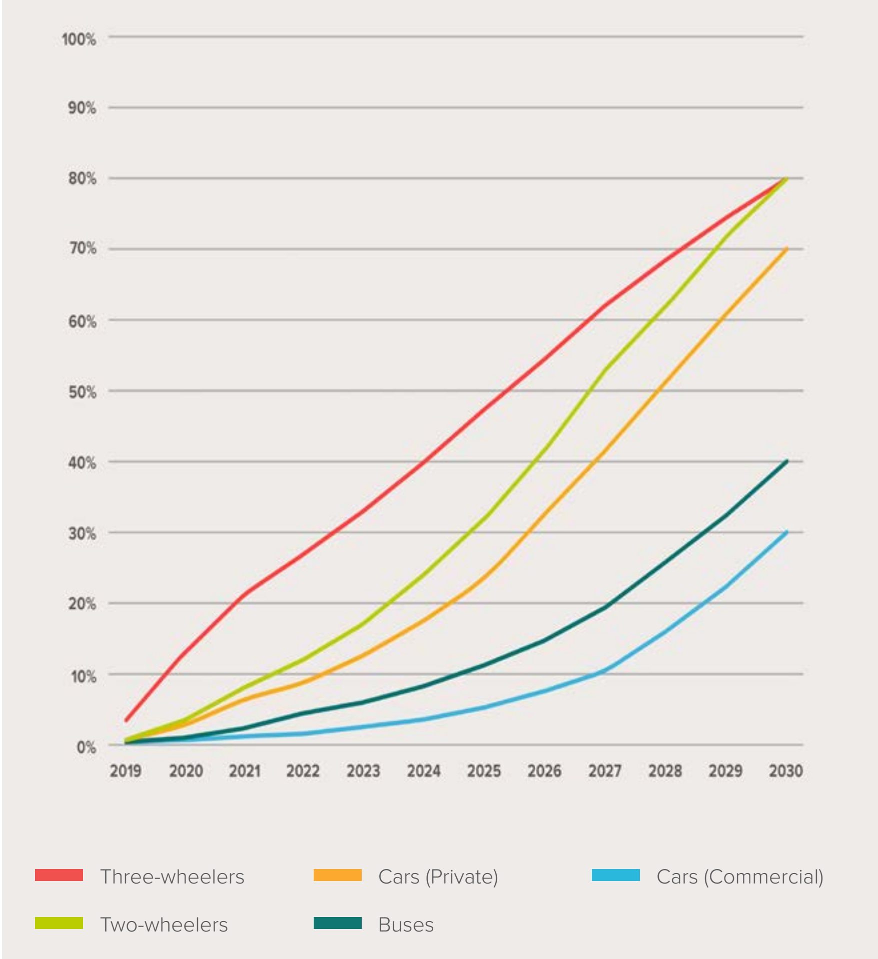
Battery cost and performance improvement trajectories could help two- and three-wheeler markets in India and other emerging market countries reach sales penetration levels of 80% by 2030.

These markets, dominated by lighter vehicles, represent an enormous investment opportunity for vehicle and battery manufacturers. Given increases in GDP per capita, vehicle ownership in India is expected to grow 7% annually until 2035. From 1991 to 2012, the number of cars, motorcycles, and scooters in India increased 7X against a 5X GDP-per-capita increase. In 2019, four million cars, 12 million auto-rickshaws, and 12 million two-wheelers are expected to be sold nationwide. From 2019 to 2035, vehicle stock of cars is expected to increase from 35 million to 96 million, while vehicle stock of three-wheelers is expected to grow from 7 million to 28 million.

Electric two- and three-wheelers are expected to become competitive on a capital cost basis by 2023, and will account for over 80% of such passenger vehicles sold by 2030 (Exhibit 14).[iii] While cars are also estimated to have a lower upfront cost by 2023, they constitute only about 30% of India's total vehicle miles traveled. Surrounding economies like Indonesia and the Philippines are likely to see similar light EV growth in the near term.[19] Policy efforts to support battery manufacturing and EV ecosystem development may enable other nations in the region to take advantage of this rapid market growth.[20]

EXHIBIT 14

India: Expected EV Sales Penetration with Significantly Cheaper and Long-Lasting Battery Technologies



[iii] Segment-wise penetration of EVs in new vehicle sales in this scenario are 30% for private cars, 70% for commercial cars, 40% for buses, and 80% for two- and three-wheelers by 2030. This scenario assumes that FAME II and other policy measures initiated by central and state governments will help trigger rapid adoption of EVs in the country.

KEY NEAR-TERM CHALLENGES

Despite this trajectory and huge market opportunities, Li-ion will not be a winner-take-all solution.

Rapid performance improvements coupled with dramatic cost reductions have made Li-ion the seemingly ubiquitous battery technology. Its characteristic high energy density (relative to its predecessors) has made it ideal for personal electronics and mobility applications, as most consumers are content to recharge these devices once or twice a day. As Li-ion production has scaled to meet growing EV demand, manufacturing and soft costs have declined precipitously, making longer-duration applications seem almost within reach. Unfortunately, analysts and investors widely agree that the costs and characteristics of Li-ion (i.e., high-power, short-duration, shallow depth of discharge, or limited life cycle) make it less suitable for longer-duration grid-tied or longer-range or weight-sensitive mobile applications (e.g., aviation). Exhibit 15 shows that the levelized cost for grid applications of Li-ion depends significantly on achieving scientific improvements associated with advanced lithium ion, in addition to cost decreases from economies of scale (see Appendix for modeling assumptions).

Li-ion technologies may be outcompeted by other technologies based on:

1. **Plateauing Performance Improvements:**
   a. **Safety:** Li-ion requires costly thermal management systems, and fire risks continue to impede more rapid deployment.
   b. **Energy Density:** High-energy and high-power applications such as heavy transport and aviation will require technology breakthroughs beyond the pace of current incremental improvements in Li-ion batteries.[iv]
   c. **Deep Discharge and Long Life Cycle:** Long life cycles are especially important for grid applications. Li-ion batteries will need to attain 2X cycle life improvements at 100% depth of discharge to remain

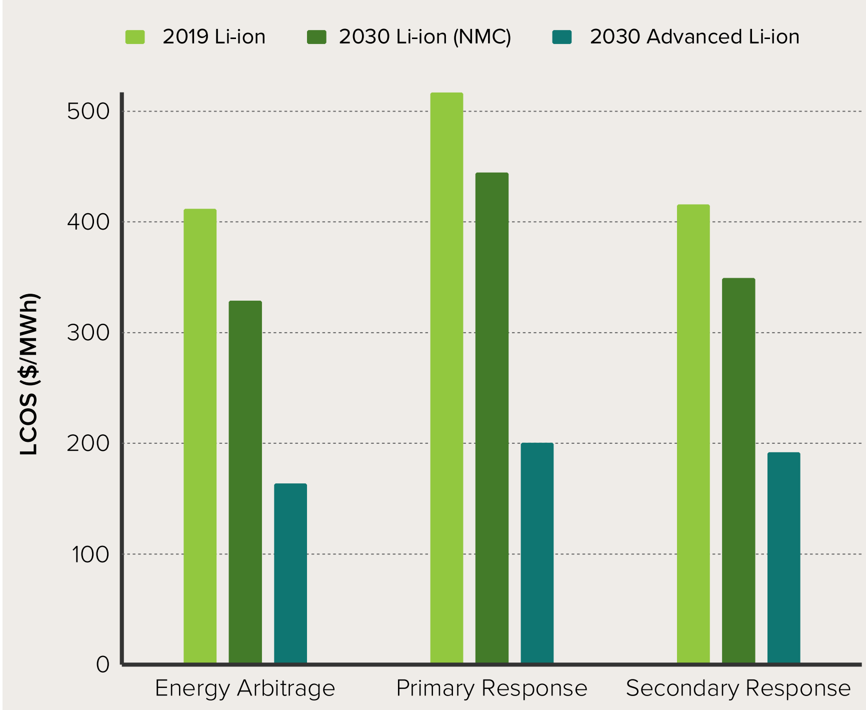
[iv] Current energy densities are <300 Wh/kg (gasoline = 12,000 Wh/kg).

competitive for today's most common grid applications on a levelized cost basis (Exhibit 15). Future markets such as integrating fast charging and long duration storage are likely better suited to other technologies.

2. **Constraints on Further Cost Decreases:**
   a. **Cobalt Supply Constraints:** Preferred Li-ion chemistries rely heavily on cobalt for stability and safety; cobalt supply, however, is limited and mostly supplied from unstable regions.
   b. **Limited Economies of Scale Gains:** As manufacturing and balance-of-system costs continue to decline, Li-ion pack costs will approach the underlying cost of raw materials, limiting the potential for further soft cost reductions.

EXHIBIT 15

Modeled Levelized Cost of Storage for Battery Technologies for Various Grid Services



In the context of grid storage, the market needs to move past making decisions on a capital cost basis, but there are challenges to using a cost-of-service-provided approach.

Transparency into levelized cost of storage (LCOS) across different grid services is crucial for making efficient decisions on battery system selection and affordable ratemaking. Unfortunately, a lack of meaningful or verifiable data threatens to slow progress on grid-tied battery adoption.

Alternatives to Li-ion could be well suited to multiple grid-tied use cases.

These technologies vary widely in their levelized cost to provide different grid services, due largely to their respective depth of discharge capabilities, degradation rates, and lifetimes. Battery technologies that offer lower degradation rates (e.g., flow, high temperature, or Li-ion LFP) could be less risky options for value-stacking use cases. Exhibit 16 shows modeled LCOS outputs for Li-ion and flow batteries under an assumed set of stacked value grid-support applications. See Appendix for details. Exhibit 17 summarizes the key performance characteristics and suitability of different battery technologies for various grid use cases.

LCOS needs to account for these value-stacking capabilities, but cumulative degradation and cycling costs for stacked value propositions are nascent.

Unfortunately, the long-term impacts of providing different grid services on a battery's cycling and degradation are poorly understood, with limited aggregated public data and significant variation between manufacturers. The US Department of Energy has created a Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems that outlines standard parameters to compare different solutions for specific use cases.[21] Such standardization is important, but the complexity (e.g., number of use cases, amount of information needed, difficulty and effort of obtaining that data) will remain a significant barrier to meaningful comparison that will only be reduced over time as storage markets mature.

EXHIBIT 16

Modeled LCOS for Flow and Li-ion Batteries For Various Grid Services, including Degradation Costs

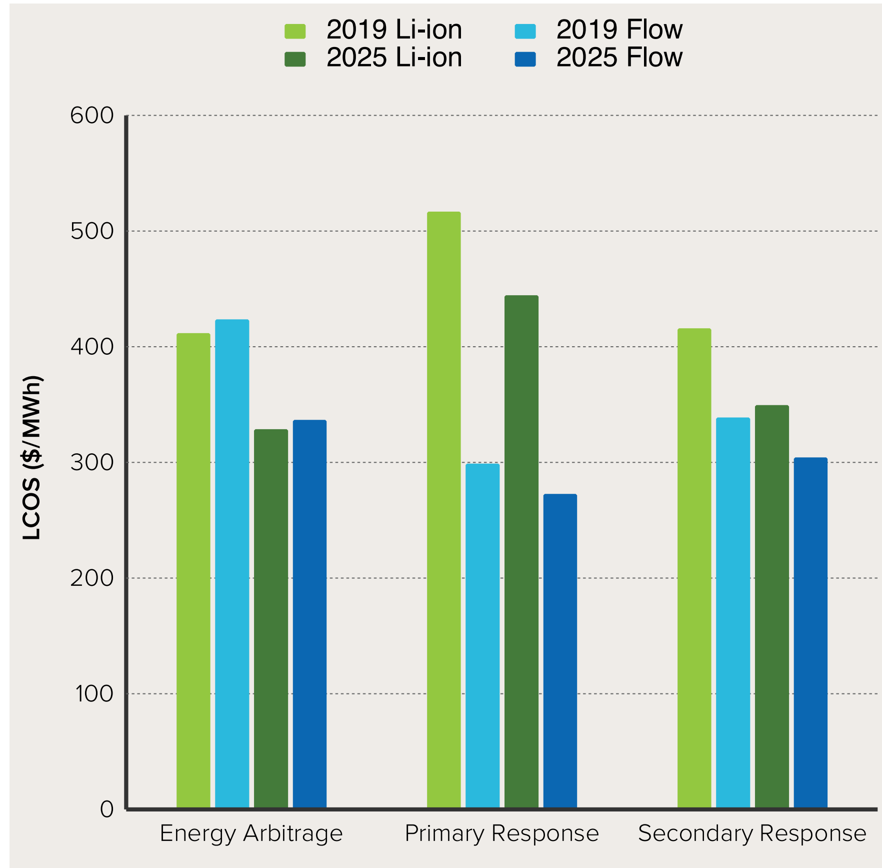


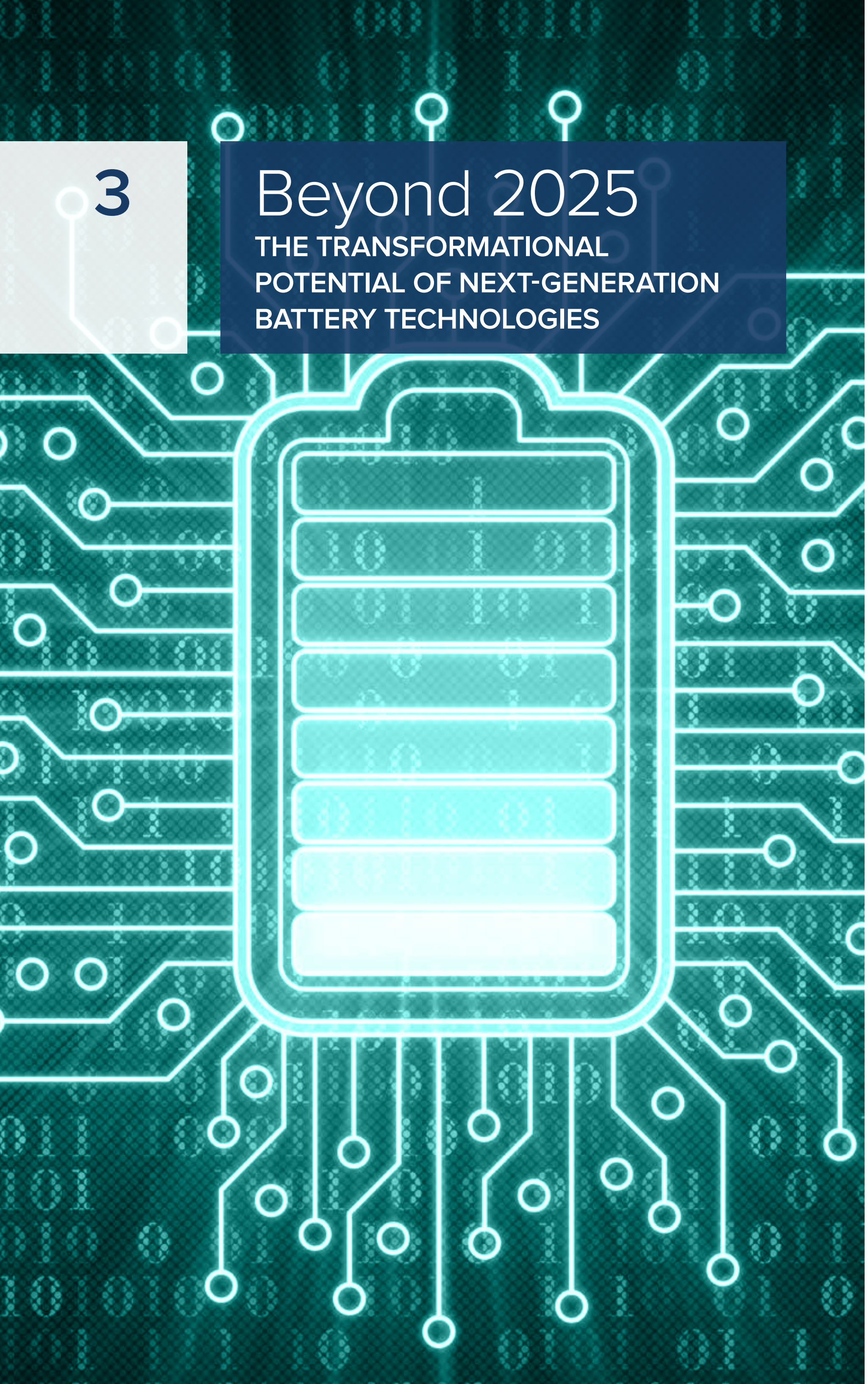
EXHIBIT 17

Battery Technology Suitability for Grid Use Cases[22,v]

	Energy Arbitrage	Primary response	Peaker Replacement	Secondary Response	Distribution and Transmission Deferral	Bill Management
	ISO/RTO			**Utility**		**Customer**
Duration (hours)	1–24	0.02–1	2–6	0.25–24	2–8	1–6
Size (MW)	0.001–2,000	1–2,000	1–500	10–2,000	1–500	0.001–10
Cycles/year	50–400	50–15,000	5–100	20–10,500	10–500	50–500
	Technology suitability for different use cases based on parameters above					
Current Li-ion	Medium Suitability	High Suitability	Medium Suitability	Medium Suitability	Medium Suitability	High Suitability
Advanced Li-ion	High Suitability	High Suitability	High Suitability	Medium Suitability	Medium Suitability	High Suitability
Flow	High Suitability	Medium Suitability	High Suitability	High Suitability	High Suitability	Medium Suitability
Zinc	Medium Suitability	Low Suitability	Medium Suitability	High Suitability	High Suitability	High Suitability
High Temperature	High Suitability	High Suitability	High Suitability	High Suitability	Medium Suitability	Low Suitability

High Suitability | Medium Suitability | Low Suitability

[v] Primary response includes applications such as frequency regulation and control. Secondary response includes applications such as following reserve, spinning and non-spinning reserve, and renewables integration. Peaker replacement refers to a system capacity mechanism to meet peak demand.



3 Beyond 2025

THE TRANSFORMATIONAL POTENTIAL OF NEXT-GENERATION BATTERY TECHNOLOGIES

DIVERSE PATHWAYS TO MARKET

An increasingly electrified, Li-ion battery-dominated world in the near term will open, in the longer term, significant new market opportunities for other emerging battery technologies that are nearing commercial readiness.

RMI's analysis of emerging battery technologies identified six categories (in addition to advanced Li-ion) with significant potential for achieving commercial production by 2025 (Exhibit 18). Potential commercialization pathways for each category are described in greater depth in the Appendix. Company commercialization timelines are examples, not endorsements, for each of the larger categories.

EXHIBIT 18

Examples of Emerging Battery Technology Commercialization Timelines

Timeline: 2018 — 2020 — 2025

Potential Commercialization Pathway

Technology	Example (timeline)	Company	MARKET ENTRY Low barrier to entry allows for early-stage prototyping	MARKET GROWTH High willingness to pay enables iterative product improvement cycles	MASS-MARKET CAPTURE Mature product available. Investments in scaling and customer acquisition
Lithium Metal	Liquid electrolyte	solid energy	Drones and UAVs	Longer Range EVs	High Power Applications
	Solid State Electrolyte	Solid Power			
Lithium Sulfur	Lithium Sulfur	OXIS ENERGY	Buses and Trucks	Aviation and Military	Longer Range EVs
Zinc	Zinc Air	NantEnergy	Low-Cost Backup and Microgrids	Defer Grid Upgrades	Ultra-Low-Cost Mobility
	Zinc Aqueous	eZn			
	Zinc Solid State Electrolyte	ionic MATERIALS			
High Temperature	High Temperature	AMBRI	Grid Balancing	Industrial Microgrids	Long Duration Grid Storage
Flow Batteries	Redox	VIONX ENERGY	Industry/ Microgrids	Long Duration Grid Storage	EV Charging Grid Deferral
High Power	Advanced supercapacitors	ZAPGO	Consumer Electronics	Hybrid-Battery Mobility	Fast EV Charging
	Sodium Ion	Natron Energy – Energy Storage Innovations			

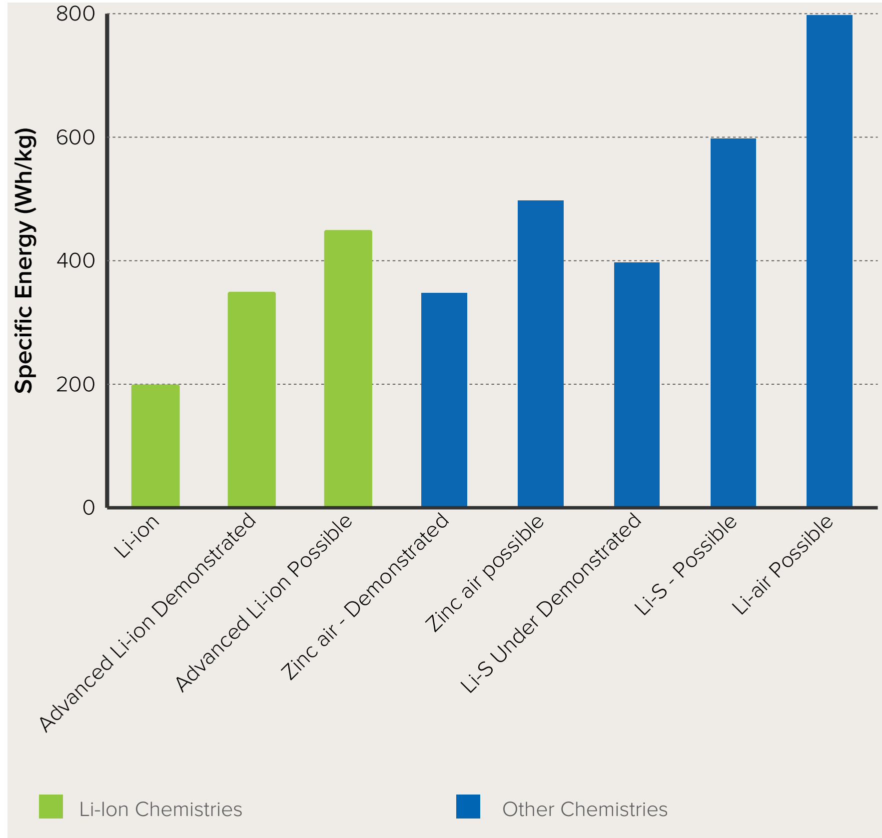
THE PROMISE OF SOLID-STATE TECHNOLOGY

Solid-state technology is poised to massively disrupt the storage industry by unlocking new opportunities for cheap, safe, and high-performing batteries.

1. **Solid state will be adopted first by OEMs that are currently pursuing advanced Li-ion for its safety and temperature characteristics**
   - Current Li-ion batteries have flammable liquid electrolytes. Thermal runaway is a persistent risk across all applications, and Li-ion will face increased scrutiny as the market continues its exponential growth.
   - Solid-state batteries are nonflammable, and could reduce dendrite growth, improve battery life, and improve performance in cold and hot climates.
   - Safety regulations will preclude the use of Li-ion batteries in applications like air travel; they also face shipping constraints.
   - Mobility and storage applications require costly temperature controls, which are increasingly targeted for cost reductions.
2. **Solid state will enable higher energy density, opening additional market opportunities**
   - Solid-state research has been driven by the desire for more energy-dense batteries, with the potential to quadruple specific energy (Exhibit 19[vi]).[23]
   - Solid state has the potential to make materials like Li-metal rechargeable.
   - Li-air has been long sought after but will depend on significant cathode improvements. Heavy R&D investments and continued improvements in zinc-air and Li-plating will make beneficial contributions.

EXHIBIT 19

Specific Energy (Wh/kg) of Different Battery Chemistries



"Once we move to solid state, you will see a whole other innovation curve."

– Dr. Gerbrand Ceder, Lawrence Berkeley National Lab

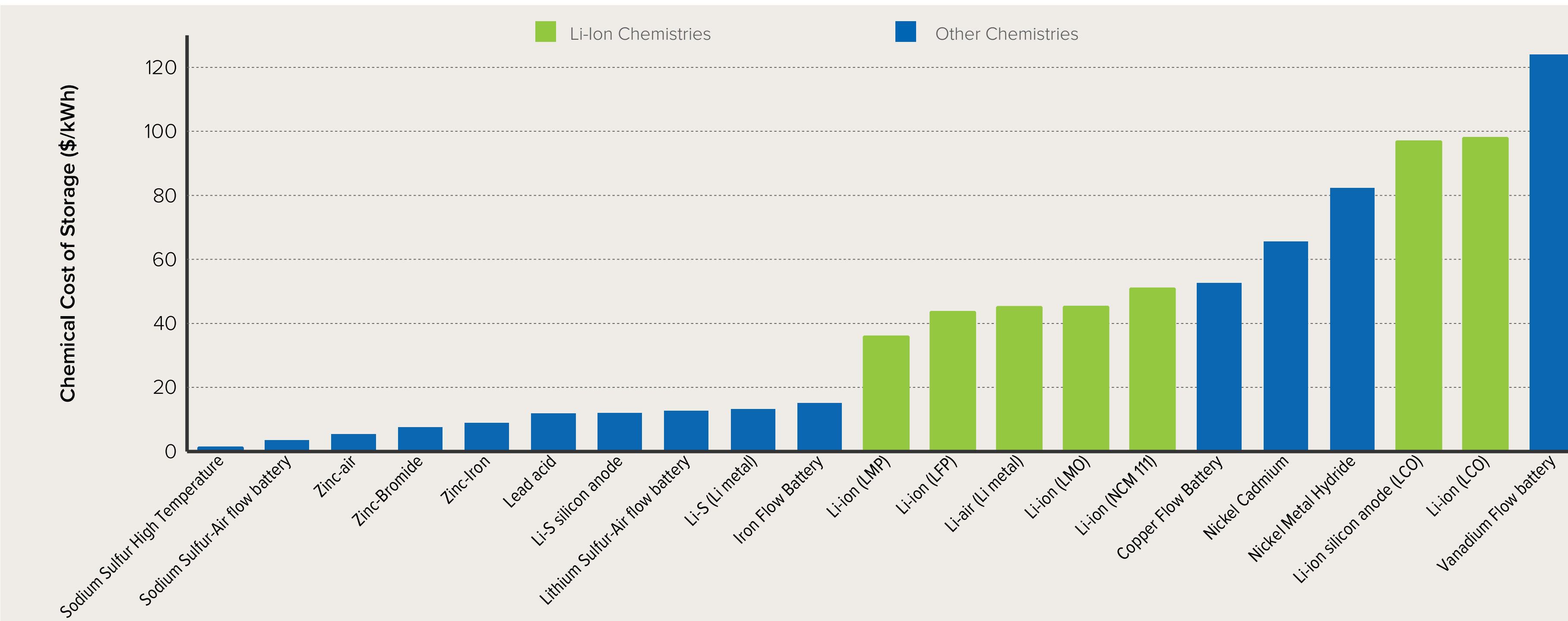
[vi] *Possible* represents possible for R&D to achieve, not theoretically possible based on personal interviews and research (Zn-air theoretical specific energy density =1,350 Wh/kg, Li-air theoretical = 11,430 Wh/kg. See Appendix for details)

3. **Solid state will enable the use of much cheaper materials**
   - Solid state could help researchers overcome rechargeability challenges in less expensive materials like zinc, aluminum, and sulfur, which could enable \$30–\$40/kWh batteries. (see Exhibit 20)
   - Some solid-state materials, such as Ionics' organic polymer, could be commercialized in Li-ion but then subsequently enable very inexpensive rechargeable alkaline batteries.

4. **Manufacturing integration is crucial to long-term success**
   - Some companies and research initiatives are focused on how to integrate solid state into existing Li-ion battery manufacturing processes, but some solid-state gigafactories are being planned that use different processes.
   - Li-metal investment must focus on low-lithium and thin film Li-foil manufacturing
   - Several solid-state companies are targeting 2024–2025 for initial EV commercial lines, but demonstrations would likely happen before then.

EXHIBIT 20

Estimated Cost of Raw Materials for Different Battery Chemistries[24]



EMERGING MARKETS: LONG-DURATION STORAGE, HEAVY TRANSPORT, AND FAST-CHARGING INFRASTRUCTURE

The potential size of and nascent demand in newly accessible battery application markets will reinforce increasing investment in R&D, demonstration, and early-stage deployment for both next-generation Li-ion and other battery technologies that are nearing commercialization.

Batteries will play a foundational role in scaling EV and related markets over the next decade. The large-scale investments in renewable energy and Li-ion batteries that support this ecosystem will also open up entirely new markets. The next sections consider each of three emerging market opportunities for advanced batteries: long-duration energy storage systems, heavy transportation, and EV charging system integration. They illustrate both the nascent market opportunity and some likely technology solutions that market actors should follow closely as they design policy, incentive, manufacturing, and investment strategies.

Long-Duration Storage

The long-duration stationary energy storage market will be large enough to commercialize new technologies.

Demand for stationary storage reached 20 GWh in 2018, and is projected to almost double every year in the next decade. This will play a large role in integrating renewable energy penetrations of 16%–20% by 2025.[25] Balancing the grid and replacing fossil fuels are expected to increase grid-connected battery support to 750 GWh over the next decade, with China and the United States projected to be the largest market segments.[26]

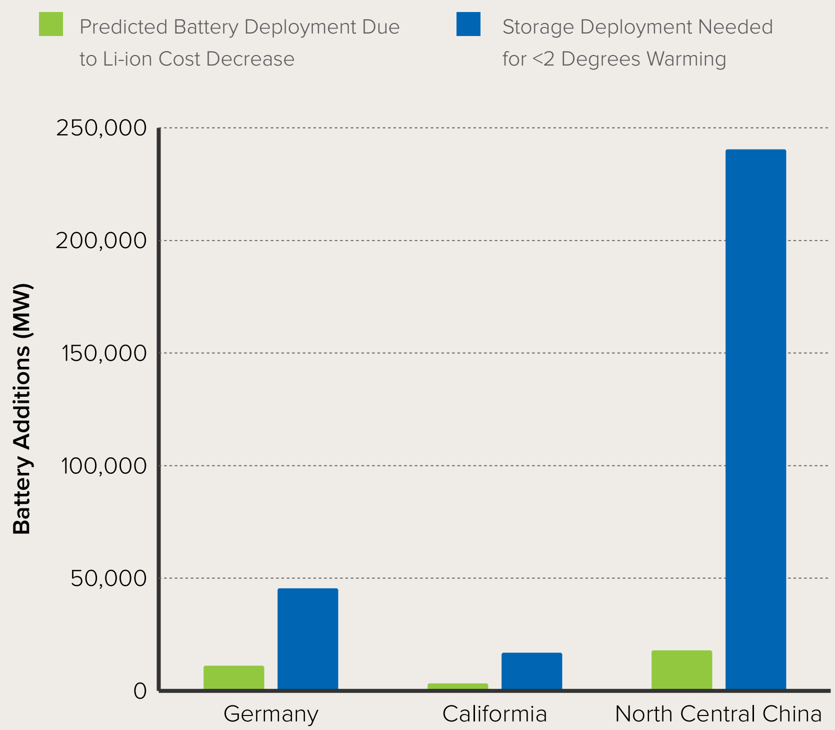
However, meeting electricity goals for <2C° global temperature increase may require deploying batteries much faster than Li-ion price decreases are predicted to enable (unless demand flexibility can be increased).

BNEF modeled the estimated amount of batteries needed to integrate the renewable energy generation required for a <2 degrees Celsius warming scenario and found that Germany, California, and North Central China required between 4 and 13 times more energy storage than is expected based on Li-ion cost decreases (Exhibit 21).[27] Aggregating this estimate would require 270 GW of additional storage by 2040 just for these three regions, on top of the 900 GW already expected globally based on price curves. A large portion of this capacity is expected to consist of storage durations in excess of four hours.

A simplified top-down analysis provides a complementary perspective. High renewable penetration modeling scenarios generally assume that 3%–7% of the total installed renewable capacity is required as additional interday energy storage to account for forecast and demand uncertainty.[28] If 60% of the 6,500 GW of current global electricity generation capacity were met with variable renewable energy, it would require between 120 and 280 GW of long duration storage, or enough capacity to power France plus Germany.[29]

EXHIBIT 21

Estimated Grid-Scale Battery Additions (MW) by 2040



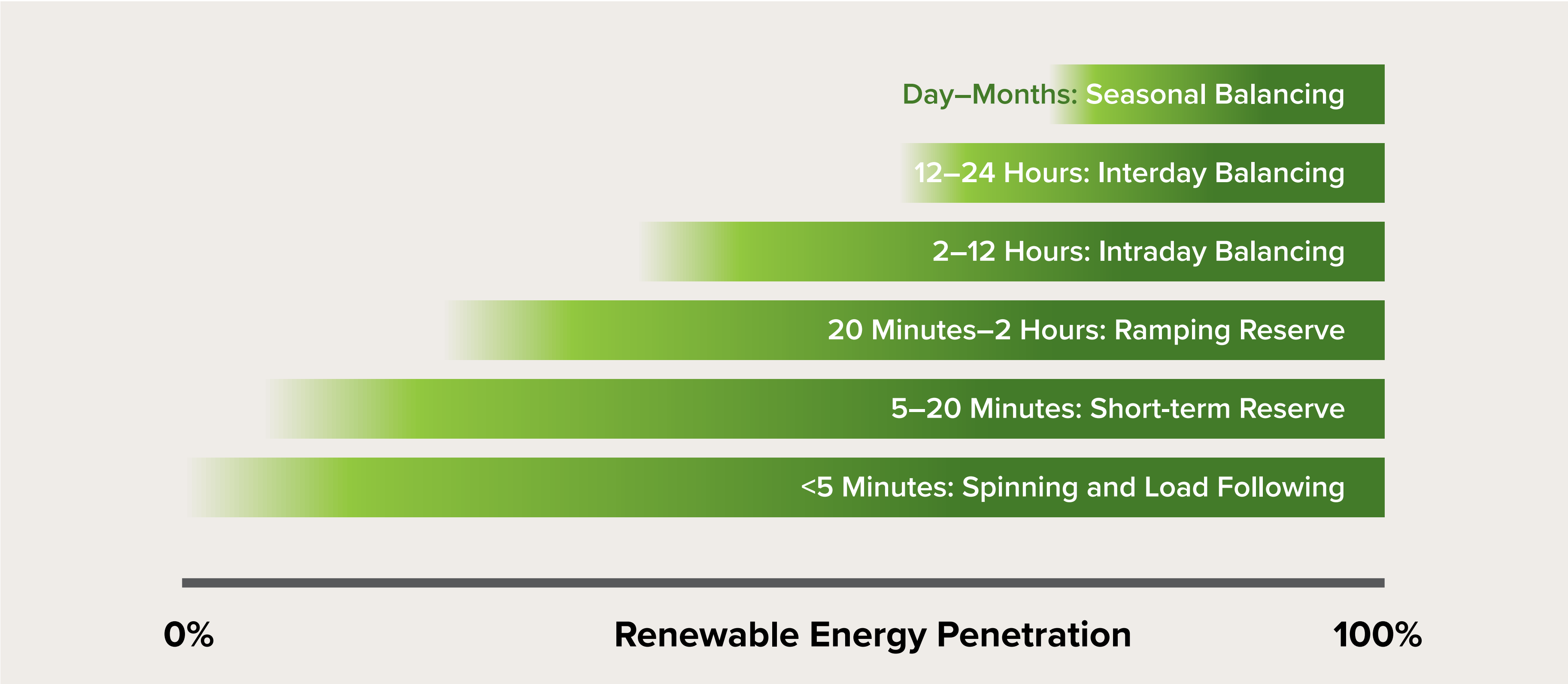
Source: Jeff Callens, "Can Wind, PV and Batteries Keep Us Within 2 Degrees?" BNEF, 2018

Longer duration storage needs will be best addressed with low-cost batteries that are less exposed to degradation and duty-cycle limitations.

As renewable energy penetration increases, batteries will need to discharge over longer periods of time at extremely low cost points. Short-duration, high-priced storage applications like peak-demand shaving and ancillary services are well suited to the performance and cost characteristics of Li-ion batteries. Grid economics for longer duration storage, however, require that storage technologies compete favorably on a levelized cost basis with least-cost generation alternatives (Exhibit 22). As storage requirements move beyond the four-hour threshold, technologies with lower duty-cycle degradation at full depth of discharge, lower material costs, and longer lifetimes will be better suited to provide those lower costs than what most analysts believe Li-ion can achieve. Market designs for specific battery durations, such as four-hours, often have unintended consequences, and can act as a disincentive for long-duration storage technologies.[30]

EXHIBIT 22

Duration Portfolio Thinking Suggests That Intraday Storage Will Be an Important Market Segment as Renewable Energy Penetrations Increase



Low-cost, long-duration technologies continue to improve with research, demonstration, and deployment.
The expected scaling markets for long-duration storage technologies focus on the value of energy over power, as is common in some resilience and deferral applications. Exhibit 23 illustrates the relative performance attributes of battery technologies that will likely be better suited for long-duration storage.

Zinc Batteries

Zinc-based anodes, coupled with low-cost cathodes, like air, are used to create an inexpensive battery, with improving cycle life. These could also include zinc alkaline batteries in the future, enabled by solid-state electrolytes.

Flow Batteries

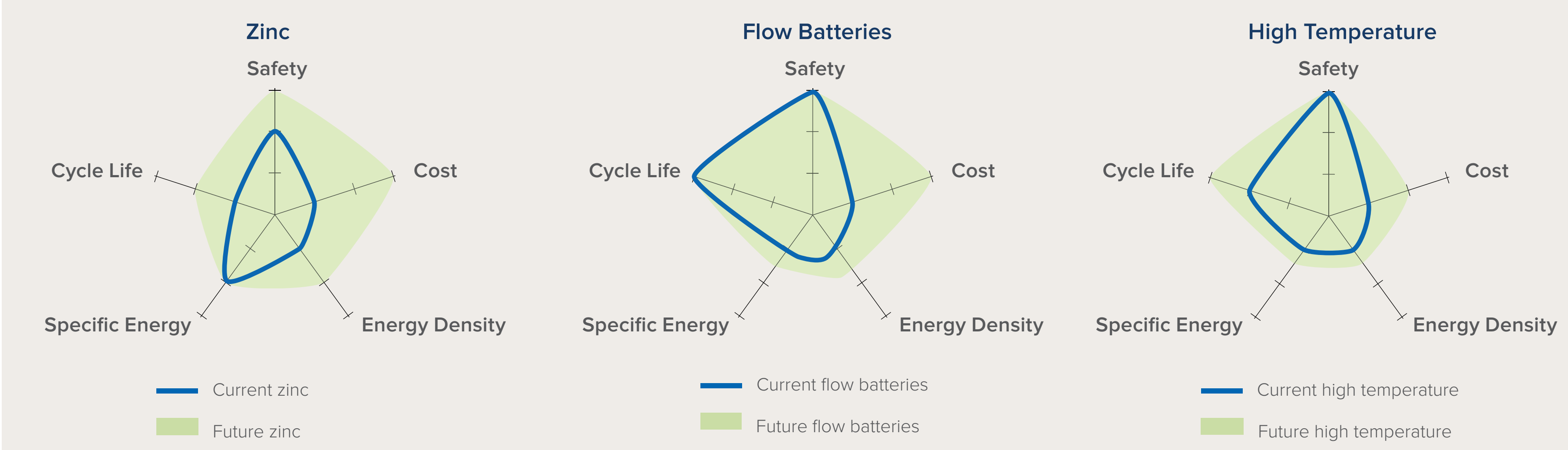
Flow batteries use externally stored fluids to generate energy as they flow past each other. They have reached a point of maturity and some can outcompete Li-ion for energy-focused, long lifetime use cases.

High-Temperature Batteries

Liquid-metal batteries could provide low-cost, long-duration grid balancing based on their safety and long life cycles and preference for active cycling, similar to traditional generators.

EXHIBIT 23

Relative Properties of Potential Long Duration Battery Technologies



Heavy Transportation

Battery technology advances are critical for expanding electrification to heavy mobility markets, which will gain increasing traction beyond China over the next decade.

Road Transport

Multiple large corporations have announced fleet electrification goals by 2030, and as of late 2018, more than a dozen countries have agreed to phase out internal combustion engines.[31] The combination of declining battery costs, mobility-as-a-service business models, increased urbanization, and carbon emission goals are encouraging the rapid electrification of:

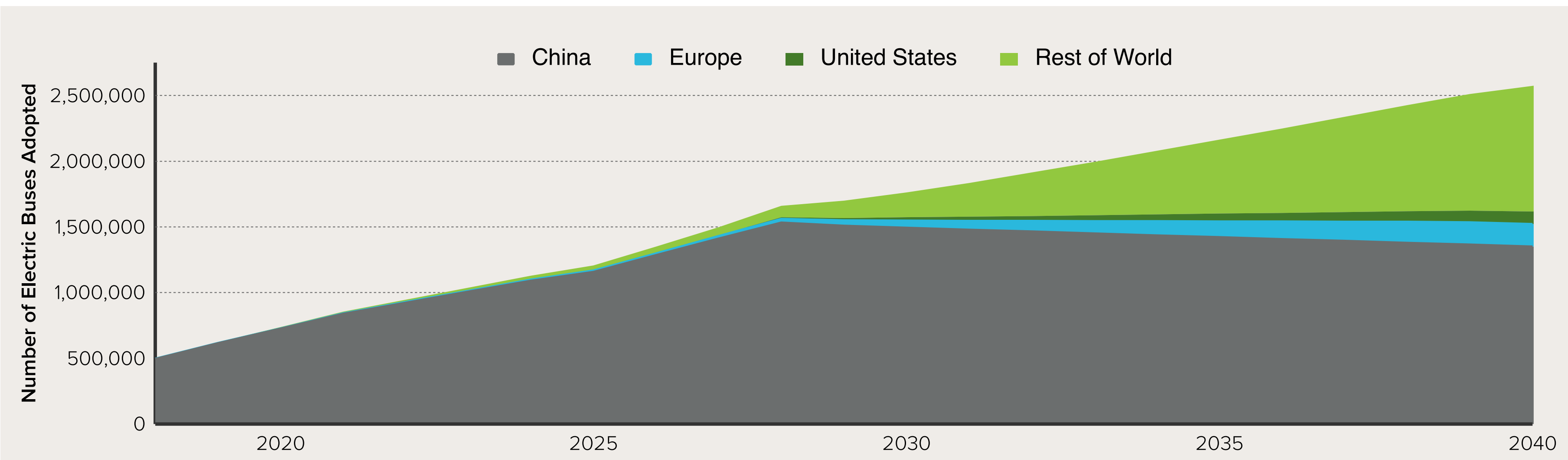
- **E-buses:** Electric buses are already cost comparable with diesel buses on a total cost of ownership basis.[32] They are expected to represent 60% of the global municipal bus market by 2030 and 80% by 2040 (Exhibit 24).[33]
- **Trucking and Other Commercial Vehicles:** Industry analysts estimate that by 2030, EVs will make up 8%, 12%, and 27% of the heavy, medium, and light commercial fleets respectively.[34]

Aviation

Emissions from aviation are expected to triple by 2050.[35] Some countries are leading early efforts to shift the industry toward electrification. Norway, for example, has committed to electrifying all short-haul flights by 2040. These flights of less than three hours of travel time represent more than 75% of all flights taken globally.[36] In fact, of the more than 39,000 new aircraft the industry expects to deliver over the next 20 years, 76% fall into this "small" size and range category (3,000-nautical mile range). At an assumed average unit price of $100 million, this represents a $3 trillion investment over that time period, or roughly $150 billion/year on a simple average annual basis.[37]

EXHIBIT 24

Annual Incremental Electric Bus Adoption Forecast



The Required Technology Advances are Achievable

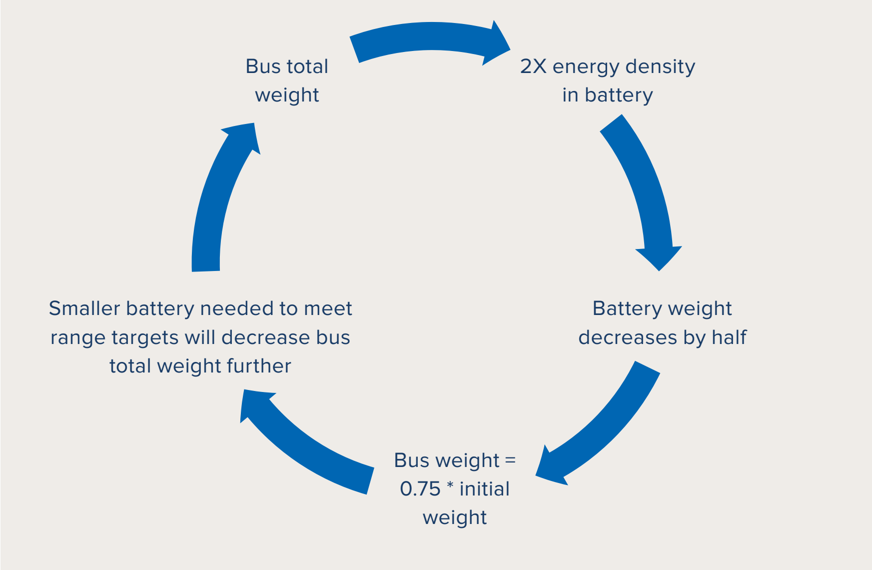
Battery technology advances, especially in safety and energy density, are crucial to scaling heavy mobility markets. But the rate of battery improvement and innovation, and the subsequent opportunities to redesign transport through systems engineering, suggests that such massive transformation is possible. In the last 10 years, for example, electric drones have ballooned into a $14 billion annual market, indicative of the possibilities when whole-systems design can help optimize cost and performance.[38]

Electric heavy transport will be enabled by advances in high energy-density and high power-density batteries.

The higher safety, energy density, and performance characteristics of advanced storage technologies will unlock whole-systems design pathways (e.g., lightweighting) to reduce total system cost.

EXHIBIT 25

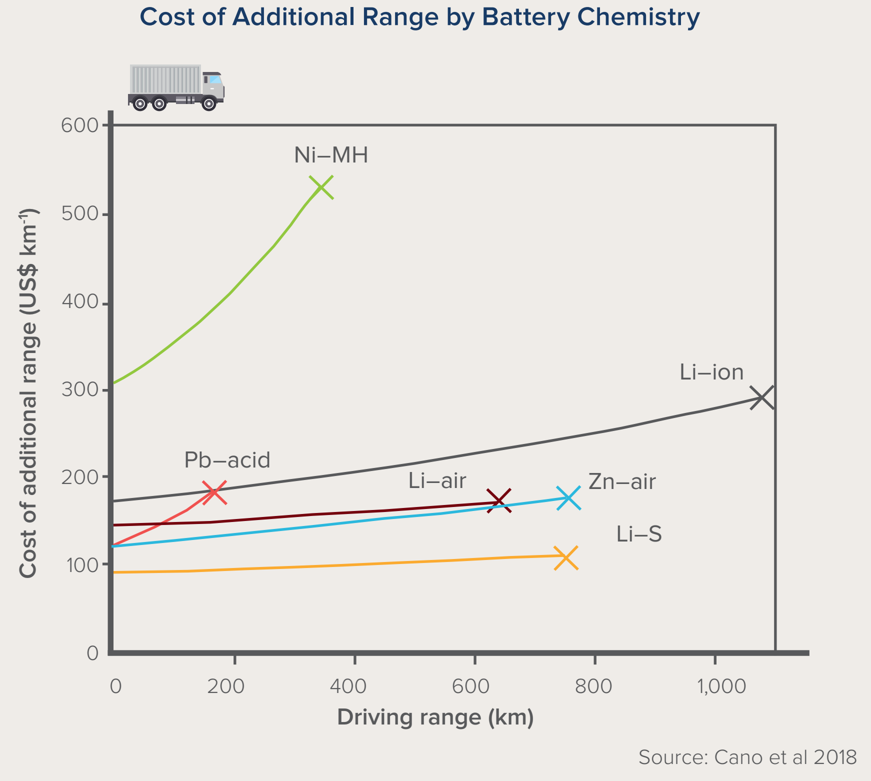
Lightweighting Design Feedback Loop



The effect of lightweighting can be understood by considering a 10-ton bus in which the original battery is 50% of the bus's total weight (Exhibit 25). Doubling the energy density would reduce the battery weight from 5 tons to 2.5 tons. This unlocks a compounding effect as the much lighter vehicle would require a significantly smaller battery to achieve the same range. This means that the cost of additional range for heavy transport is much smaller for high energy-density batteries (Exhibit 26).[39]

EXHIBIT 26

High Energy Density Chemistries Are Crucial for Enabling Long-Distance Heavy Mobility



Additionally, lightweighting with battery materials that are safe enough to be incorporated into the structural elements of the vehicle will generate additional system efficiencies (Exhibit 28). High-power batteries (e.g., supercapacitors) will be especially important for regeneratively capturing and leveraging inertia, and can be used to get vehicles up to speed without depleting the energy stored in primary batteries.

Exhibit 27 illustrates the relative performance attributes of battery technologies that may help unlock larger-scale adoption of electric heavy transport.

Li-Metal Batteries

Li-metal batteries with improved electrolytes, such as solid state, can have higher energy density.

Li-Sulfur Batteries

Li-S batteries are enabled by solid-state and hybrid electrolytes to take advantage of high energy density and low material costs.

High-Power Supercapacitors

Electrochemical supercapacitors using graphene and sodium-ion batteries are a low-cost, high-power opportunity with significant energy density improvements from previous supercapacitors.

EXHIBIT 27

Relative Properties of Battery Technologies That Could Accelerate Electric Heavy Transport

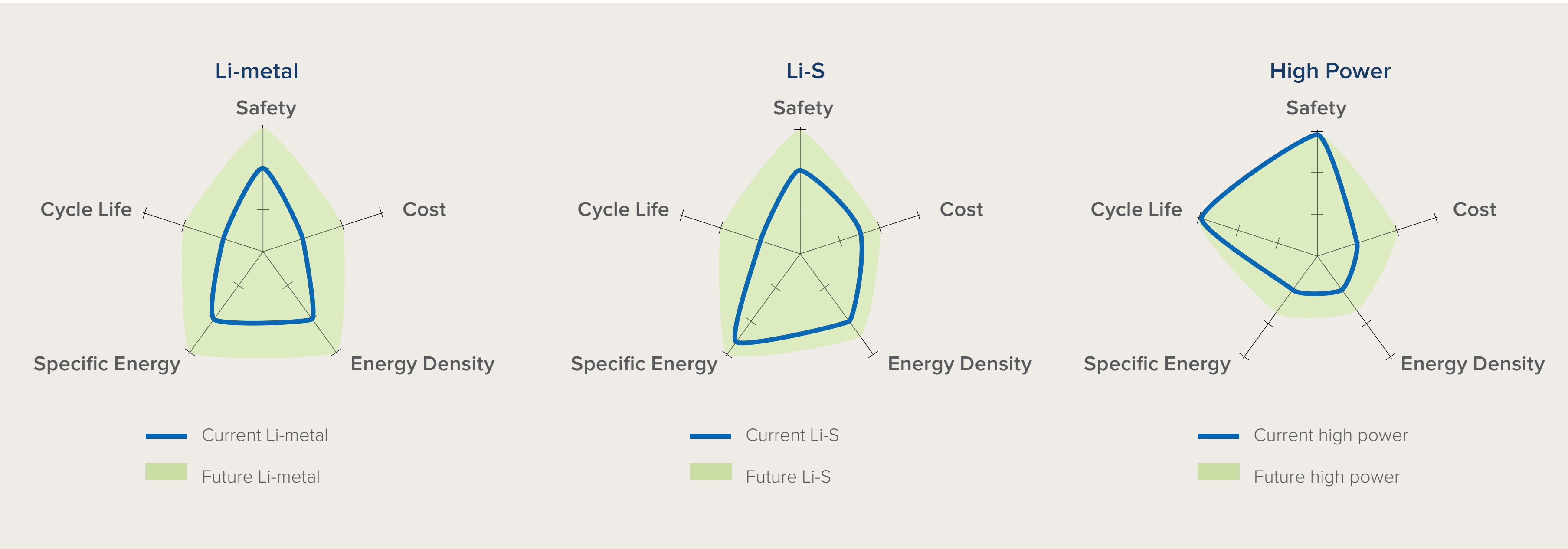
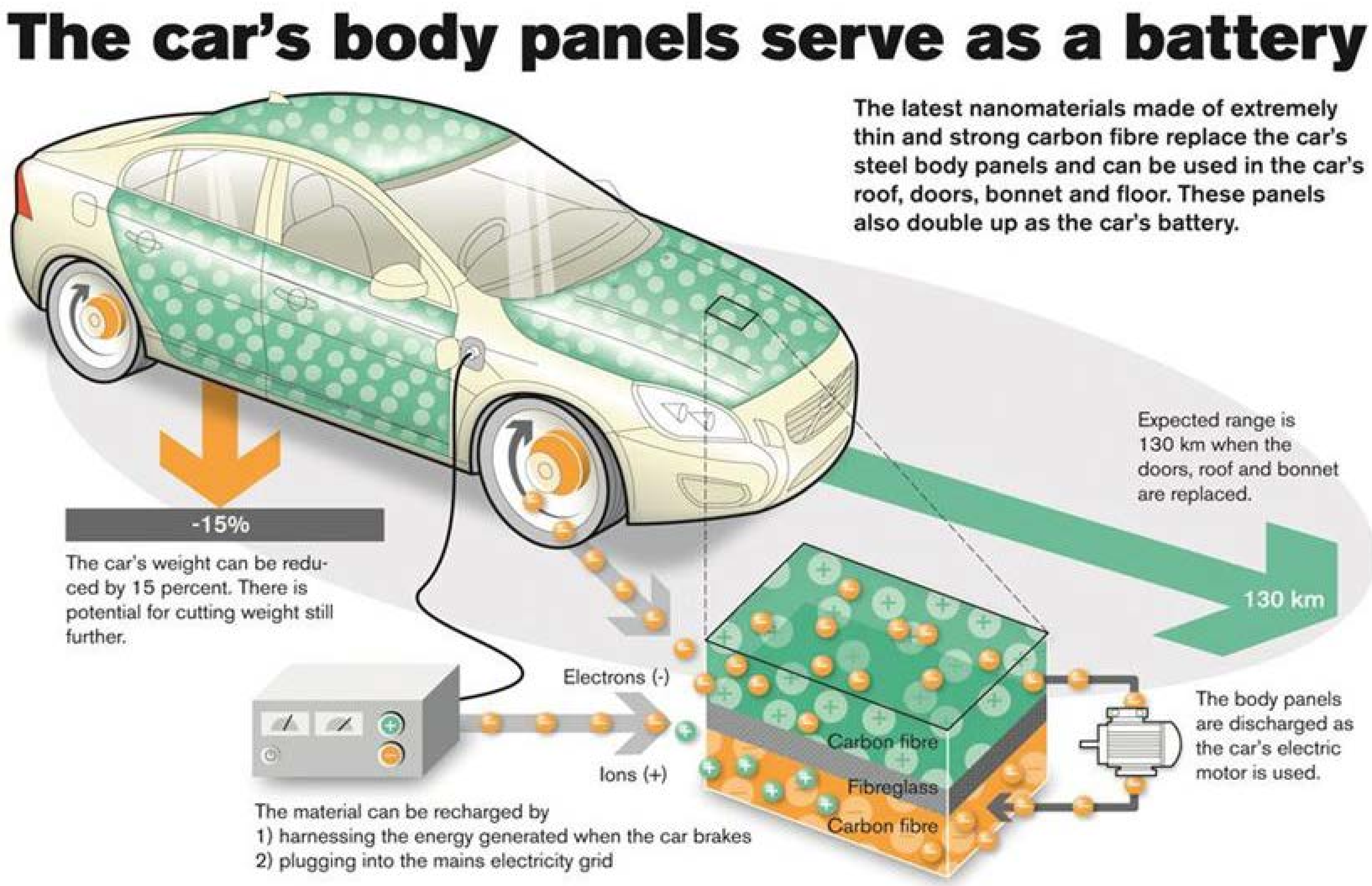


EXHIBIT 28


The car's body panels serve as a battery
The latest nanomaterials made of extremely thin and strong carbon fibre replace the car's steel body panels and can be used in the car's roof, doors, bonnet and floor. These panels also double up as the car's battery.
-15%
The car's weight can be reduced by 15 percent. There is potential for cutting weight still further.
Expected range is 130 km when the doors, roof and bonnet are replaced.
130 km
Electrons (-)
Ions (+)
Carbon fibre
Fibreglass
Carbon fibre
The body panels are discharged as the car's electric motor is used.
The material can be recharged by
1) harnessing the energy generated when the car brakes
2) plugging into the mains electricity grid

Electric Vehicle Fast-charging Infrastructure

Fast-charging infrastructure requires massive expansion to meet the needs of a rapidly growing EV market.

In 2025, more EVs will be sold than are currently in use in 2019. Today, more than 630,000 charging stations around the world support around 5 million EVs. By 2025, analysts estimate that there will be 30 million EVs on the road, necessitating an increase in the amount of charging needed. Without significant investment in accessible charging infrastructure,[40] that exponential growth in EV adoption may slow by 2040, despite continued battery cost declines. Assuming one DC fast charger for every 10 EVs in 2030 would mean a necessary 10 million DC fast charging stations globally by 2030.

Batteries as EV support infrastructure

Charging stations, and specifically DC fast chargers, can add significant costs for the owner and customers using that equipment. This results from both the significant electrical and other infrastructure upgrades required and the expected costs of increased demand charges against the owners' electric utility account. Strategically siting energy storage at or near fast-charging infrastructure could help smooth demand spikes and strain on the grid, thereby lowering overall system costs and enhancing reliability.

Fast-charging infrastructure costs can be minimized with batteries that couple high-power fast charging with long lifetimes and low cycle costs, even with multiple complete discharges per day.

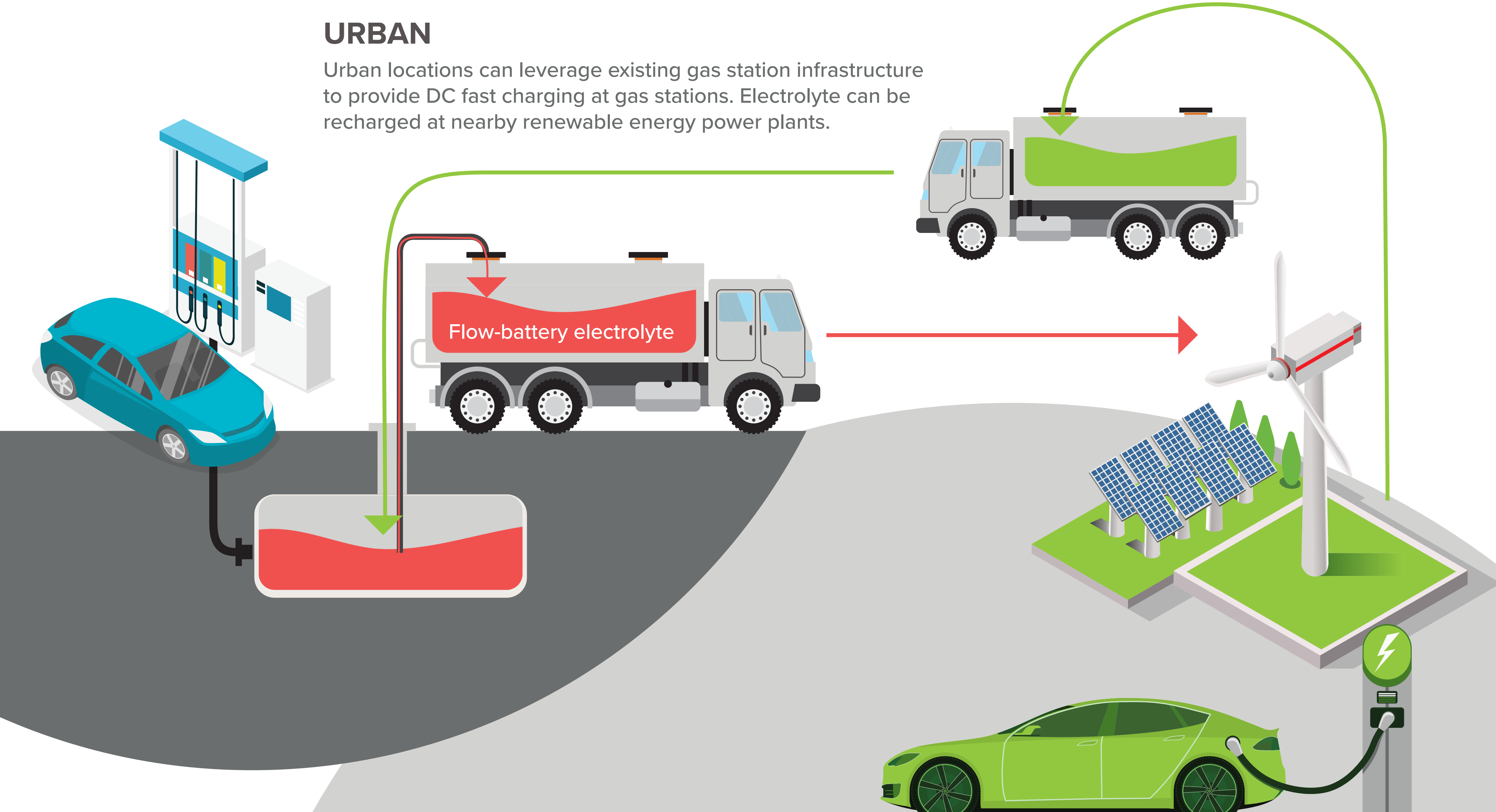
Direct current (DC) fast charging installations currently span a wide range of capital costs—between $4,000 and $51,000 per charger—due primarily to electrical upgrades, trenching, and boring.[41] The aforementioned increases in demand charges may also create an economic barrier to their adoption. These system costs could be significantly reduced by co-designing fast chargers with batteries that could serve in a demand buffering capacity. The emissions reduction impact of this approach could be enhanced through grid intelligence software that optimizes the recharging of those batteries based on the real-time penetration of renewables on the grid. Flow batteries could also provide an opportunity to repurpose urban gas stations with lower upgrade costs, since liquid electrolyte could be refilled by exchanging or adding electrolyte that is recharged from nearby renewable energy production facilities (Exhibit 29).

Research and development for batteries that can reduce grid upgrade and management costs is providing a suite of solutions that could help reimagine optimal approaches to grid infrastructure and vehicle-to-grid interactions to support the electric mobility transition. Flow batteries and high-power batteries (discussed above under *Long Duration Storage* and *Heavy Transportation*, respectively) are two such technologies. Their relative performance attributes are shown again for comparison in Exhibit 30.

EXHIBIT 29
Battery-Based Strategies for Integrating DC Fast Charging

URBAN

Urban locations can leverage existing gas station infrastructure to provide DC fast charging at gas stations. Electrolyte can be recharged at nearby renewable energy power plants.

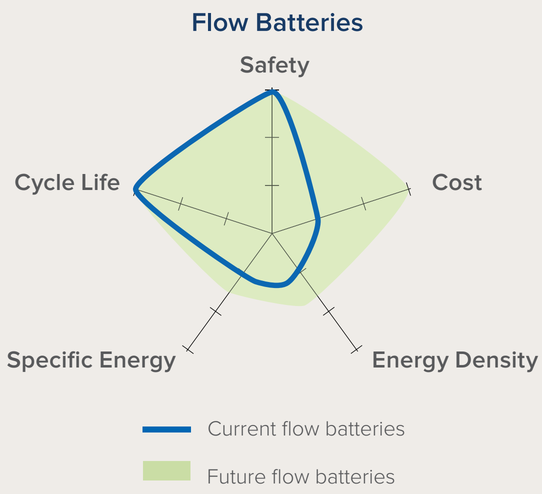


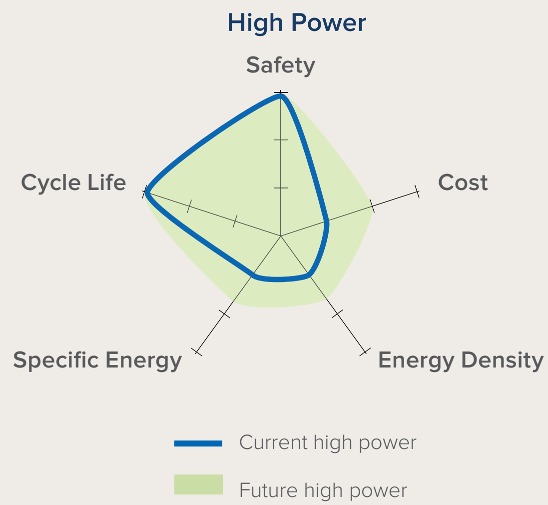
RURAL

Rural locations co-located with energy production can use high-power batteries for fast charging that can provide more than 100,000 cycles.

EXHIBIT 30

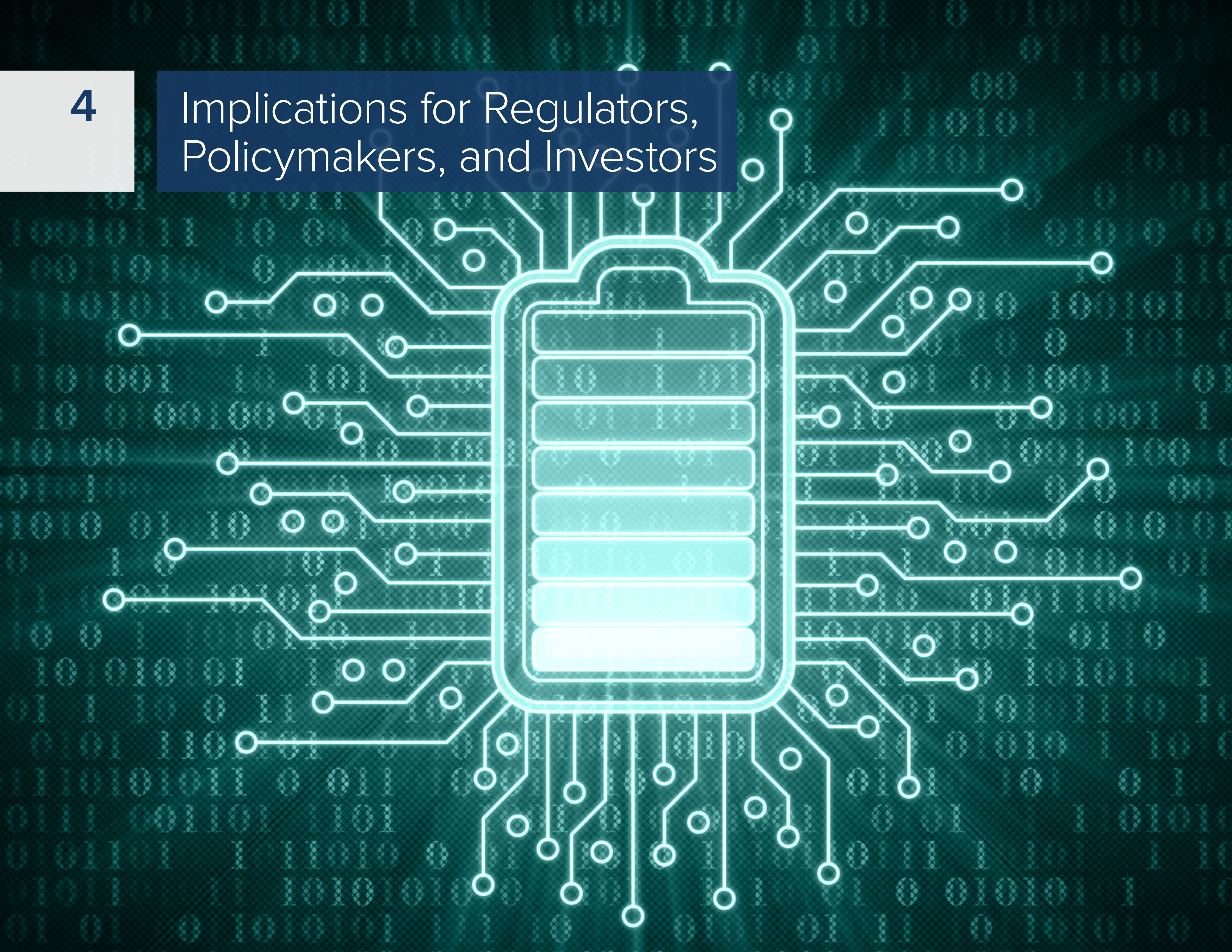
Relative Properties of Battery Technologies That Could Accelerate or Enhance DC Fast-charging Infrastructure Build-out





4

Implications for Regulators, Policymakers, and Investors



Implications for Regulators, Policymakers, and Investors

Capturing the massive economic opportunity underlying the shift to battery-based energy systems requires an ecosystem approach. The increasing and divergent mobility and grid-tied storage applications that breakthrough battery technologies can address hold incredible potential to reduce carbon and other polluting emissions while unlocking enormous new sources of economic value. The growing scale of public and private investment, as well as the accelerating momentum in the EV and renewable energy markets, make it clear that these energy storage technologies will play a crucial role in our energy future.

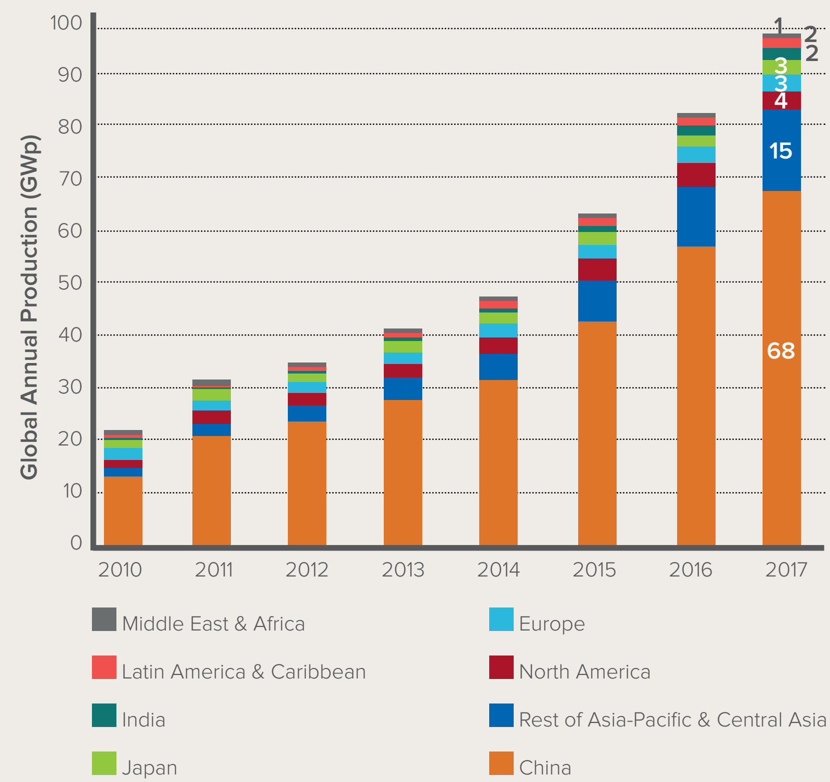
As cost and performance improvements continue to outpace analyst forecasts, investors, vehicle OEMs, and other value chain players are racing to meet expected Li-ion battery demand while competitively pursuing incremental and step-change improvements that can reduce costs or open up entirely new end-use markets. Similarly, national governments are scrambling to incentivize battery and component manufacturing and ongoing research, development, and deployment as they recognize the massive scale of lost economic potential and the inherent national security risks of relying on foreign suppliers. Supporting this type of innovation and energy system transformation, however, requires an ecosystem approach that combines and aligns these private and public sector commitments.[42]

Regions that fail to develop such an ecosystem will sacrifice those economic gains to their global trading partners, as has been the case with China's dominance over solar photovoltaic manufacturing. China has rapidly ascended to the position of global renewable energy superpower. This has particularly been the case with solar PV manufacturing, where early and significant investments in large-scale manufacturing eventually led to overproduction and subsequent price drops that forced many competitors out of business (Exhibit 31).[43]

In contrast, Chinese turbine manufacturers supply almost exclusively in-country installations.[44] As shown in Exhibit 32, early offshore wind power market development support in Denmark and other European countries and a robust US onshore wind market have contributed to a diverse and competitive supplier landscape.[45]

EXHIBIT 31

Global Annual PV Industry Production by Region (GW)

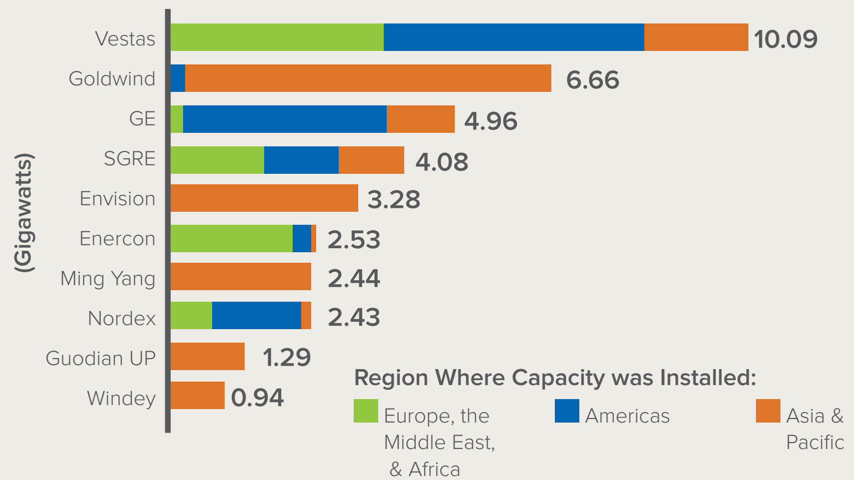


Data: Up to 2009: Navigant Consulting; since 2010: IHS. **Graph:** PSE GmbH 2018

© Fraunhofer ISE

EXHIBIT 32

2018 Onshore Wind Power Manufacturing Output, Top 10 Global Suppliers (GW)

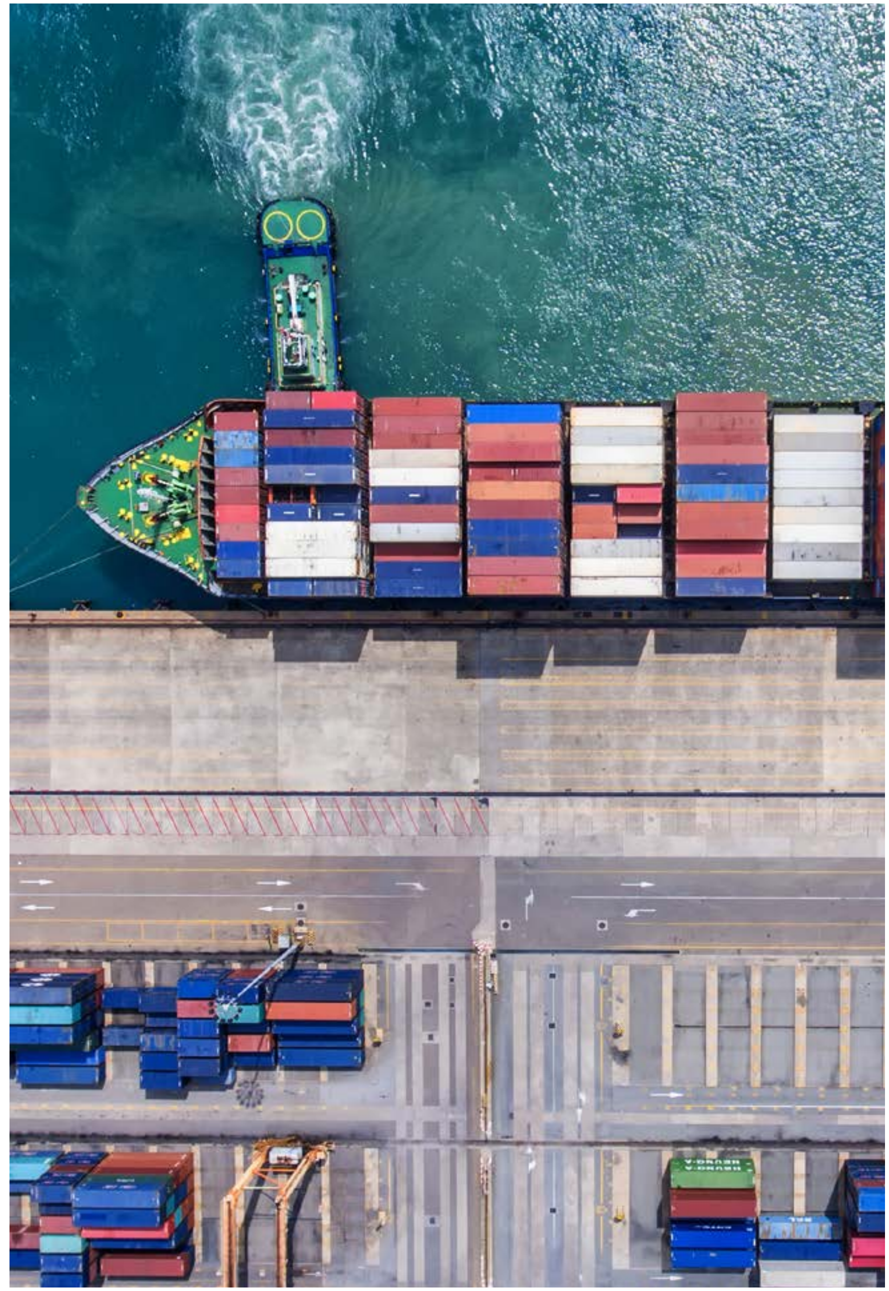


Notes: Only includes onshore wind capacity.
SGRE is Siemens Gamesa Renewable Energy.

Source: BNEF

"No country has put itself in a better position to become the world's renewable energy superpower than China. In aggregate, it is now the world's largest producer, exporter, and installer of solar panels, wind turbines, batteries, and electric vehicles, placing it at the forefront of the global energy transition."

–*IRENA, A New World: The Geopolitics of the Energy Transformation*



Without coordinated action to bolster other regional ecosystems, the trajectory for Li-ion battery manufacturing could follow solar PV's path.

In the electric mobility sector, China has a glaring lead in both battery manufacturing and EV deployment over the rest of the world. China is already the world's largest EV market (Exhibit 33) and can currently claim more than 60% of installed battery manufacturing capacity.[46] This has largely been driven by China's New Energy Vehicle (NEV) program, which set the country's first EV production and deployment goals in 2009, including subsidies offered exclusively to domestic suppliers.[47] Several extensions and enhancements to the program created a level of policy certainty that resulted in an explosion of EV models and vehicle and battery manufacturing capacity.

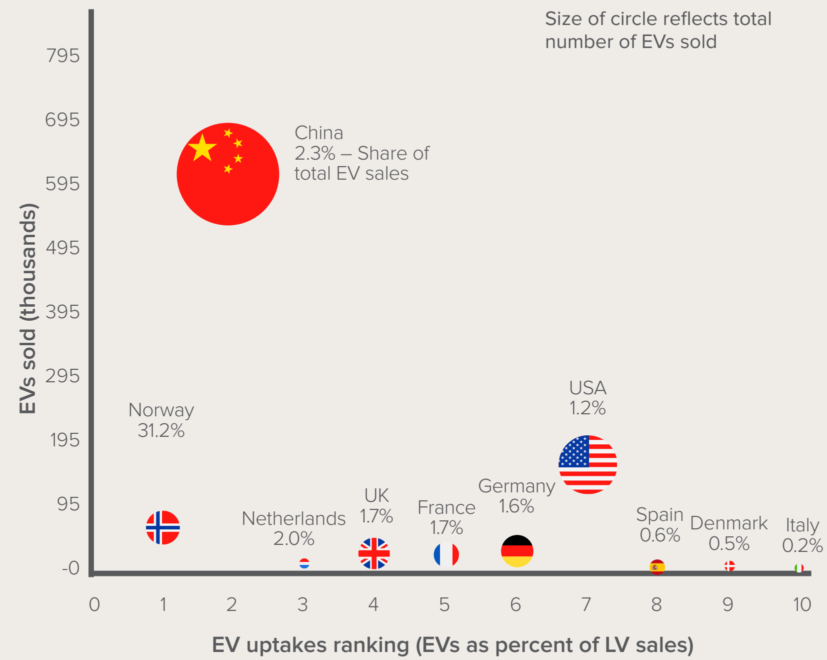
Next-generation Li-ion and alternative battery technologies, however, represent a diverse set of opportunities for continued investment, innovation, and value capture in the battery-based economy.

The pathway for non-Li-ion grid-tied storage technologies and some of the more innovative battery technologies currently approaching commercialization is less evident. Analysts forecast a relatively distributed profile of stationary energy storage deployments globally, suggesting that learning rates and economies of scale are less likely to be captured by any one global player (Exhibit 34).

In the case of nascent end-use applications enabled by expected battery technology advancements, a diverse and complementary ecosystem of suppliers, integrators, and OEMs is likely to emerge. Developing an innovation ecosystem that can effectively support so many divergent opportunities is challenging, but the cost of inaction may outweigh the risk of some investments failing to pan out. This puts regional governments and their public- and private-sector stakeholders at a critical crossroads for determining their respective roles in the future battery economy.

EXHIBIT 33

Comparison of EV Sales and Penetration by Leading Ten Countries, 2017

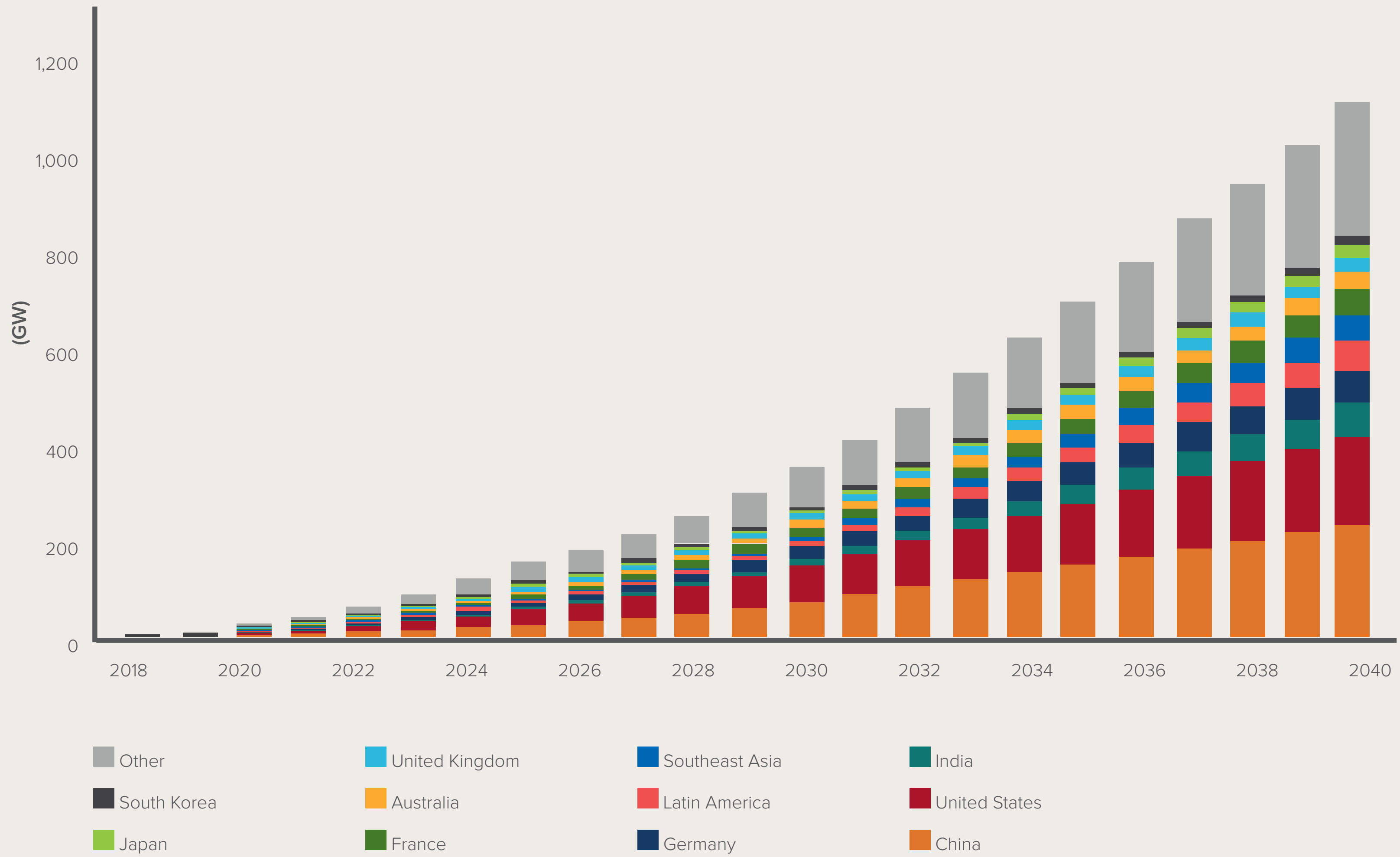


In 2017, the U.S. was the second largest purchaser of EVs, after China. However, six countries, including China, had greater EV sales as a percentage of their domestic market.

Source: *IHS Markit "Reinventing the Wheet: Mobility and Energy Future" Service*

EXHIBIT 34

Global Cumulative Energy Storage Installations



Source: *BNEF*

The current state of support ecosystems for battery storage technology focuses heavily on mobility applications and encouraging domestic manufacturing capacity, with emerging efforts tailored to grid-tied storage applications.

The exhibits on the following pages provide a comparative overview of battery technology support ecosystems in the four largest greenhouse gas-emitting countries (China, the United States, the European Union, and India).[vi] Major policy and investment actions are categorized across each of four categories of ecosystem supports, all of which play a key role in driving new technology adoption. The elements shown are intended to illustrate different approaches to supporting market development and are not comprehensive.

Two major trends are evident across each ecosystem:

- **Mobility markets are driving demand and cost declines.** The anticipated exponential growth in EV adoption has driven each of these nations' focus primarily toward mobile applications for advanced battery technologies. End-use demand support in the form of EV targets or incentives (or outright bans on ICE vehicles) are the most common shared elements. More recently, several countries have announced investments to support advanced R&D or to bolster the development of domestic battery manufacturing capacity.

- **The nascent grid storage market is about to take off.** Manufacturing- and supply chain-focused support specifically for grid-focused storage are harder to find. More effort is currently focused on ongoing R&D, demonstration projects, and, in particular, regulations to better enable storage to compete on level terms with primary power sources. In the past two years, the United States, China, and the European Commission have all taken steps to allow energy storage better access to power markets. As utilities, grid operators, and integrators gain more experience with Li-ion and other advanced (and longer-duration) batteries, cost and regulatory barriers will quickly diminish, unlocking a flood of new storage capacity demand to balance the variability of renewable energy generation with zero emissions.

[vi] The European Union is included as a single governing body given its shared policy approach to addressing economic and climate-related issues.

EXHIBIT 35

Key Elements of China's Battery Technology Support Ecosystem

<table>
<tr><th colspan="4">CHINA</th></tr>
<tr><th>Research & Development</th><th>Demonstration & Commercialization</th><th>Scaled Manufacturing & Supply Chain</th><th>Demand Generation</th></tr>
<tr><td rowspan="2">(2019) Siemens and Tianmu Lake Institute of Advanced Energy Storage to open battery research center. First center to co-locate third-party testing, R&D verification, and technology services. Located near large manufacturers.</td><td></td><td colspan="2">(2009–2019) New Energy Vehicles Program: Subsidy program targeting 7 million battery electric, plug-in hybrid, or fuel cell vehicles sold by 2025; includes private vehicles and buses.</td></tr>
<tr><td>(2019) China Tower commits to purchase 5 GWh of second-life Li-ion batteries to provide telecom tower backup power; the largest such commitment to date</td><td>(2018) New Energy Vehicle Mandate Policy: Provides quota and credit system for manufacturers.</td><td>(2014–2016) Central government and some cities and public organizations required to have vehicle fleets comprising 30% EVs by 2016; (2016) goal increased to 50%.</td></tr>
<tr><td></td><td>(2019) 720-MWh, 4-hour battery storage pilot approved to support renewable energy push</td><td></td><td>(2019) Ancillary services market will transition from basic compensation mechanism to a market integrated with spot energy prices by 2020; demand for grid-tied storage expected to "skyrocket" by 2024.</td></tr>
</table>

Mobility-focused Efforts

Grid-focused Efforts

China's Undisputed Dominance

Scale and policy certainty matter. China's support for EVs and domestic manufacturing started early, was large scale, and has remained relatively consistent (Exhibit 35). The magnitude of those targets and the associated subsidies (~$10,000 per vehicle produced) have been key drivers for a surge in battery and vehicle manufacturing. While many vehicle OEMs may wind down as subsidies tighten, market leaders will have gained a significant lead in production volumes and associated learning rates versus their global competitors. China's persistent development of upstream ore processing and key material and component manufacturing capabilities also provides an advantage.

EXHIBIT 36

Key Elements of the European Union's Battery Technology Support Ecosystem

<table>
<tr><th colspan="4">EUROPE</th></tr>
<tr><th>Research & Development</th><th>Demonstration & Commercialization</th><th>Scaled Manufacturing & Supply Chain</th><th>Demand Generation</th></tr>
<tr><td>(2018) Northvolt breaks ground on Swedish battery R&D center</td><td></td><td>(2017) European Commission announces the European Battery Alliance to create a competitive, sustainable battery-manufacturing value chain in Europe; quickly followed by a vision of 10–20 gigafactories. More than 260 organizations have joined.</td><td>(Multiple) Bans on petrol and diesel cars: Norway (2025); Sweden (2030); France and UK (by 2040); Germany (vehicles 100% emissions-free by 2030)</td></tr>
<tr><td colspan="2">(2019) German Federal Ministry of Education and Research launches the €500 million Battery Cell Research Production Center, a new R&D and large-scale industrial manufacturing plant for Li-ion cells</td><td colspan="2">(2017) Germany commits to allocate €1 billion through 2021 for local companies with competitive proposals for Li-ion production; (2018) France announces a similar commitment for €700 million. Includes support for public charging stations.</td></tr>
<tr><td colspan="2">(2019) France and Germany unveil a $5.6–$6.7 billion alliance (the "Airbus for batteries") to develop next-generation batteries for EVs</td><td>(2018) Sweden's Northvolt raises $1 billion to complete funding for large battery plant</td><td>(2016) Germany releases an EV incentive scheme worth about €1 billion, with €4,000 off the purchase of fully electric cars</td></tr>
<tr><td colspan="2">(2019) CATL increases investment in German R&D center from €240 million to up to €1.8 billion</td><td>(2018) Poland and Germany announce a cooperation on battery cell production in eastern Germany and western Poland</td><td>(2018) EU ministers agree on 35% cut to CO_2 emissions from cars by 2030</td></tr>
<tr><td colspan="2">(2014–2020) Framework Programme for Research and Innovation, Horizon 2020, granted ~€335 million to battery-based projects for grid energy storage and low-carbon mobility</td><td>(2019) France and Germany seek antitrust approval from the European Commission for a cross-border consortium that would produce Li-ion cells</td><td>(2019) European Parliament adopts market design rules finalizing the Clean Energy for All Europeans package, which opens up electricity markets to energy storage.</td></tr>
<tr><td>`</td><td>(2014–2018) European Institute of Technology Knowledge and Innovation Communities InnoEnergy (EIT InnoEnergy KIC) and RawMaterials (EIT RawMaterials KIC) spend up to €112 million in energy storage demonstration and deployment</td><td></td><td></td></tr>
</table>

Mobility-focused Efforts

Grid-focused Efforts

Europe's Awakening

The European Commission has rapidly accelerated its support for the advanced battery value chain over the past three years, driven largely by a fear of dependence on and lost economic opportunity to China and the rest of Asia. Analysts now expect Europe to overtake the United States in terms of installed manufacturing capacity in the next few years. Notably, a large share of that new capacity will be built by Chinese and other Asian companies.[48]

EXHIBIT 37

Key Elements of the United States' Battery Technology Support Ecosystem

<table>
<tr><th colspan="4">UNITED STATES</th></tr>
<tr><th>Research & Development</th><th>Demonstration & Commercialization</th><th>Scaled Manufacturing & Supply Chain</th><th>Demand Generation</th></tr>
<tr><td>(2016) Pacific Northwest National Lab launches the Battery 500 Consortium, a five-year, $50 million effort to achieve 500 Wh/kg energy density using Li-metal batteries</td><td></td><td>(2009) $2.4 billion in federal grants awarded under the American Recovery and Reinvestment Act to manufacturers of Li-ion cells, battery packs, and materials</td><td>(2009–2019) Federal tax credit for EV purchases; more than half of US states provide some form of EV purchase incentive</td></tr>
<tr><td>(2019) DOE launches ReCell, its first Li-ion battery recycling R&D center, with a focus on reducing dependence on foreign sources of battery materials</td><td></td><td></td><td>(2016–2026) VW settlement: $2 billion of funding for EV charging infrastructure</td></tr>
<tr><td colspan="2">US DOE's ARPA-E program has funded many EV and grid-tied storage projects, including batteries, automotive controls, and efficient EV chargers as well as a $30 million long-duration storage program announced in 2018.</td><td></td><td>(2018) California sets goal of 5 million zero emission vehicles (ZEVs) by 2030 with bigger ZEV subsidies</td></tr>
<tr><td></td><td>(2019) 1,000 MWh long-duration energy storage demonstration project announced in Utah that combines compressed air storage, hydrogen storage, large flow batteries, and solid-oxide fuel cells</td><td></td><td>(2013–2019) Several states have gigawatt-scale, grid-tied energy storage targets (e.g., CA, NJ, NY); others have significant but lesser incentives or goals</td></tr>
<tr><td></td><td></td><td></td><td>(2018) FERC Order 841: requires RTOs/ ISOs to remove barriers to energy storage participation in wholesale capacity, energy, and ancillary service markets</td></tr>
<tr><td></td><td></td><td></td><td>(2018) Order 845: revises definition of generating facility to include electricity storage and enables favorable interconnection</td></tr>
</table>

Mobility-focused Efforts

Grid-focused Efforts

United States' Start and Stop Approach

Demand for EVs in the United States has grown steadily thanks to a combination of federal tax credits and state and local incentives. However, lack of more cohesive or comprehensive federal support has kept demand growth to only a fraction of that seen in China and has not been enough to drive significant domestic battery manufacturing capacity. Some analysts cite the lack of consistent federal EV demand support as a critical contributor to what may be future US dependence on Chinese suppliers.[49]

EXHIBIT 38

Key Elements of India’s Battery Technology Support Ecosystem

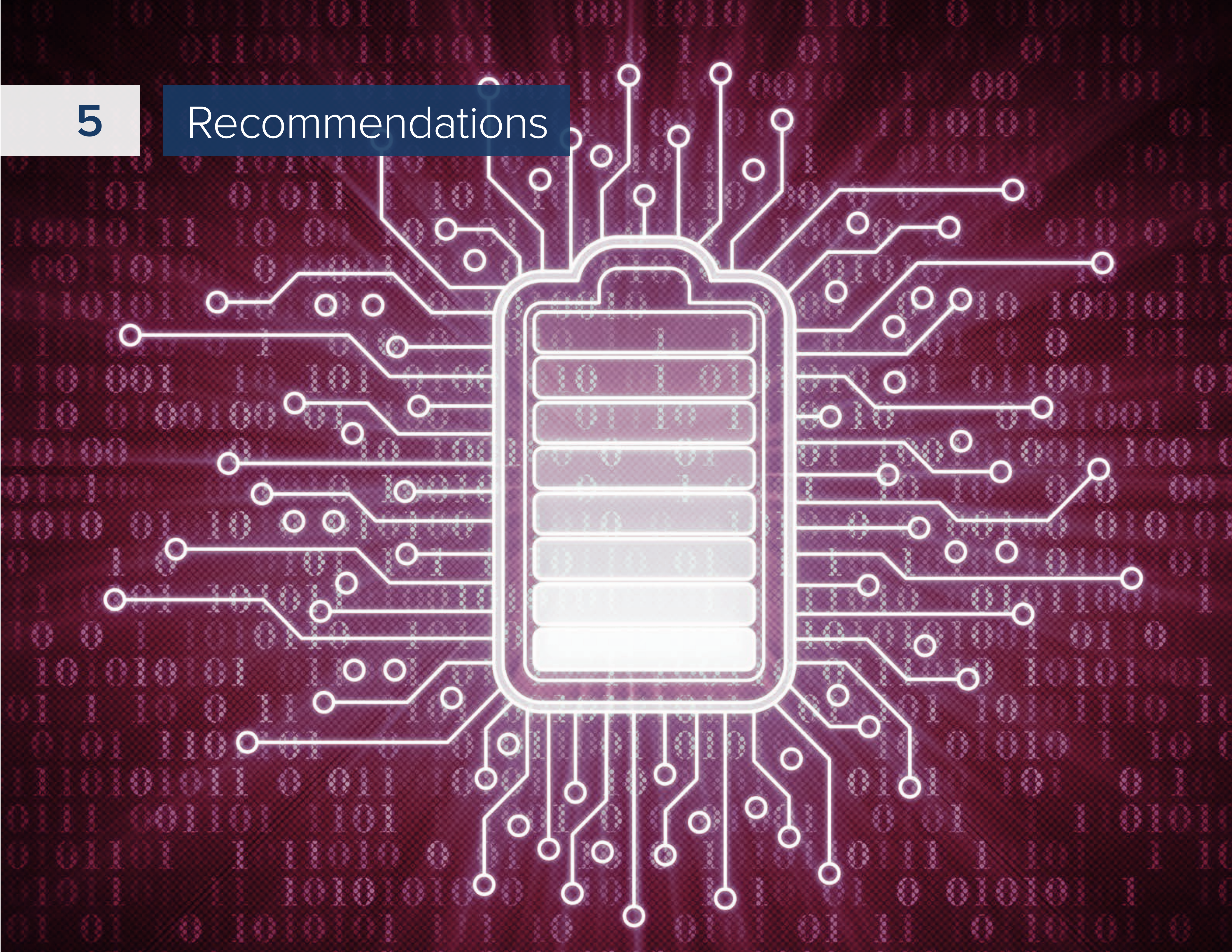
<table>
<tr><th colspan="4">INDIA</th></tr>
<tr><th>Research & Development</th><th>Demonstration & Commercialization</th><th>Scaled Manufacturing & Supply Chain</th><th>Demand Generation</th></tr>
<tr><td>Indian Institute of Technology Madras has an R&D center devoted to new and advanced battery technology</td><td></td><td rowspan="2">(2019) Cabinet approves National Mission on Transformative Mobility and Battery Storage, including two Phased Manufacturing Programmes (PMPs), each valid until 2024, to support 1) setting up large-scale, export-competitive integrated batteries and cell-manufacturing gigaplants and 2) localizing production across the entire EV value chain.</td><td>(2017) Federal goal: 100% EV sales by 2030</td></tr>
<tr><td colspan="2">Central Electrochemical Research Institute (CECRI) has set up India’s first indigenous Li-ion fabrication facility for batteries used in defense, solar-powered devices, railways, and other high-end uses.</td><td>(2019) India approves $1.4 billion for EV purchase incentives</td></tr>
</table>

Mobility-focused Efforts

India’s Rapid Acceleration

India has made significant progress in the past two years in signaling its commitment to both an electric fleet and supporting a robust domestic industry across the EV value chain, including battery and cell manufacturing. As evidenced by the adoption of the National Mission on Transformative Mobility and Battery Storage, India’s ministers appear determined to maximize the economic benefits of a rapid shift to electric mobility in India’s rapidly growing urban areas.

5 Recommendations



Recommendations

As Li-ion battery costs and performance continue steadily improving, ecosystem actors may be tempted to assume its long-term dominance across applications. This report has shown, however, that these improvements will instead create footholds for a divergent set of battery technologies with performance characteristics that are better suited to those use cases than today's Li-ion batteries. The following recommendations are intended to help key stakeholders continue to develop battery technology innovation ecosystems that anticipate this shift.

Planners and Policymakers

Think comprehensively and strategically about opportunities in the looming storage market. The market will grow rapidly. While Li-ion will dominate in the near team, new technologies (both advanced Li-ion and alternative chemistries) will unlock additional applications sooner than expected. Consider areas where such nascent opportunities could emerge by keeping up to date on new technologies and how they can help solve emerging energy transition challenges.

Help innovators demonstrate bankability. The noise and excitement surrounding Li-ion can serve to diminish attention and funding from other promising, near-commercial technologies. Consider opportunities to bring competing technologies to market through:

- Demonstration funding
- Data-sharing platforms and incentives
- Testing standards and accessible, independent testing facilities
- Innovative re-insurance approaches to back up OEM warranties

Incentivize the diversification of grid-tied storage use cases. Incentives for early adopters to apply storage technologies to a broader set of uses (e.g., ancillary services, arbitrage) can deepen collective knowledge of storage's value as well as the cost impacts of performance degradation and cycling impacts.

Take a long view on supply challenges. There will be fluctuations in lithium supply, but the market will adjust.

Segment EV policy supports based on vehicle size:

- Smaller EVs (including two- and three-wheelers) will be faster to electrify than larger vehicles; create local policies to facilitate consumer adoption of smaller EVs.
- Consider incentives for larger companies to support shared/corporate R&D and ownership for larger vehicles.

Investors

Diversify across near-term and long-term commercialization plays. Consider participating in focused investment partnerships that support both early-stage R&D and precommercial battery innovations, the risks and investment timelines of which may not align with traditional venture capital criteria.

Collaborate to speed collective time to market. Support open innovation, accelerator, and innovation testing platforms to help speed the vetting of technologies and sharing of lessons across the startup ecosystem.

Mix and match to spot new opportunities. Markets and applications that are a best fit for some precommercial battery technologies may not exist today. Consider what new applications a technology could unlock, as well as how hybrid technology systems might offer unique value propositions (e.g., pairing two battery types to support an EV fast-charging station).

Adopt a whole systems design perspective. Look at battery-integrated products from a system perspective to capture efficiency and safety improvements (e.g., batteries integrated into vehicle structure).

Learn from and invest in earlier markets. Watch and invest in first markets (e.g., drones, microgrids, fast-charging consumer devices, and non-wire alternatives) to gain early insights into longer-term, larger opportunities. Also consider that smaller devices and EVs will be faster to electrify than large devices.

Look beyond Li-ion for competitive grid storage. Alternative technologies to Li-ion (e.g., zinc and flow batteries) are already competitive to Li-ion batteries for stationary applications (e.g., non-wire alternatives and back-up generation). Early investors could capture a first-mover advantage.

Diversify and reduce risk by partnering across the value chain:

- Encourage technology providers to engage with battery system integrators and proven manufacturers early on in their development cycles to accelerate learning and time to market.
- Leverage new products from reinsurance companies (e.g., Munich Re) that reduce end customer technology exposure.

Regulators

For Mobility and Grid Applications:

Prioritize safety. Poorly vetted technologies, bad manufacturing, and dangerous installations can set the entire industry back.

Create fair rules and do not prescribe a winning technology. Lay the groundwork for open access and competition for a variety of storage technologies; set standards for acceptable levels of performance and let the market choose which technologies to apply.

Require data transparency to accelerate learning and efficiency. Create standards for data reporting (with either requirements or incentives for participation) for technology OEMs and integrators to share manufacturer-specific lifecycle, cycling, and technology costs with regulatory and research institutions to improve and speed policy evaluations and enable more efficient and effective market design.

For Grid Applications:

Update resource planning processes with up-to-date information. Ensure that electric utility, grid operator, state, and regional planning efforts (including integrated resource plans) adopt realistic, forward-looking assumptions and scenarios about the rapidly falling costs of storage and renewable energy technologies.

Level the playing field between storage and other demand-side resources. Develop planning, procurement, and measurement, reporting, and verification (MRV) approaches that create equal opportunity among utility-owned storage, customer-owned storage, and demand-side flexibility resources. Drive toward all-source flexibility resource procurements (versus storage-only procurements).

Develop pathways to integrate storage at different levels of grid operation and control. Energy storage can provide enormous value to the grid under several paradigms, each of which should be explored and developed. These include: 1) customer-owned and operated storage and vehicle charging subject to distributed control; 2) dispatchable distribution-level storage resources controlled by distribution grid operators; and 3) dispatch or market-controlled flexibility resources linked to wholesale markets.

Support utility pilot programs. Encourage and support utilities in developing experience with procurement and integration of grid-tied storage.

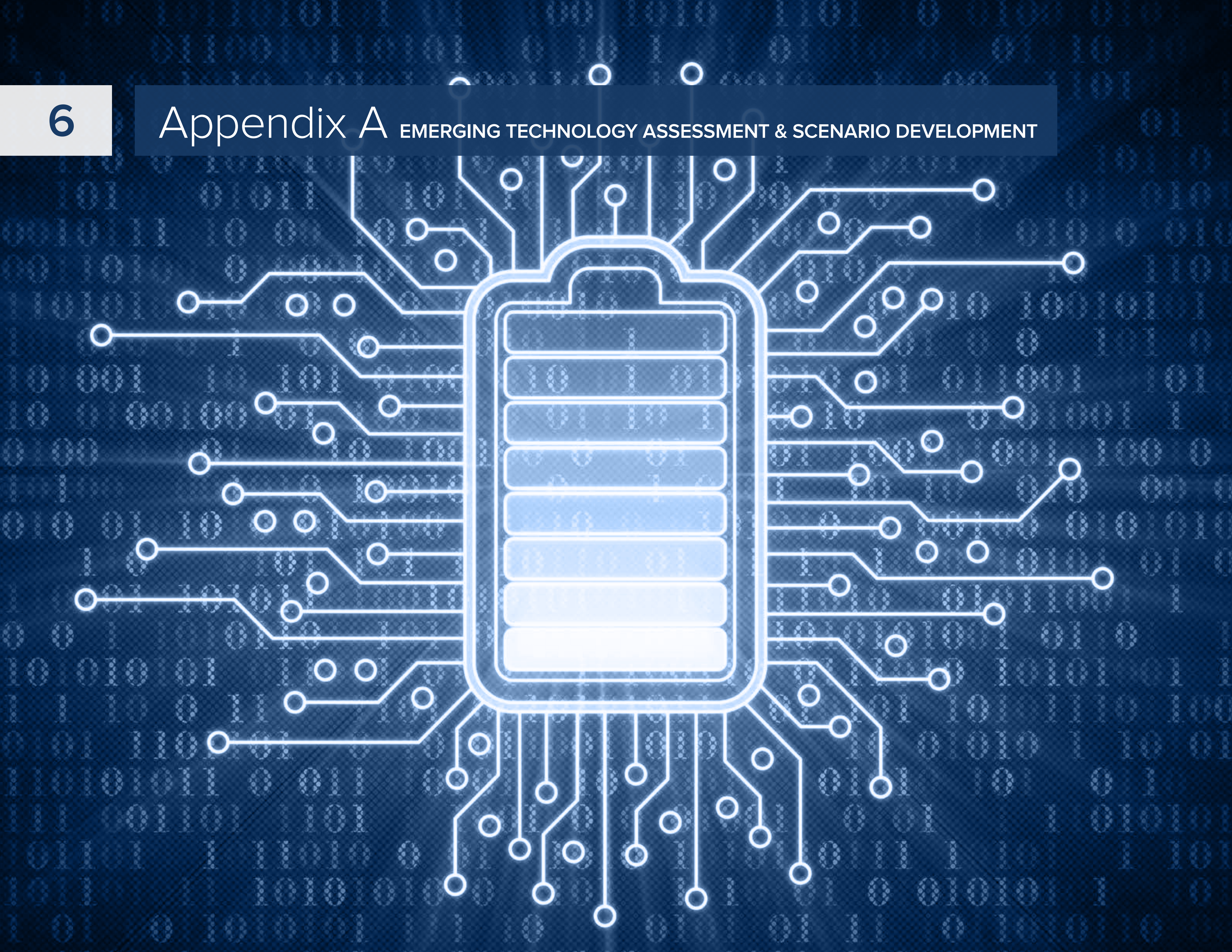
Support common tools and data reporting for LCOS. Create tools and data platforms that can help understand LCOS under various duty cycles and revenue-stacking value propositions.

Broaden the scope of opportunity:

- Disaggregate grid-flexibility resource procurements so that short-term and longer-term storage technologies can be optimized to meet different needs; move beyond procurements for four-hour storage.
- Consider longer-term procurement contracts to help new entrants diminish risk and orient toward longer-term thinking.
- Look beyond Li-ion for competitive grid storage options (e.g., zinc and flow batteries).

6

Appendix A EMERGING TECHNOLOGY ASSESSMENT & SCENARIO DEVELOPMENT



METHODOLOGY

The first phase of this study assessed the advanced battery technology landscape and developed plausible scenarios for these batteries' cost and performance based on both published and unpublished expert knowledge of the state of the art for emerging technology solutions. This section discusses each of three main work streams in this first phase: 1) Preliminary Technology Selection; 2) Expert Interviews and Site Visits; and 3) Scenario Development.

1. Preliminary Technology Selection

Electrochemical Focus

Energy storage technology innovation is evolving rapidly. Research labs, start-ups, battery manufacturers, and others are working on multiple battery and storage technologies at various stages of research, development, and commercialization. These technologies employ multiple means to store energy, including electrochemical, mechanical, thermal, and chemical energy, each of which could play a critical role in accelerating energy transitions toward a clean energy future.

Although exciting progress has been made across all forms of energy storage, this research focuses on electrochemical energy storage technologies. The pace of innovation in electrochemical battery technology is accelerating as researchers pursue higher-performing and less expensive solutions to meet growing market demand. This increasing demand stems largely from the modularity and diverse applicability of lead-acid and Li-ion batteries, which have benefited greatly from economies of scale that have driven prices down close to their theoretical minimum values. The ability to employ these batteries across multiple, scalable use cases in both stationary and mobile applications provides a unique advantage against other—usually stationary—energy storage technologies.

Several such non-electrochemical energy storage technologies and products that claim significantly lower cost and improved performance have recently emerged. Some of these technologies are likely to play a critical role in advancing energy transitions, particularly in stationary storage applications—behind and in front of the meter. Yet, most of these technologies are still in early stages of their development and few examples are available to estimate future prices for these technologies. Regardless of this report's primary focus, however, many of its findings—particularly as they relate to regulatory and policy implications—apply to multiple storage technologies, electrochemical or otherwise.

Technology Assessment Criteria

For the purpose of this study, the authors applied four main criteria during an initial literature review to arrive at a shortlist of battery technologies for detailed assessment. These criteria include:

- **Expected Performance Improvement:** A selected technology must be capable of achieving better performance than current Li-ion batteries against one or more metrics, including improved safety, energy density, specific energy, duration, or charge rate. Battery cells should demonstrate energy density of greater than 300 Wh/kg and specific energy greater than 600 Wh/l, provide more than six hours of continuous energy output, or show a significant increase in safety or charge/discharge rates. Significantly improved performance will be critical for gaining a foothold in competitive markets.

- **Expected Cost Reductions:** A technology must be capable of surpassing cost estimates for Li-ion technologies based on its underlying materials costs. New chemistries and designs have transformational cost-reduction potential over current Li-ion, for example due to use of cheaper materials or new and improved manufacturing processes.

- **Expected Time to Market:** A technology should be at a stage of research and development such that it can be piloted in a specific use case by 2030. Multiple technologies are in various stages of R&D; this study required that they be sufficiently developed to forecast their commercialization pathways and hypothesized first-markets with a reasonable degree of confidence.

- **Modularity and Scalability:** Modular designs for energy storage enable lower costs (as less customization is needed), augmentation of energy and capacity, flexibility in design of storage systems, and exclusion of faulty cells. Scalability arises from applicability across multiple use cases and replicable designs that can be readily mass-produced, thereby driving economies of scale.

2. Secondary Research and Expert Interviews

Following this initial down selection, the authors completed additional secondary research (existing reports and scientific articles) as well as a set of expert interviews and site visits with emerging technology companies in the battery space and other key industry stakeholders. Interviews were conducted with the following individuals and organizations:

- ZAF
- Nant Energy
- EnZinc
- Form Energy
- Ambri
- Malta
- Solid Energy
- Solid Power
- Ionic
- Vionx
- Primus
- ESS
- Sion Power
- Ampaire
- Polyplus
- Pellion
- Sila Nanotechnologies
- Zap Go
- Natron
- General Motors
- Ford
- Dr. Shao Horn (Massachusetts Institute of Technology)
- Dr. Gerd Ceder (Lawrence Berkeley National Lab)
- Todd Stribley (US Department of Energy)
- Dr. Paul Albertus (University of Maryland)
- Dr. Brad Ullrick (Argonne National Lab, US Department of Energy)
- Dr. Venkat Viswanathan (Carnegie Mellon University)
- Jay Goldin (Munich Re)
- Dr. Scott Litzelman (ARPA-E, U.S. Department of Energy)
- Engie
- Electric Power Research Institute (EPRI)

3. Scenario Development

The authors used findings from the primary and secondary research to develop scenarios describing potential price points and performance metrics for new battery technologies relative to baseline forecasts for existing technologies. These scenarios are not meant to be predictions, per se, but rigorously informed technological assumptions that warrant careful consideration by regulators, policymakers, and industry stakeholders. The study also assessed the expected timing for market-entry and production scaling of each breakthrough battery technology and evaluated its potential competitive advantage relative to Li-ion batteries. The authors used this analysis to map each emerging battery technology to specific end uses based on its potential cost and relevant performance characteristics (e.g., cycle life, specific energy, energy density, and safety).

While lithium-ion batteries currently dominate the market, these new chemistries and technologies could dramatically shift cost and performance thresholds, with far-reaching implications. The expected commercialization pathways for these technologies vary drastically: some advances depend on a few technological improvement iterations at the lab-scale, while others require public- and private-sector support to emerge from the “innovation valley of death” and reach manufacturing readiness levels where economies of scale savings can materialize. This is why careful assessment of time-to-market and potential scaling challenges is critically important to understanding the implications for national and global energy markets and strategies.

SUMMARY FINDINGS BY TECHNOLOGY

For each technology assessed, the following pages provide a high-level summary of the technology's key performance characteristics, projected cost and performance improvement metrics, and potential commercialization pathways.

Advanced Li-ion

Li-ion technology may diversify further, albeit along pathways that are compatible with existing manufacturing processes. Advances in Li-ion could create a more energy-dense battery that is less sensitive to supply chain constraints. Advanced Li-ion batteries may help battery costs decrease by a factor of three.

Battery Characteristics

Lithium-ion batteries have come down in price significantly. Innovations will improve performance incrementally, but with reduced cycle life in the next decade.

Key Improvement Pathways

- **Low/No-Cobalt Cathode:** Low-cobalt NMC and cost and performance improvements in other Li-ion chemistries, like LMO, LFP, or LTO
- **Silicon Anode:** Replacing graphite with silicon anode for higher energy density

Impact on Other Performance Characteristics

- Advanced Li-ion battery chemistries could double the specific energy (between 250 and 450 Wh/kg) and improve cost sensitivity to cobalt supplies.
- Reaching a cycle life beyond 1,500 cycles is a primary goal for advanced Li-ion in the coming decade, as is improving safety for new chemistries.

EXHIBIT A1

Relative Performance Attributes for Advanced Li-ion

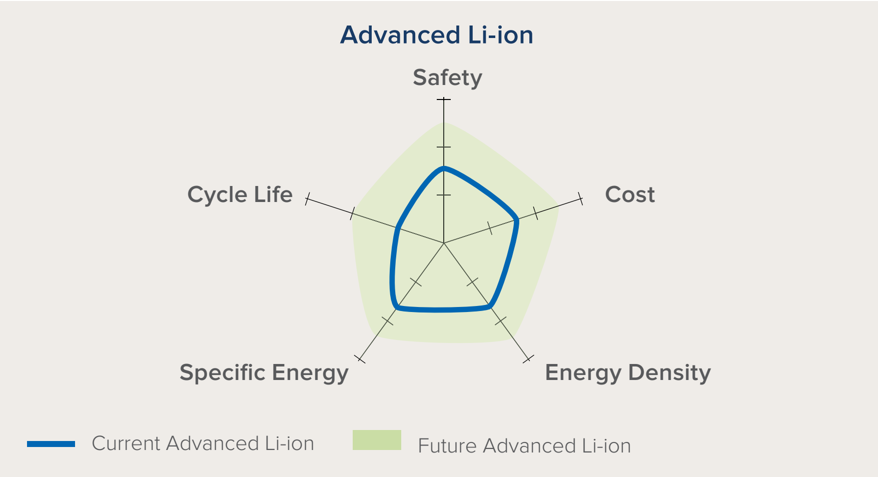
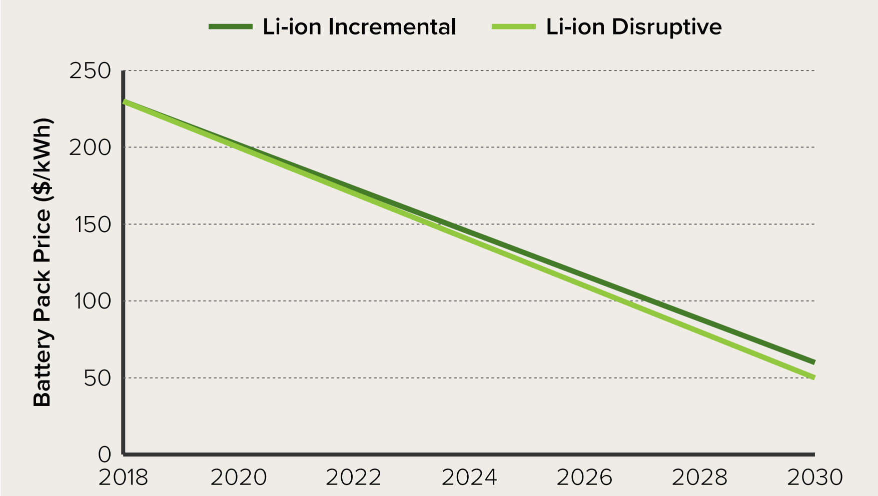


EXHIBIT A2

Advanced Li-ion Battery Price Scenarios



Potential Commercialization Pathways

EXHIBIT A3

Potential Commercialization Pathways for Advanced Li-ion Batteries

	Market Entry: Low barrier to entry allows for early-stage prototyping	**Market Growth:** High willingness to pay enables iterative product improvement cycles	**Mass-Market Capture:** Mature products; investments in scaling and customer acquisition
Potential Market Pathway	Low-cobalt battery adoption for passenger EVs	Consumer electronics scale manufacturing of more energy-dense Li-ion batteries	Economies of scale for more energy dense batteries will enable long-range and larger EVs
Details	• Mobility demand will drive low-cobalt technology adoption • Meeting demand for battery production at low prices will drive integration of low-cobalt technologies • Companies like Tesla are already incorporating low-cobalt chemistries into production lines	• Consumer electronics, which need to pack more energy in less space, will provide first markets for silicon anodes	• Technology and scaling improvements from drones and consumer electronics could enable longer-range mobility applications with silicon and low-cobalt chemistries • Higher energy density is critical for electrifying more energy- and power-intensive mobility applications
Required Improvements	Meeting safety requirements with low-cobalt cathodes	Limit volumetric expansion (silicon)	Safety and cycle-life improvements

Lithium-Metal (Li-Metal)

Li-metal batteries, which provide high energy density, will become rechargeable due to electrolyte innovation. Solid-state electrolytes can enable new and previously unsafe chemistries and reduce system costs by removing or reducing safety and controls equipment. In a disruptive scenario, Li-metal batteries may reduce battery cell costs 3 times with high performance.

Battery Characteristics

Li-metal batteries with improved electrolytes, including solid state, can be more energy dense (between 400 and 600 Wh/kg) and safer for more diverse applications. Safety improvements can enable higher-performing and more cost-effective future chemistries.

Key Improvement Pathways

- **Liquid electrolyte:** Liquid electrolytes are being engineered to limit dendrite growth from Li-metal anodes.

- **Solid-state electrolyte:** Multiple types of solid-state electrolytes, which can be effective at reducing or eliminating dendrite growth from Li-metal anode, are being pursued.

Impact on Other Performance Characteristics

- While solid-state electrolytes themselves may be more expensive than liquid electrolytes, they may enable lower-cost materials. Li-metal batteries will chart an eventual path to the commercialization of Li-air batteries, which—while unlikely in the next ten years—is considered an ideal combination of cost and performance.

- Realizing additional savings will also depend on manufacturing improvements for Li-metal foils that reduce foil thickness and the amount of lithium in the battery.

- Solid-state electrolytes, through the virtue of being safer, can reduce total pack cost through reduced use of safety and cooling technologies.

EXHIBIT A4

Relative Performance Attributes for Li-Metal Batteries

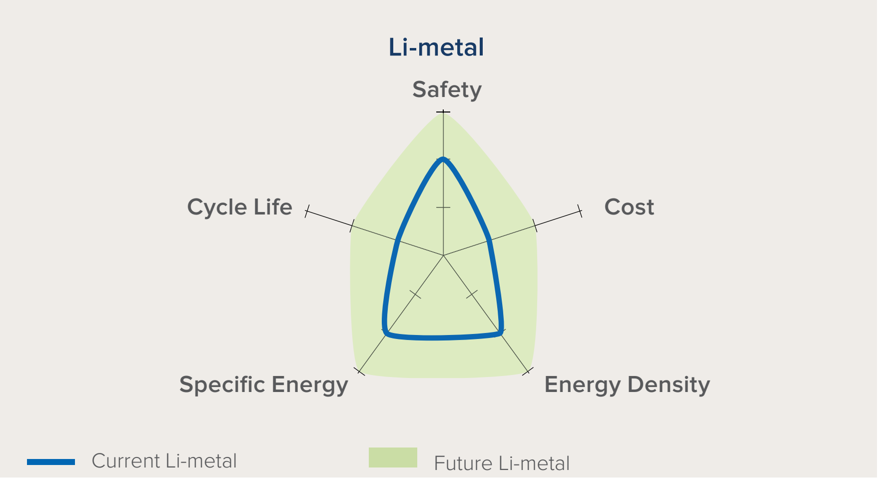
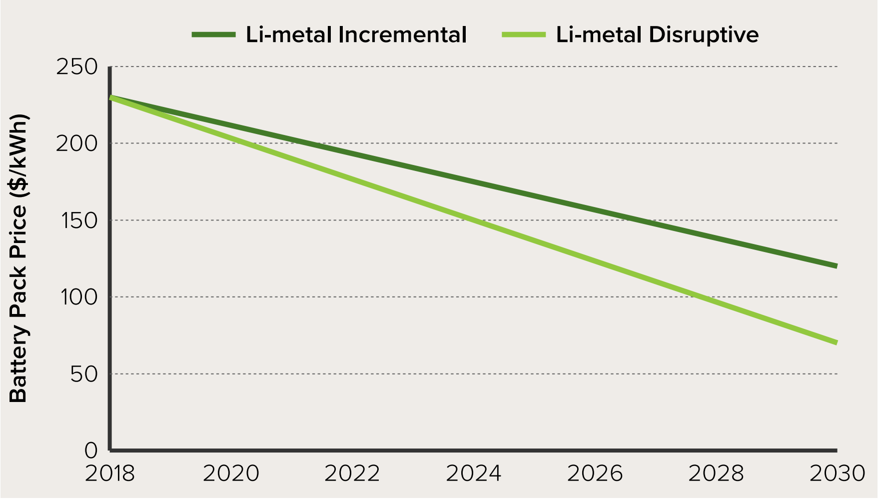


EXHIBIT A5

Li-metal Battery Price Scenarios



Potential Commercialization Pathways

EXHIBIT A6

Potential Commercialization Pathways for Li-metal Batteries

	Market Entry: Low barrier to entry allows for early-stage prototyping	**Market Growth:** High willingness to pay enables iterative product improvement cycles	**Mass-Market Capture:** Mature products; investments in scaling and customer acquisition
Potential Market Pathway	Drones and unmanned aerial vehicles (UAVs) will provide a first market for technology validation	High-specific-energy chemistries will enable longer range EVs	High-energy-density chemistries for high-performance applications
Details	• High-energy-density batteries are targeting weight sensitive applications with relatively short cycle life needs • Solid-state electrolytes can enable applications subject to cold temperatures found at high altitudes	• 400–600 Wh/kg specific energy will mean that batteries have much more energy per battery weight installed. This will translate to compounding savings in terms of driving range.	• High-energy-density batteries can help to address hard-to-electrify mobility segments such as trucking, shipping, and aviation, which require a large amount of energy due to weight burden and often function in extreme conditions
Required Improvements	Test and integrate at scale into manufacturing facilities	• Improved cycle life to >500 • Test and integrate at scale into manufacturing facilities	Scale Li-metal manufacturing facilities

Lithium-Sulfur (Li-S)

Lithium-sulfur batteries could enable heavier and weight-sensitive mobility applications. Lithium sulfur has high specific energy and low material costs from the use of sulfur as the cathode and will likely be cost-competitive with future high-performance Li-ion batteries.

Battery Characteristics

Lithium-sulfur could potentially combine high energy density with low material costs. This likely cannot be commercialized, however, without solid-state electrolytes enabling its development.

Key Improvement Pathways

- **Dual Electrolyte:** Improvements in dual solid state and liquid electrolytes may enhance safety and performance.

- **Sulfur Cathode:** Nanotechnology is being used to improve sulfur performance, with a focus on reducing cathode swelling.

Impact on Other Performance Characteristics

- Li-S is expected to have significantly higher energy per cost, given the use of the low-cost sulfur cathode.

- Technology companies are targeting cycle-life increases from the currently achievable 500 cycles to more than 1,500 cycles over the coming decade.

EXHIBIT A7

Relative Performance Attributes for Li-S Batteries

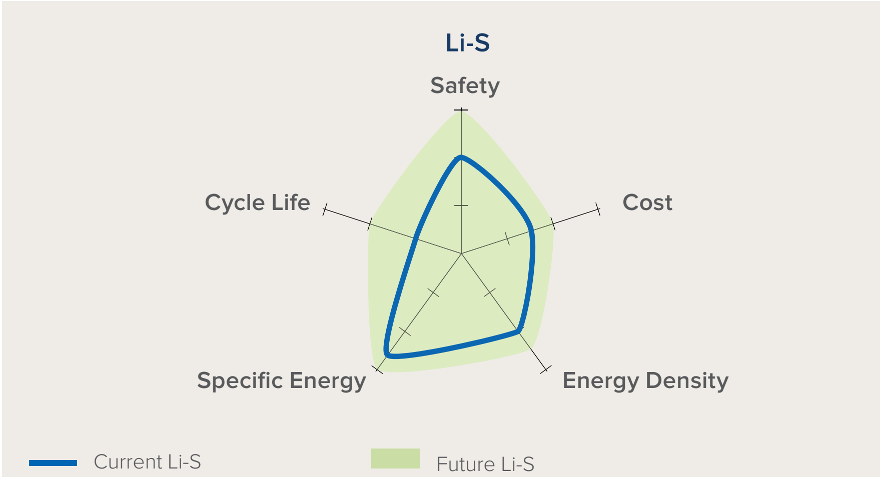
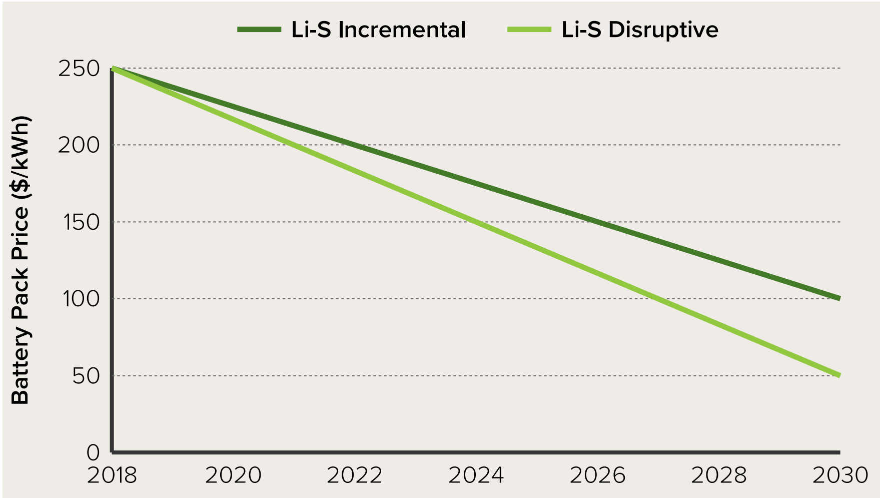


EXHIBIT A8

Li-S Battery Price Scenarios



Potential Commercialization Pathways

EXHIBIT A9

Potential Commercialization Pathways for Li-S Batteries

	Market Entry: Low barrier to entry allows for early-stage prototyping	**Market Growth:** High willingness to pay enables iterative product improvement cycles	**Mass-Market Capture:** Mature products; investments in scaling and customer acquisition
Potential Market Pathway	Buses and trucks are early-adoption target applications	Aviation and military applications will benefit from Li-S	Economies of scale could enable next-generation EVs
Details	• Focus is on developing Li-S batteries for electric buses and trucks due to the higher energy and power needs in heavier vehicles currently powered by diesel engines	• A future market for Li-S batteries is short-distance aviation. Initial focus on high-altitude long-endurance (HALE) UAVs and satellites • Ability to operate at low temperatures makes it possible to use this technology at very low or high elevations	• Learning from other entry markets may enable Li-S to compete with other high-energy-density technologies, especially due to its weight advantage • A Li-S light-duty EV could achieve a range of 300–400 miles
Required Improvements	Increase cycle life to >500	• Continue to increase cycle life and demonstrate use cases	Drive costs down from economies of scale in other markets, manufacturing expansion

Zinc

Zinc-based batteries could be a better performing, inexpensive, and non-toxic alternative to lead-acid batteries. Zinc coupled with low-cost cathodes (like air) can create an inexpensive battery with improving cycle life. Zinc batteries are already cheaper than Li-ion and will continue to decrease in cost.

Battery Characteristics

- A zinc anode with air as a cathode optimizes material costs to make a battery with relatively high specific energy.
- Some zinc products have lower power density than Li-ion and currently limited cycle life.

Key Improvement Pathways

- **Zinc anode/electrolyte:** Improvements to limit dendrite formation are critical to rechargeability and cycle-life improvements. This includes both solid state and liquid electrolyte innovation for zinc-air and zinc alkaline batteries.
- **Cathode improvements:** Cathode improvements for zinc-air batteries can increase specific energy and overall cell efficiency.

Impact on Other Performance Characteristics

- Zinc batteries are both relatively safe and environmentally friendly.
- Zinc-air models achieve 500–1,000 cycles with a specific energy (350 Wh/kg) slightly higher than current Li-ion chemistries. Future goals are to increase this to 500 Wh/kg and to get more than 1,500 cycles.

EXHIBIT A10

Relative Performance Attributes for Zinc Batteries

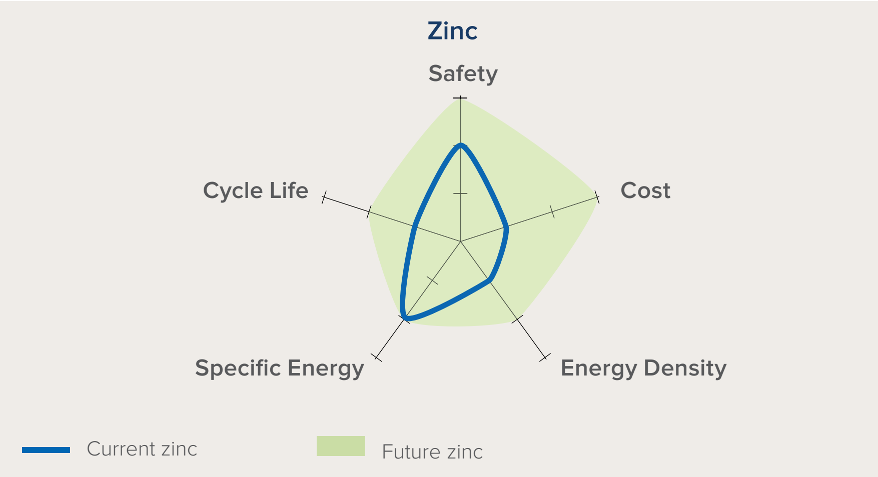
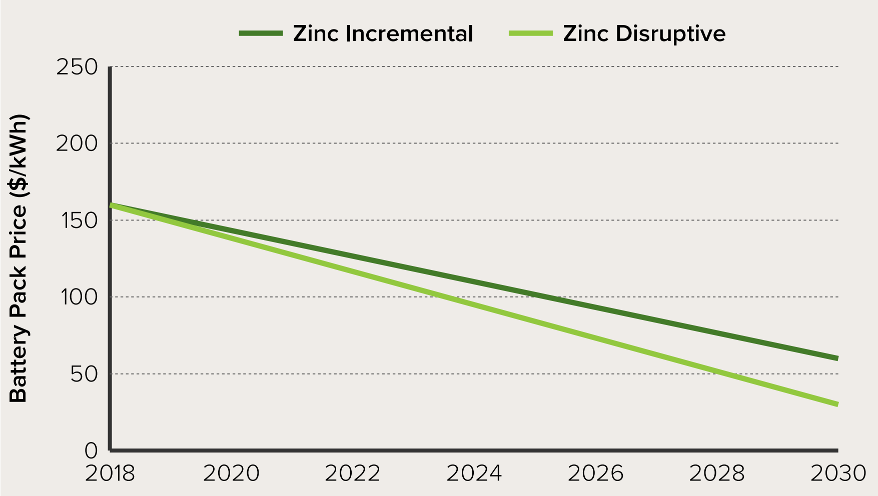


EXHIBIT A11

Zinc Battery Price Scenarios



Potential Commercialization Pathways

EXHIBIT A12

Potential Commercialization Pathways for Zinc Batteries

	Market Entry: Low barrier to entry allows for early-stage prototyping	**Market Growth:** High willingness to pay enables iterative product improvement cycles	**Mass-Market Capture:** Mature products; investments in scaling and customer acquisition
Potential Market Pathway	Low-cost backup and microgrids will have an environmentally safe alternative to lead acid	Low-cost zinc batteries can defer transmission and peaker-plant capacity	Economies of scale can open durable and low-cost mobility applications to zinc batteries
Details	• Zinc batteries are already in the market, primarily for off-grid applications like cell phone towers and microgrids in emerging economies • Zinc batteries are an attractive technology for applications that are cost sensitive and not space limited	• Zinc-air's low cost could relieve capacity constraints that occur <100 times/year • Companies are demonstrating continual improvements in cycle life with innovations like solid-state electrolytes • Some utilities have established zinc grid-scale pilots, but zinc batteries are still gaining industry acceptance	• Low cost, high safety, and low weight are beneficial for mobility applications that have historically used lead-acid batteries (e.g., trucking or three-wheelers)
Required Improvements	While several Zn-air companies are ramping up commercial production, other companies are focused on using Zn-nickel batteries as a stepping-stone to improving their Zn-air technology		Increased cycle life

Flow

Flow batteries have reached a point of maturity and can outcompete Li-ion for long duration storage (e.g., durations greater than six hours).

Battery Characteristics

- Flow batteries use externally stored fluid to generate energy as they flow past each other.
- While not an energy-dense battery, it provides large-scale and long-term reliable energy storage.

Key Improvement Pathways

- **Redox:** Many flow battery chemistries are well known and are in a phase of process cost optimization. Example chemistries include vanadium, zinc, copper, bromide, and iron.

Impact on Other Performance Characteristics

- Flow batteries can reliably provide high power for long durations and can last for more than 20,000 cycles at 100% depth of discharge.
- They are unlikely to compete with Li-ion for durations of less than six hours and will become more competitive as they are used for longer durations.

EXHIBIT A13

Relative Performance Attributes for Flow Batteries

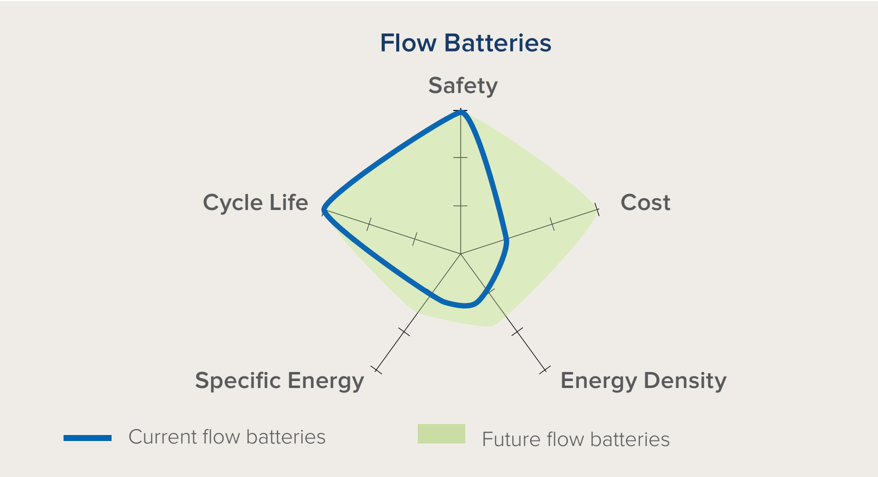
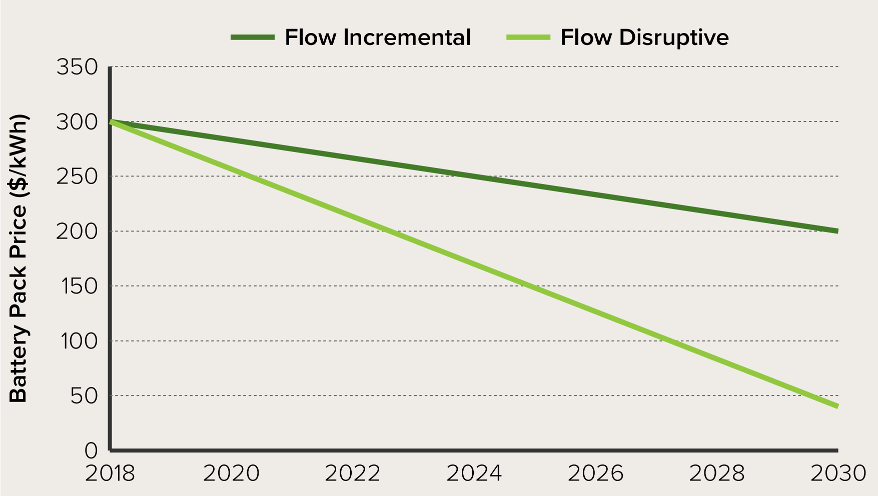


EXHIBIT A14

Flow Battery Price Scenarios



Potential Commercialization Pathways

EXHIBIT A15

Potential Commercialization Pathways for Flow Batteries

	Market Entry: Low barrier to entry allows for early-stage prototyping	**Market Growth:** High willingness to pay enables iterative product improvement cycles	**Mass-Market Capture:** Mature products; investments in scaling and customer acquisition
Potential Market Pathway	Industrial microgrids can benefit from reliable high power and long durations	Grid balance and infrastructure deferral will be a critical early market	EV charging can be implemented with minimal infrastructure upgrades
Details	• Flow batteries can have high power output, high reliability, and long-duration capabilities that can be used for applications such as remote mining, which can benefit by removing diesel costs and supply line constraints	• Flow batteries will be an important grid asset for balancing as renewable penetration increases • Transmission and distribution deferral can mitigate congestion upgrade costs. • Energy duration can be extended by adding additional fluid at a relatively low marginal cost	• The ability to scale the amount of energy stored in the system by recharging and adding additional fluid means that EV charging could be implemented with minimal system upgrades and with similar maintenance routines relative to those currently used
Required Improvements	Cost decreases from improved process design	Development of long-term-storage market mechanisms	Development of an integrated EV charging and storage offering

High Temperature

High-temperature batteries could provide energy shifting or peaking capacity based on safety and long life cycle. New high-temperature chemistries using liquid metal components could outcompete Li-ion for long duration grid applications greater than four hours.

Battery Characteristics

- Batteries can deliver continuous cycling up to 100% depth of discharge without capacity fade degradation.

- Emerging cells are safer due to low toxicity, low flammability, and lack of internal membranes. Cell materials are inactive at low temperature and are tolerant of over charge, over discharge and short circuits.

Key Improvement Pathways

- **Liquid metal:** These batteries could provide low-cost, long-duration grid balancing based on their safety and long life cycle.

Impact on Other Performance Characteristics

- Liquid metal batteries are best suited to constant active cycling that maintains elevated temperatures and thereby increases battery efficiency, similar to thermal power plants.

- Liquid metal batteries are relatively safe due to their non-conductivity at room temperatures.

EXHIBIT A16

Relative Performance Attributes for High-Temperature Batteries

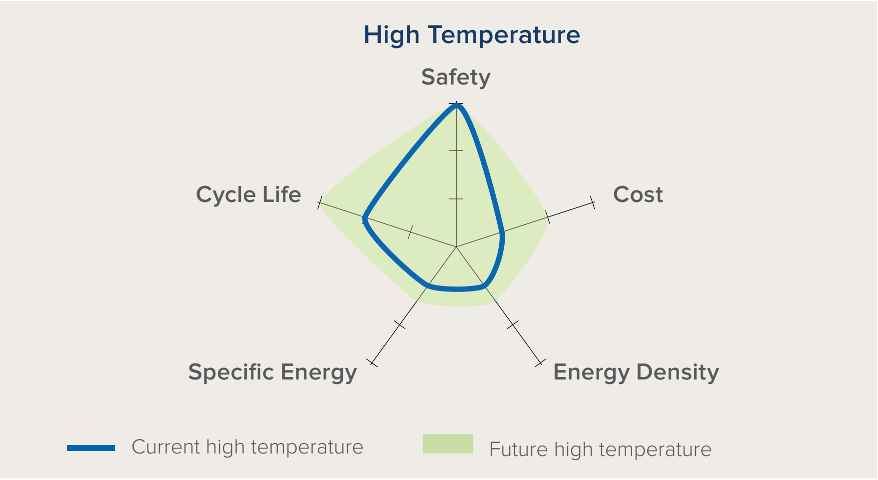
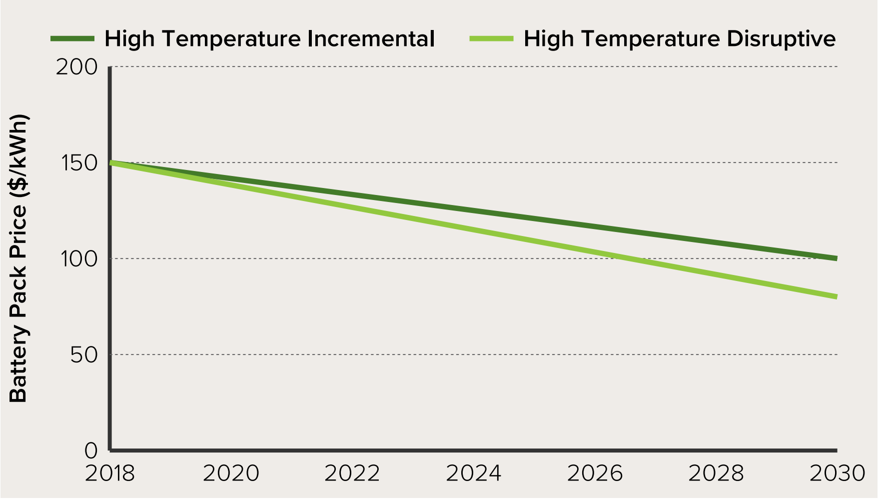


EXHIBIT A17

High-Temperature Battery Price Scenarios



Potential Commercialization Pathways

EXHIBIT A18

Potential Commercialization Pathways for High-Temperature Batteries

	Market Entry: Low barrier to entry allows for early-stage prototyping	**Market Growth:** High willingness to pay enables iterative product improvement cycles	**Mass-Market Capture:** Mature products; investments in scaling and customer acquisition
Potential Market Pathway	Grid balancing will be a critical first market	Long duration storage can become increasingly valuable over time	
Details	• High-temperature batteries can provide reliable high power, fast response, and long duration grid balancing • Low-cost manufacturing and component cost can enable competitiveness with Li-ion	• High-temperature batteries can provide reliable, long duration storage • As renewable energy generation proliferates, the need for long duration storage that can stack multiple grid value propositions will become increasingly important	
Required Improvements	Innovators need to identify integration partners	Long-duration market design evolution	

High Power

High-power storage could enable fast EV charging and high-power applications. Sodium ion and nanocarbon-based ultracapacitors aim to have significant improvements in specific energy relative to previous supercapacitors, which could dramatically improve their value in high-power and fast-charging applications.

Battery Characteristics

- Capacitors are different from batteries in that they do not hold as much energy but have higher power density that can charge and discharge rapidly.
- This can make them useful in hybrid or fast charge/discharge use cases.

Key Improvement Pathways

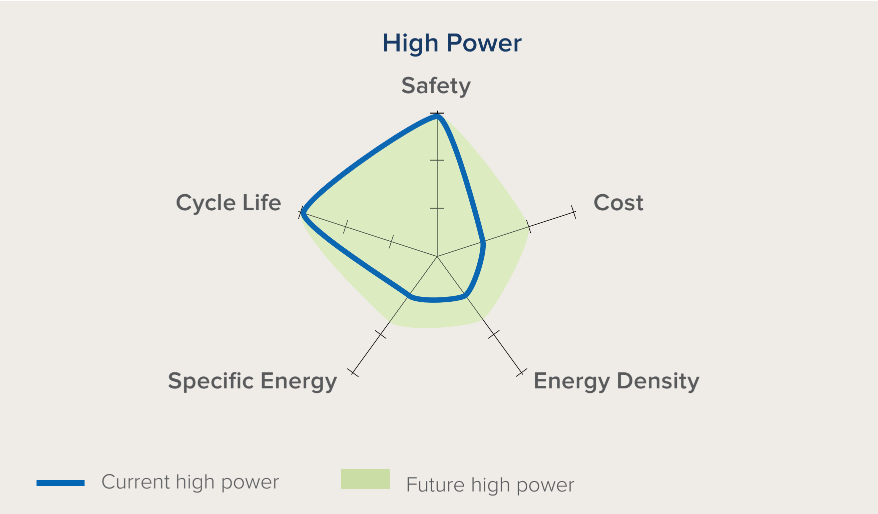
- Nanocarbon: Electrochemical double-layer capacitors using graphene and improved electrolytes blur the line between battery and supercapacitors.
- Sodium-ion batteries are a low-cost, high-power opportunity.

Impact on Other Performance Characteristics

- Targets for improvements in specific energy suggest that high-power devices will increase by a factor of 10 relative to today's super capacitors.
- High-power technologies could provide more than 100,000 charge and discharge cycles.

EXHIBIT A19

Relative Performance Attributes for High-Power



Potential Commercialization Pathways

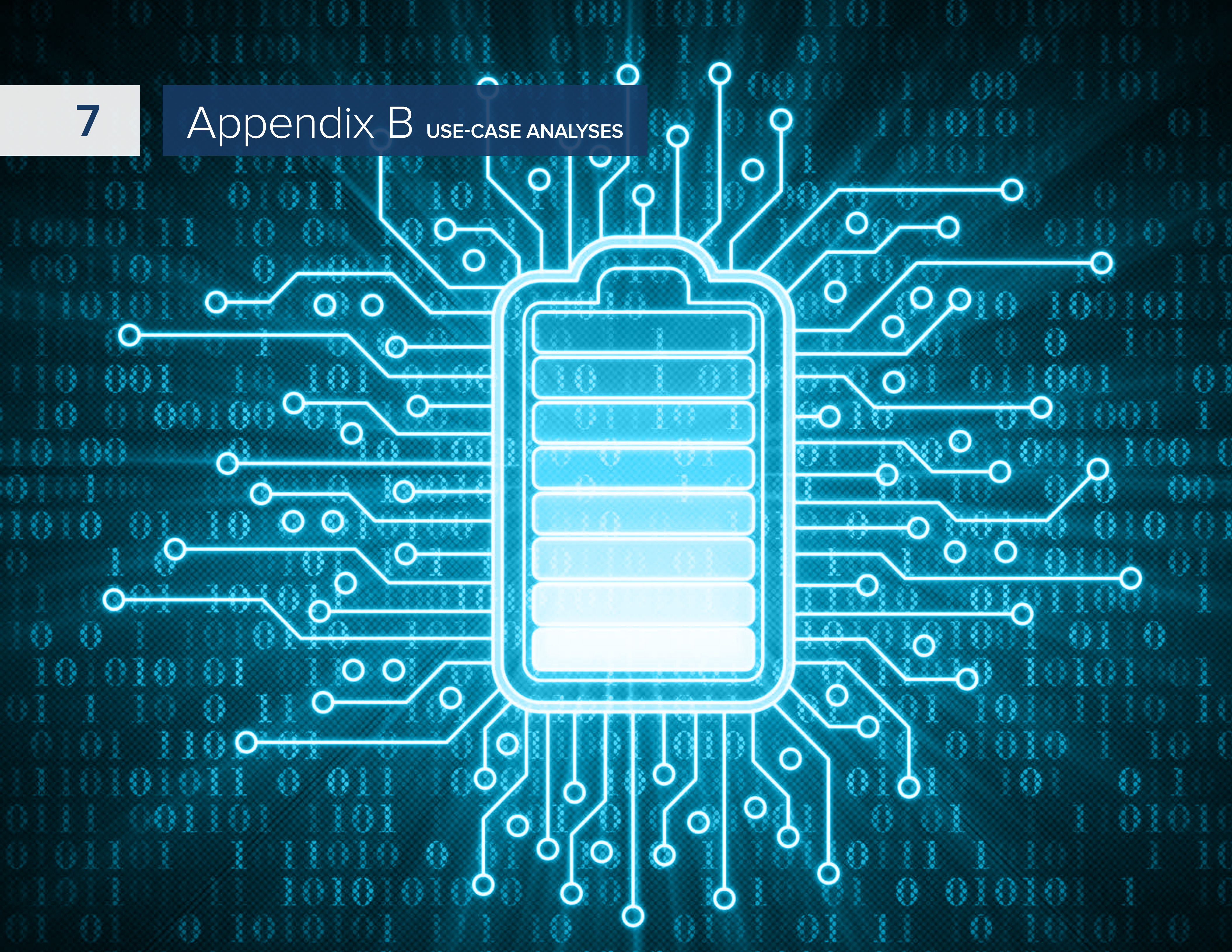
EXHIBIT A20

Potential Commercialization Pathways for High-Power Batteries

	Market Entry: Low barrier to entry allows for early-stage prototyping	**Market Growth:** High willingness to pay enables iterative product improvement cycles	**Mass-Market Capture:** Mature products; investments in scaling and customer acquisition
Potential Market Pathway	Consumer electronics and appliances will be an important first market	Mobility applications will perform better with hybrid systems	Fast-charging infrastructure can leverage long-lifetime, high-power applications to manage EV system charging
Details	• Significant improvements in high-power devices could initially be integrated into consumer electronics that will benefit from being able to charge in seconds or minutes • These products can validate lifetime and safety, paving the way for scaling	• High-power applications: Specific power of >3,000 W/kg has been realized, along with higher energy density relative to previous high capacitor technologies • Regenerative charging: Super-capacitors can be paired with more energy-dense batteries for improved fast-charging hybrid battery mobility products	• Fast-charging applications could be able to charge an EV battery in minutes • High-power batteries with energy density similar to lead-acid batteries can enable charging infrastructure without significant grid upgrades
Required Improvements	Initial products being deployed in small consumer electronics	Large-scale, high-quality manufacturing improvements	Pilots that enable fast EV charging to validate cost and benefits

7

Appendix B USE-CASE ANALYSES



Using the cost and performance scenarios developed in the first phase, RMI ran updated analyses of several existing analytic models to project the potential differential impacts on market adoption of disruptive battery technology breakthroughs. This section summarizes the updated assumptions that the authors applied to each of these models to estimate these scenarios.

CLEAN ENERGY PORTFOLIO MODEL UPDATES

The authors updated the RMI Clean Energy Portfolio (CEP) model for two different battery scenarios.

- **Scenario 1:** This scenario is based on the expected improvement curve between today's Li-ion batteries and advanced Li-ion batteries. It follows the incremental Li-ion scenario shown in Exhibit A21.

- **Scenario 2:** This disruptive scenario assumes that zinc alkaline solid state or flow batteries achieve $40/kWh battery pack cost by 2030.

For a compete discussion of RMI's CEP model see *The Growing Market for Clean Energy Portfolios* (RMI 2019).[51]

ELECTRIC VEHICLE MODEL UPDATES

RMI has a total cost of ownership (TCO) model for estimating the all-in costs (e.g., capital, operations, maintenance) for owning and operating a vehicle on a per-mile basis across its lifetime. The model includes assumptions for each of two-wheel (e.g., motorcycles, scooters), three-wheel (e.g., rickshaws), and four-wheel (light-duty) vehicles in India and various sized four-wheel vehicles in the United States. This comparison helps account for key differences between the two markets in available models and consumer preferences. In the model version run for this study, the authors used the EV battery cost assumptions in Exhibit A21 to construct both an incremental (advanced Li-ion) and a disruptive (alkaline solid state) scenario for electric vehicle TCO.

EXHIBIT A21

Assumed Battery Prices ($/kWh) for the Incremental (Advanced Li-ion) and Disruptive (Alkaline Solid State) Scenarios

Scenario	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Advanced Li-ion	$230	$202.50	$175	$147.50	$120	$112.50	$105	$97.50	$90	$82.50	$75	$67.50	$60
Alkaline Solid State							$95	$84.20	$73.30	$62.50	$51.70	$40.90	$30

LEVELIZED COST OF STORAGE

RMI updated the 2018 levelized cost of storage model developed by Oliver Schmidt et al. to account for the projected battery costs in each technology scenario, including cycle-life degradation costs for each of the use cases shown in Exhibit A22. Exhibits A23 and A24 provide technology specifications for each of the Li-ion and flow battery cases modeled.[52]

EXHIBIT A22

Levelized Cost of Storage Use-Case Specifications

	Arbitrage	Primary	Secondary
Size (kW)	100,000	10,000	100,000
Discharge duration (hours)	4	0.5	1
Annual cycles	300	5,000	1,000
Charging cost ($)	0.05	0.05	0.05
Depth of discharge	0.9	0.4	0.6

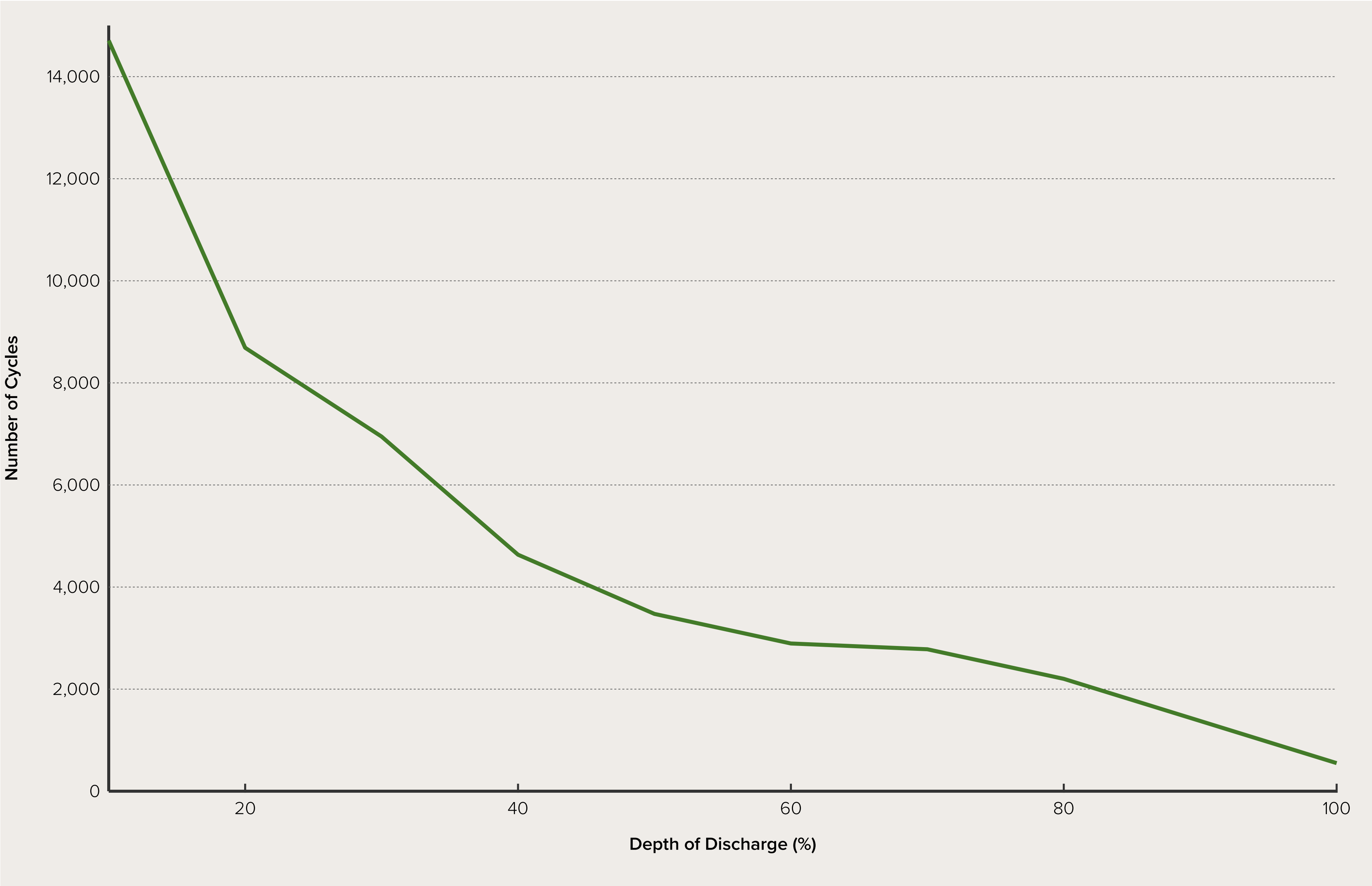
EXHIBIT A23

Levelized Cost of Storage Technology Specifications

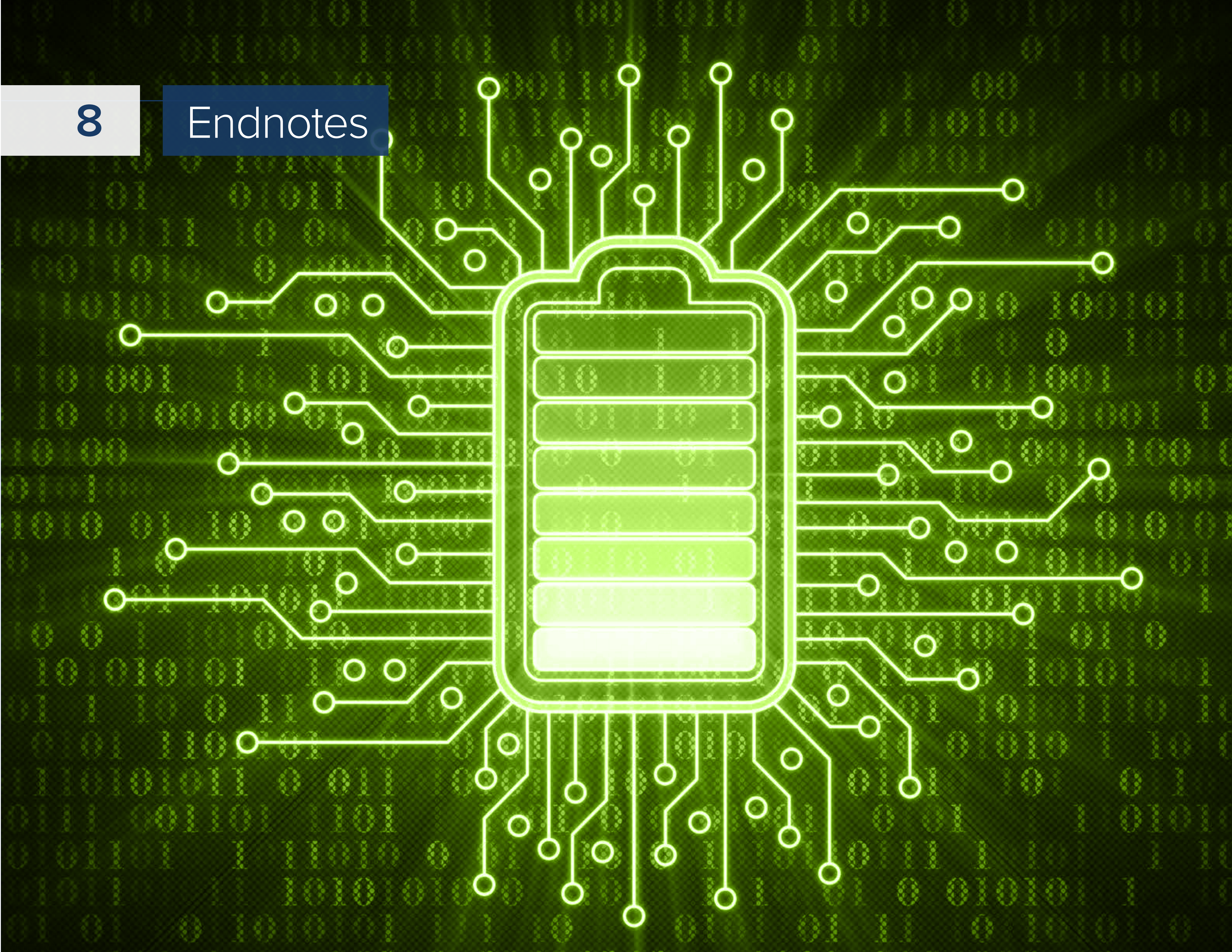
Technology	Li-ion 2019	Li-ion 2025 (NMC)	Li-ion 2030 (NMC)	Advanced Li-ion 2030	Flow 2019	Flow 2025	Flow 2030
Specific power cost ($/kW)	70	70	70	70	58	58	58
Specific energy cost ($/kWh)	237	176	176	90	350	173	50
Fixed O&M ($/kW)	10	10	10	10	39	39	39
Variable O&M ($/kW)	0.0003	0.0003	0.0003	0.0003	0.1	0.1	0.1
Energy replacement cost as % of specific energy cost	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Round-trip efficiency	0.86	0.86	0.86	0.86	0.75	0.75	0.75
Cycle life (cycles at possible depth of discharge)	See Exhibit A24; Li-ion cycles curve @ DOD	See Exhibit A24; Li-ion cycles curve @ DOD	See Exhibit A24; Li-ion cycles curve @ DOD	See Exhibit A24; Li-ion cycles curve @ DOD	20,000	25,000	30,000
Shelf life (years)	10	10	10	10	20	20	20
Construction time (years)	0.5	0.5	0.5	0.5	1	1	1

EXHIBIT A24

Modeled NMC Cycle Life



8 Endnotes



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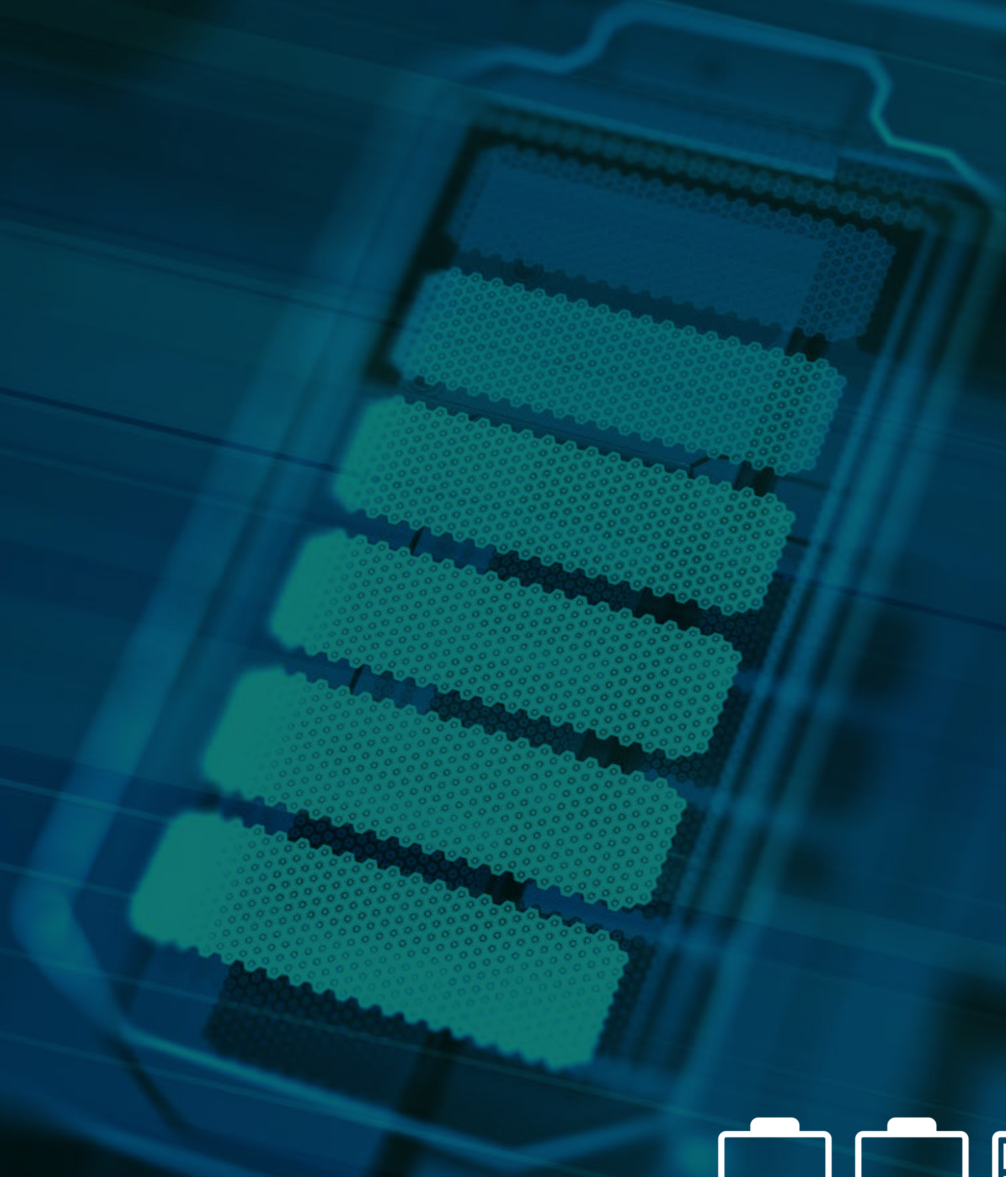

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