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JULY 2024

Fast-Changing Innovation: The Battery Race Powers Forward

The energy transition has been quietly accelerating for almost a full decade. Electrification and the pursuit of a clean, green and circular economy has driven industry and consumers alike to shift demand in favor of a technology that is arguably still not quite on par with conventional alternatives. Batteries are vital to the electrification narrative. In this white paper, we aim to explore the fast-changing innovation curve behind batteries, particularly the ones that will be powering your car in the not-too-distant (and for some, present) days.

The opportunity, as we see it from the public markets, is expansive. The entire value chain from mining to end application is being built on new infrastructure and technology, with incremental new demand being announced on what feels like a monthly basis. We are agnostic toward any particular part of the value chain – but are laser-focused in finding superior technologies and assets we believe can withstand volatile cycles, as is common in all growth industries. Currently, our focus sits within the realm of energy storage. We believe that batteries are the most common solution to the problem, with aging grid infrastructure, more renewables on the grid and higher demand for electricity coming from the shift to electric vehicles.

Key takeaways include:

- The growth in electrification is massive, with battery demand currently well outpacing supply in the near to medium term.
- Battery design is being led by the automotive industry—largely to produce consumer vehicles.
- The race is on toward a $100/kWh (kilowatt hour) battery pack cost target, deemed the tipping point at which total cost of ownership becomes a “no-brainer” for the consumer.
- Solid-state batteries are extremely attractive due to their inherent safety: they don’t use liquid electrolytes and are better at charging fast.
- Energy storage systems have been a rapidly expanding market globally.
- Storage solutions are extremely diverse, with entirely different technologies depending on the application.

Consumers Push for Energy Efficiency

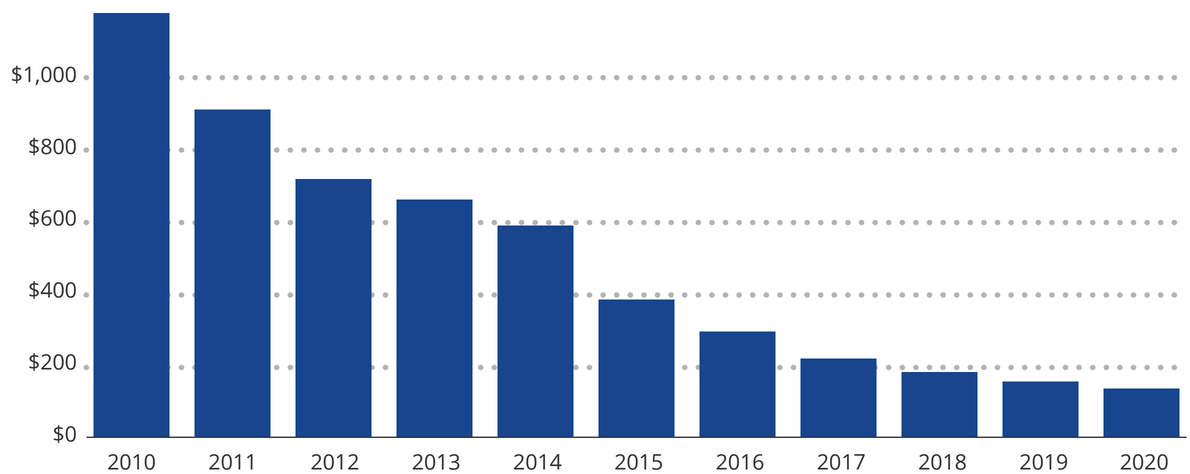
Consumers have spoken, and governments across the globe have vocalized and written into policy overwhelming support for industries becoming more sustainable, energy efficient and minimizing their carbon footprint. Tesla, Inc., for example, while often seen as a poster child of electrification, represents only the very tip of a massive iceberg of growth in electric vehicles (EVs): the proverbial "elephant in the room." EV stock is projected to grow to 35x its current size.[1] Meanwhile, roughly two billion internal combustion engines (ICE) remain in use all over the world.[2] This number comprises not only passenger vehicles, but also generators, trucks, trains and ships: all potential future adopters of battery technology.

Further upstream, another world of opportunity opens up with the utilities industry: batteries are as much as 30% cheaper[3] than conventional peaker plants. Peaker plants are power plants that generally operate only when there is high (peak) demand for electricity and are usually powered by coal or natural gas. In order to replace peaker pants, the U.S. alone needs to add 30-100 GW (gigawatt) of 4-hour duration battery storage[4].

In short, the growth in electrification is massive, with battery demand currently well outpacing supply in the near to medium term. The critical factor for hyper-speed adoption, however, is, cost. Led by innovation in the automotive industry, the race is on toward a $100/kWh battery pack cost target, deemed the tipping point at which total cost of ownership (TCO) becomes a "no-brainer" for the consumer.

Electric Vehicle Battery Prices Near $100/kWh Watershed

A BloombergNEF survey shows the average price of lithium-ion battery packs at $137 per kilowatt-hour. At $100/kWh, EVs are as cheap to make as gas cars.



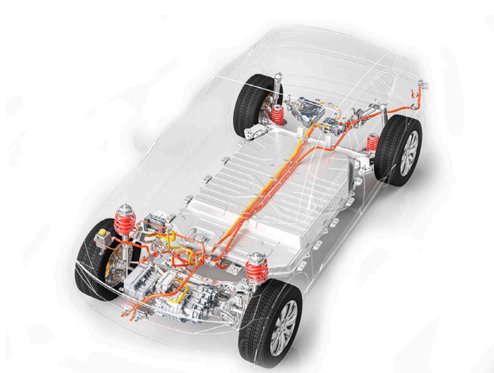
Source: BloombergNEF

Part I: Electric Vehicles

Battery design is being led by the automotive industry—largely to produce consumer vehicles. To understand why certain technologies are chosen over others, we need to dive into what factors are driving the need for certain traits.

What Exactly Is an EV Battery?

An electric vehicle battery is a rechargeable battery designed specifically for a high kilowatt hour (kWh) capacity. They differ from starting, lighting, and ignition (SLI) batteries in that they are "deep cycle", i.e. they are designed to provide power over a long period of time. The EV battery is characterized by a high power-to-weight ratio (which measures performance) and high energy density (which measures storage capacity). And, given they are the bulk of the weight in a passenger vehicle, a smaller, lighter battery is desirable as it maximizes performance.



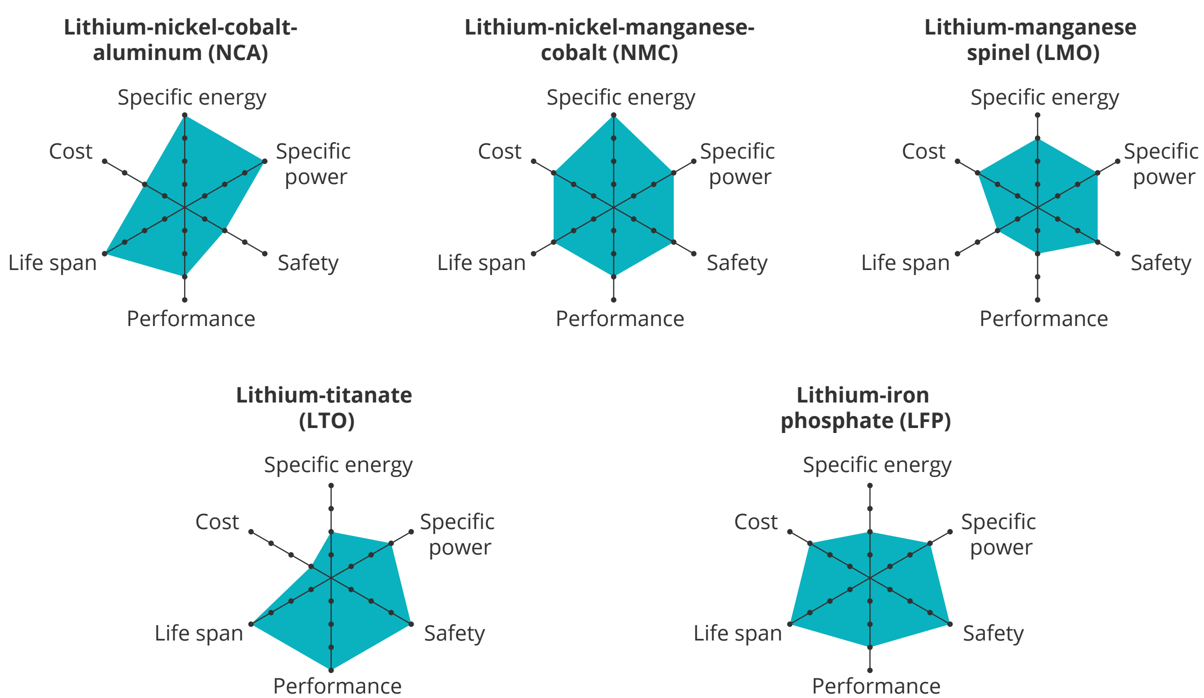
The chemistry universally used for the EV battery is lithium-ion. Lithium (Li) is the lightest metal (with atomic number 3) on the periodic table. Initially developed for the small electronics market and used in smartphones and computers, lithium-ion's high energy density packaged in a small container became naturally attractive to the automotive industry. The technology has become more refined and cheaper over the past three decades with battery cycles increasing from <500 to over 3,000 today and costs declining over 10% each year to almost $100/kWh today.[5] Due to these technological advances, different variations of the lithium-ion chemistry began to emerge for specific applications and energy demand uses. Other types of technology have been widely used for decades and improved upon, but, in our view, an overwhelming amount of capital and research has gone into continuing lithium-ion development, largely due to its mobile nature.

Battery Breakdown: Chemistry and Form Factor

Chemistry: One size does not fit all

When we discuss "chemistry," we are generally referring to the elemental makeup of the cathode material in the battery. In a lithium-ion rechargeable battery, ions are transferred back and forth between the anode and cathode through an electrolyte. These three active materials are the most important parts that determine the performance of the battery. Anode materials offer a higher lithium-ion storage capacity than do cathodes, making the cathode material the limiting factor with regard to battery performance and, subsequently, the center of focus for academia and scientists. As a result, the industry has developed a number of lithium-based chemistries using component materials such as nickel (Ni), manganese (Mn), iron (Fe) and cobalt (Co). As seen in the Tradeoffs of Battery Chemistries graphic, there has not been one clear winner; each material has positive attributes, but also drawbacks and limitations. Battery manufacturers have doubled down on certain chemistries, improving on new or existing technologies they believe to be the most cost competitive while optimizing on five additional variables: specific energy (commonly referred to as energy density; the higher the energy density, the lesser weight/space the battery needs to store a given amount of power), specific power (rate at which stored energy is generated relative to weight), safety (Li-ion is highly corrosive/reactive/explosive), performance and life span. Today, it appears that the chemistries most suitable for passenger vehicles are NMC (nickel-manganese-cobalt), NCA (nickel-cobalt-aluminum) and LFP (lithium-iron phosphate).

Tradeoffs of Battery Chemistries

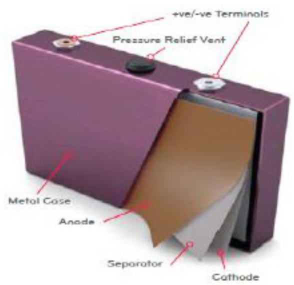
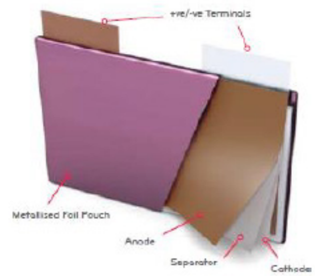


Source: BCG research

Form factor: Packaging matters

In concert with chemistry, form factor is the other major consideration in battery design. Form factor concerns the battery's size, shape and other physical attributes.

Battery Formats

Category	Cylindrical	Prismatic	Pouch
			
Specs and market			
Overview	Smallest and most mature	Biggest and heaviest cell, but highest cell-to-pack efficiency	Highest cell energy density due to the skip of can, but worst cell-to-pack efficiency
Typical Cathode (2020)	NCA & NMC	NMC & LFP	NMC & LFP

Source: Johnson Matthey Battery Systems; Bernstein

There are three battery formats currently used in the electric vehicle battery market today: cylindrical, prismatic and pouch. Prismatic cells are used by 60% of the market,[6] given their relative large size and manufacturing efficiency, with the rest of the market split between cylindrical and pouch. Certain chemistries work better with certain form factors, as the different physical formats highlight intrinsic limitations among the battery materials.

Types of Battery Formats

Cylindrical cells are the most mature battery format. The design was used in 3C (computer, communication, consumer) electronics for decades and manufacturing processes are both automated and consistent. The cells have higher energy density than their prismatic and pouch counterparts. However, given their small form factor, a battery needs thousands of cylindrical units, requiring a sophisticated battery management system. Another limitation of cylindrical cells is that the mechanical structure limits an increase in power and life span/cycles are lower.[7]

Until mid-2020, Tesla exclusively used an NCA chemistry in small cylindrical cell format, augmenting it with a sophisticated thermal management system to monitor each individual cell, improving safety significantly.

Prismatic cells currently account for 60% of EVs sold. It uses an aluminum casing for higher mechanical reliability and safety, the latter being a critical factor in battery development for automotive applications. The downside is that it is the heaviest format—which lowers energy density. However, it is the lowest priced format on a per kilowatt-hour basis. Given its rigid casing, prismatic cells are the optimal format for future solid-state technologies (which use a solid electrolyte, rather than liquid), insulating the fragile electrolyte. Meaningful innovation is being driven toward further reducing pack level weight and cost. Industry consensus is generally most favorably inclined toward this battery format.

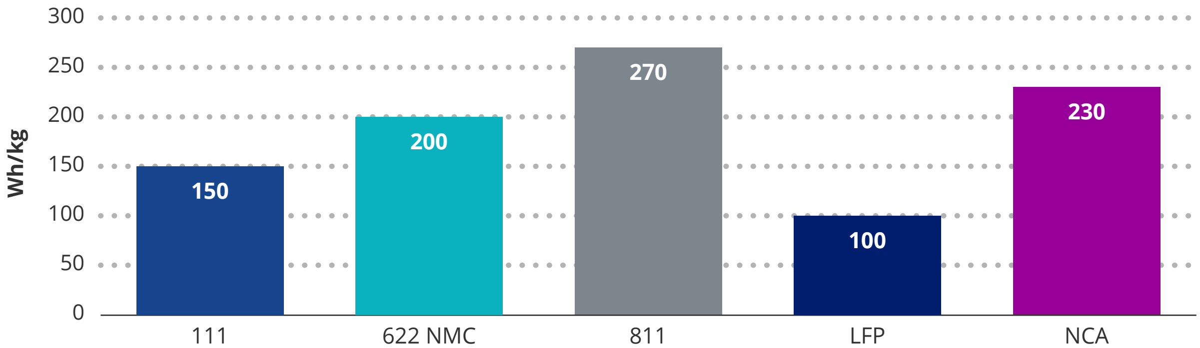
Pouch cells boast the highest energy density and are lighter than prismatic cells. Given the lack of hard aluminum casing, pouch cells make for a more flexible design. However, due to its lack of exterior "protection" (the cell is contained in an actual aluminum foil pouch), it suffers in cell-to-pack efficiency, which increases pack cost and makes for a less competitive design compared to prismatic. Safety is another issue with pouch cells as, compared to prismatic, heat travels faster given the relative lack of insulation.

Chemistry and form factor are the two most important considerations in assessing the viability of future lithium-ion technologies. The two go hand in hand, as certain chemistries can only exist within a certain form factor. With cost paramount, scientists are looking to design an optimal chemistry with corresponding form factor that will be able to deliver on all the elements that matter for a consumer battery operating under vastly varied outdoor conditions, terrains, and driving environments. Specifically, developers look to address five additional variables: specific energy, specific power, safety, performance and life span.

Battery Technology Advancements

Battery technology is evolving rapidly and innovation over the next decade is trending heavily toward: 1) higher-nickel cathodes, particularly for NMC, which in prismatic format has more potential than other formats for energy density improvement; and 2) further advancement in reducing cost from cell-to-pack design. Major global manufacturers such as LG Chem, Contemporary Amperex Technology Co. Limited and BYD Auto are pushing toward the most advanced (and most costly) iteration of NMC: 811 (80% nickel, 10% manganese, 10% cobalt).[8] This is a continued progression from NMC 111, NMC 532, and NMC 622, which are chemistries nearly all major battery original equipment manufacturers (OEMs) produced over the past eight years.

NMC Chemistry – Energy Density by Type



Source: SNE Research

As technology progresses toward even higher nickel content, certain manufacturers are pursuing variations on legacy NMC chemistries, finding alternative ways to optimize energy density while keeping a keen eye on cost. New entrants are approaching the actual manufacturing process from a different angle—Norwegian battery manufacturer FREYR is utilizing a patented manufacturing process to deliver a chemistry-agnostic lithium-ion battery using a third of the manufacturing steps in a conventional process.[9] The result is a highly cost-competitive battery with performance similar to its conventionally-manufactured cousin, but with lower capital expenditure (CapEx) and operational expenditure (OpEx) costs.

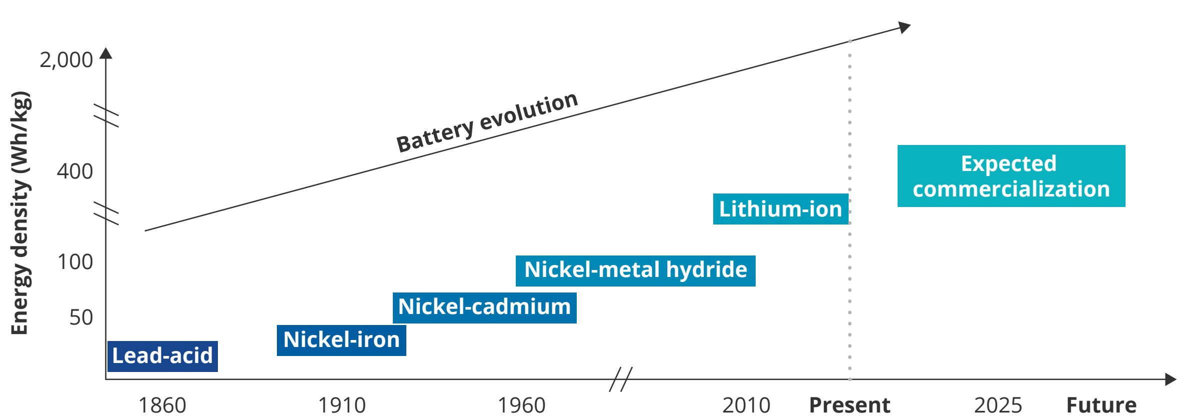
In addition to manufacturing innovation, OEMs are focusing on improving cell-to-pack technology, which allows for higher volume efficiency by directly assembling battery cells into the pack (no module components), thereby reducing the weight of the overall battery pack and improving energy density.

Solid State: The Next Frontier

Much anticipation in the scientific community revolves around the commercialization of solid-state lithium batteries. A solid state is extremely attractive due to its inherent safety from not using liquid electrolytes, versus lithium-ion, as well as its conduciveness to fast charging.

The Battery Evolution

Auto OEMs globally are investing in startup R&D houses focused on developing solid-state (S-S) chemistries in a push to increase EV range (S-S designs could deliver as much as 50% more energy density[10]) and, in the long term, reduce cost (manufacturing S-S batteries could cost 40% that of current lithium-ion designs[11]). While commercialization is not expected for at least another half decade, with some automakers planning mass adoption of the technology closer to 2030, the natural evolution toward achieving higher energy density marches on.



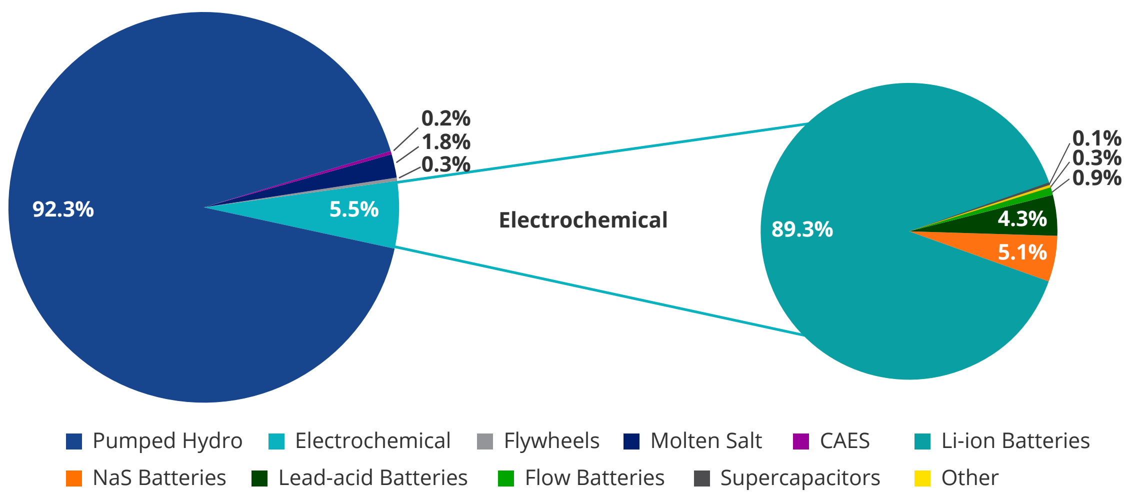
Source: https://www.futurebridge.com/blog/solid-state-batteries/

Part II: Energy Storage

A Battery for Every Application

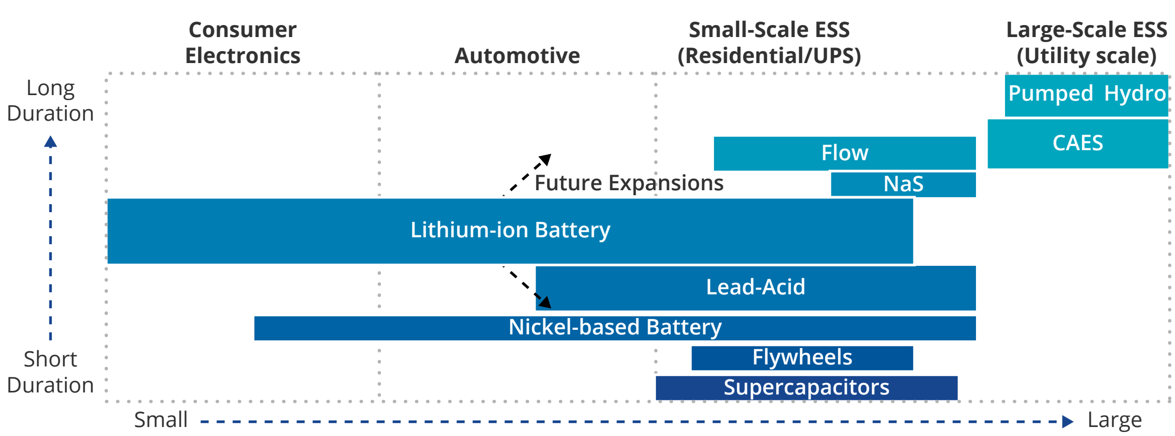
When we eliminate the size and weight constraints that limit EV applications to lithium -ion technologies, the battery world becomes much bigger. Energy storage systems have been a rapidly expanding market globally, with industry forecasts suggesting over 10% annual growth for the next decade. Unlike the EV market, storage solutions are extremely diverse, with entirely different technologies depending on the application (small-scale versus large-scale, short-duration versus long-duration). In this market, lithium-ion remains a dominant player given continuously falling costs (a benefit from the ramp in scale for EVs). However, the advantage narrows once demand for more than a few hours of power is required. For long-duration, larger-scale use cases, the major technologies currently deployed are pumped hydro, compressed air energy storage, sodium-sulfur batteries and flow batteries, explained below.

Accumulated Global Energy Storage Market Capacity (2000-2019)



Source: CNESA Global Energy Storage Database

Storage Solution Applications



Source: Sandia National Laboratory, Navigant and Bernstein Analysis

Pumped hydro comprises over 90% of energy storage currently in place globally (measured in units of power). It utilizes two water reservoirs at different elevations that can generate power as water moves down through a turbine. The storage capacity is defined by the size of two bodies of water—barring space and ecological constraints, this storage system is highly cost competitive.

Compressed air energy storage uses surplus energy to compress air during off-peak hours which is then held in an underground reservoir and released during peak hours. The compressed air is run through a turbine and generators, which supply power to the grid.

Sodium-sulfur batteries are constructed from liquid sodium and sulfur. Energy density and cycle life are high, but pure sodium is highly flammable when introduced to air and moisture. With increasing commercialization and cost reductions from lithium-ion technologies, this technology has become less competitive over time.

Flow batteries are an older technology, although recent innovations addressing some of the safety elements of traditional flow designs have made this technology more promising for longer-duration requirements and, in many instances, highly competitive and cheaper than lithium-ion alternatives.

Go With the Flow

In our view, commercial and industrial (C&I) and utility-scale storage applications will likely continue their robust growth trajectory. Older technologies, such as the flow battery, may be making a comeback in C&I and utility applications. This is due to mid-term cost pressures within lithium-ion battery components, as corporations look to meet increasingly widespread mandates to diversify energy storage sources and provide grid stabilization.

Today's technology and cost curve are economically competitive for lithium-ion up to four hours duration, but any longer calls for flow batteries, which tout duration multiples above. Energy storage company, ESS, Inc., has designed an iron-based flow battery, a safer and less expensive alternative to the traditional vanadium electrolyte (requires vanadium to be suspended in sulfuric acid). In addition, incremental cost of storage (effectively increasing the electrolyte) is <$20/kWh, with duration up to 12 hours.

The Energy Transition Is Here to Stay

Ultimately, there will be winners and losers in the battery race, even with a vast market and growing demand. The automotive industry is leading battery design and, as cost is a critical factor to adoption, the development of a $100/kWh battery pack would put electric vehicles on par with conventional vehicles, in terms of price. We are particularly excited about next-generation solid-state battery chemistries that push the limits of energy density across widespread applications. Additionally, energy storage systems have been rapidly expanding and the diversity of storage solutions show the potential of the battery world beyond electric vehicles. We continue to keep an eye on patents filed, particularly by major players such as Toyota, Samsung and LG Chem. We believe the investment opportunity encompasses the entire value chain as it is being fueled by new infrastructure and technology. In our view, batteries are the most common solution to energy storage due to aging grid infrastructure, an increase in renewables on the grid and higher demand from the transition to electric vehicles.

[1] Wood Mackenzie (https://www.woodmac.com/press-releases/323-million-electric-vehicles-will-be-on-the-roads-by-2040/)

[2] Industr.com (https://www.industr.com/en/internal-combustion-engine-the-road-ahead-2357709)

[3] Clean Energy Council (https://www.cleanenergycouncil.org.au/resources/resources-hub/battery-storage-the-new-clean-peaker)

[4] EIA

[5] Bloomberg (https://www.bloomberg.com/news/articles/2020-12-16/electric-cars-are-about-to-be-as-cheap-as-gas-powered-models)

[6] Bernstein

[7] VanEck

[8] VanEck

[9] Freyr Battery

[10] Solid power

[11] BloombergNEF (https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/)

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