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Lithium Ion Battery Industrial Base in the U.S. and Abroad

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Executive Summary

Introduction

Between 2005 and 2016, Li-ion battery sales grew from 8 GWh per year to 89 GWh per year, largely driven by the increased demand for electric vehicles (EVs). EVs continue to gain in popularity—over a million were sold in 2017, and single-year sales are projected to rise to 10 million passenger vehicles in 2025, and 28 million in 2030. These EV sales projections will directly translate into additional battery production; by 2028, global Li-ion battery production is expected to reach 1200–1600 GWh, roughly 15 times 2016 levels. Li-ion battery production is an increasingly important part of the automotive economy.

Many different chemistries can be employed in a Li-ion battery. The properties of these batteries such as their energy-carrying capacity, weight, power output, longevity, and safety are critically dependent on the underlying chemistry of the battery, as well as the design of specific components in the battery such as the anodes, cathodes, electrolyte, and separator. Battery system design is a key discriminator between EV manufacturers, because it directly affects the EV's performance, driving range, and cost. Significant battery research and development (R&D) is taking place across the globe to improve battery characteristics.

Raw Materials and Refining

Lithium, cobalt, and the graphite form of carbon are critical elements used in Li-ion batteries. Raw materials costs are an important fraction of the cost of the battery system. These critical elements must first be extracted from the ground through mining and then be refined into chemicals that can be utilized in the manufacture of batteries. The United States has a limited presence in the global supply chain for the raw materials used in Li-ion batteries:

- Several countries (primarily Australia, Chile, and Argentina) are currently mining lithium, and U.S. mining companies are involved in various of those mining projects. There are domestic reserves of lithium but currently little domestic mine production. With respect to refining, about half the lithium refining capacity is concentrated in China, followed by Chile and Argentina. The United States lacks any real large-scale, domestic lithium-refining capacity.
- Almost 70% of all cobalt is mined in the Democratic Republic of Congo (DRC), where there are serious concerns about human rights and child labor violations.

Chinese-owned mines in the DRC account for about half the output. Like lithium, refining of cobalt is concentrated in China (over 60%); the output of the second highest refiner, Finland, is roughly one-fourth that of China. The United States lacks cobalt-refining capacity.

- About two-thirds of the graphite used in Li-ion batteries is synthetic, and the remainder is mined and refined. China accounts for over half of the mined graphite worldwide and all the commercial-scale graphite refining. Synthetic graphite, which is roughly twice the cost of natural mined/refined graphite, is produced mostly in Asia, but the United States has a small domestic capacity.

Battery Cell Components

The four key components in battery cells are the cathode, anode, electrolyte, and separator. Despite there being a diversity in cathode chemistry, over 60% of cathodes were manufactured in China in recent years, the remainder largely produced in Japan and South Korea. As of 2018, most commercial production of battery anode materials was concentrated in China; a single company accounted for 70% of global production. U.S. companies have a major role in supplying separators but a minimal role in supplying electrolytes.

Battery Cells

Battery cells, which are the fundamental unit that can supply energy for a vehicle, are often made near EV-production facilities to minimize the cost and logistics (including safety concerns) of transporting cells to the EV assembly line. For EVs made in the United States, cell manufacturers have set up cell factories near the auto plant or co-located with the auto plant. Consequently, there are battery-production facilities in the United States, but all of the top cell manufacturers are Asian corporations.

R&D Investment

Investment in battery technology by the U.S. Government (including the Department of Energy, the Department of Defense, the National Science Foundation, and the National Aeronautics and Space Administration) has produced many viable startup companies with valuable intellectual property (IP) in areas such as anode manufacturing, solid-state electrolytes, and other next-generation battery technology. But because of the lack of domestic cell and component manufacturers, overseas investment in these home-grown technologies is almost inevitable. When novel battery technology achieves the readiness level at which scale-up is logical and necessary, increased foreign investment occurs, and IP can migrate overseas along with the actual manufacturing efforts.

Legislation's Impact on the U.S. Supply Chain

The Patent and Trademark Law Amendments Act, commonly called the Bayh-Dole Act, is the legislation that governs federally funded research and the IP rights associated with that research. The Bayh-Dole Act entitles contractors to retain ownership of inventions they make using government funds (although the government does retain rights to use the invention for government purposes). This gives contractors considerable leeway to choose the fate of the IP, but they do have obligations, one of which being that the inventions should be "substantially" manufactured in the United States. But because battery components are almost exclusively manufactured overseas, any promising battery component technology company benefiting from Bayh-Dole provisions would, from the outset, have little choice but to base its manufacturing overseas. In some cases, foreign entities outright purchase the U.S. startup and own the associated IP. This highlights a key gap in the Bayh-Dole Act, namely, that it does not address the foreign purchase of U.S. companies developing IP funded by the U.S. Government, thereby allowing U.S. taxpayer-funded R&D to benefit the competitiveness, corporate profits, and labor force of foreign companies. While the foreign purchase of U.S. startups may have been a rare event when the act was first conceived in 1980, it is now commonplace. Given that the path from research to product development is complex and increasingly involves foreign investment and ownership transactions in this and many other industries, it seems that the time is right for a rethinking of the Bayh-Dole Act.

Conclusions

While there are some bright spots for U.S. corporations in the Li-ion battery supply chain, U.S. auto manufacturers are largely reliant on overseas companies to supply the raw materials, cell components, and cells needed for the EVs they produce. In many cases this may not be a disadvantage for the automakers; however, it may become a disadvantage if, for example, there are bottlenecks or interruptions in parts of the supply chain. Further, U.S. automakers that lack expertise in the energy storage technology will have less of an influence on the directions of Li-ion battery developments. Meanwhile, U.S. industry in general will miss out on a growing and profitable segment of the transportation sector. For these reasons, it would be desirable for U.S. industry to have more of a leadership role in the production of Li-ion batteries, especially next-generation batteries.

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1. Introduction

A. Growth of the Lithium-Ion Battery and EV Markets

At the start of the 20th century about one-third of all cars on the road were propelled by electric motors (Department of Energy 2014). These first electric vehicles (EVs) offered conveniences that internal-combustion engine vehicles of the time could not offer—they were easier to start than hand-cranked, gas-powered vehicles, and they could be charged anywhere electricity was available. Despite their limited range, they made a quiet and convenient transportation choice in populated areas where appropriate road infrastructure existed. Their popularity began to wane around 1910 as internal-combustion-engine technology advanced, a burgeoning petrochemical industry took hold, and improving road infrastructure encouraged longer trips, turning the tide in favor of gasoline-powered vehicles (Beard and Reddy 2019).

Interest in electric vehicles ramped up again after several decades. In the late 1990s, General Motors produced a limited number of electric vehicles called the EV 1 and offered them for lease to the public, although they ultimately discontinued the program. In spite of the EV 1's demise, the EV/internal-combustion engine competition had changed. There was a growing international concern about greenhouse gas emissions, an ongoing unease about oil supplies, and a recently established lithium-ion battery technology base that enabled a large step forward in the energy-carrying capacity of rechargeable batteries. By the late 2000s, EVs once again became commercially available. Although these EVs were initially viewed as an oddity embraced by environmentally conscious consumers,[1] a consensus eventually emerged among the major auto manufacturers that electrified propulsion was the future of mobility. As part of this transformation, lithium-ion battery manufacturers have taken on an outsized importance in the automotive sector, both as a key to influencing the future of the auto industry and as an economic engine in their own right. Huge investments have been made across the globe in battery production, manufacturing techniques, and research and development (R&D) by automakers, battery suppliers, governments, and even firms outside the battery sector that want a shot at this new market and have enough cash to spare.

[1] We note that performance-oriented drivers are enthusiastic about EVs as well: due to the physics of electric propulsion, EVs have remarkable acceleration performance compared with vehicles propelled by internal-combustion engines.

Vehicle battery energy storage is typically measured in watt-hours (Wh). In 2005, Li-ion batteries were produced at the rate of 8 GWh[2] per year worldwide, and these were used almost exclusively in portable electronic devices; by 2016, 89 GWh of lithium-ion batteries were produced—an elevenfold increase—and EV applications had outpaced portable electronics as the dominant application (Sanders 2017).

EVs must compete with the considerable driving distances that gas-powered vehicles can travel. One gallon of E10 gasoline holds about 33.7 kWh of energy, and a typical passenger car gas tank may have an 18-gallon capacity, totaling about 600 kWh of energy available in a full tank.[3] The internal-combustion engine vehicle suffers from serious inefficiencies, however, so a large fraction of this energy reserve is lost. The thermal efficiency of the internal-combustion engine itself might only be about 30%, and when other losses are accounted for, a 20% overall efficiency "to the wheels" is typical (Fuel Economy n.d.). Thus, the 600 kWh of fuel becomes a 120 kWh usable energy store. Despite the inefficiencies, this stored energy can still propel the vehicle in excess of 400 miles (depending on the type of driving).

An electric drive system by contrast is about 85% efficient and has the potential to regenerate energy while braking. These factors allow the EVs to beat gas-powered cars in efficiency by a large factor. For typical city/highway combined-driving cycles, and accounting for all losses to the wheels and energy recovery from regenerative brakes, the EV achieves roughly 80% overall efficiency—considerably more than the 20% realized in a gas-powered car (Fuel Economy n.d.). Nevertheless, an EV battery must still hold copious amounts of energy to travel a practical distance. A typical 2019 model year EV in the United States contains a 60 kWh battery. To put that in perspective, the average daily electricity usage of U.S. residential customers is 30 kWh (U.S. Energy Information Agency 2019); consequently, a topped-off late-model EV battery could keep the average residence running for 2 days.[4] On the road, assuming a typical value of 4 miles of range per kWh of energy stored (which encompasses the overall efficiency of the EV),[5] the 60 kWh battery allows for a maximum of about 240 miles between charges, which lags the 400-plus mile range of gas-powered vehicles.

EVs have other challenges, particularly in the cost of the battery, which is a large fraction of the vehicle's purchase price. In the 2017/2018 timeframe, the typical cost for a

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[2] For large storage capacities, kWh, MWh, and GWh are used, corresponding to a thousand, million, and billion watt-hours, respectively.

[3] 600 kWh of energy would keep a 100 W incandescent light bulb operating for 250 days.

[4] Charging EVs will have a large impact on the electrical grid. If each residential customer purchases one EV, this could increase U.S. electrical demand by 30%, assuming vehicle energy usage of 25 kWh/100 mi and a typical value of 40 mi/day of driving.

[5] Typical EV energy usage is about 25 kWh per 100 miles of driving, according to www.fueleconomy.gov, corresponding to 4 mi/kWh.

vehicle battery system was about $200/kWh, or about $12,000 for a 60 kWh EV battery (Watanabe 2017). Thus an EV battery alone costs about 1/3 of the entire cost of a $30,000 gas-powered family sedan.

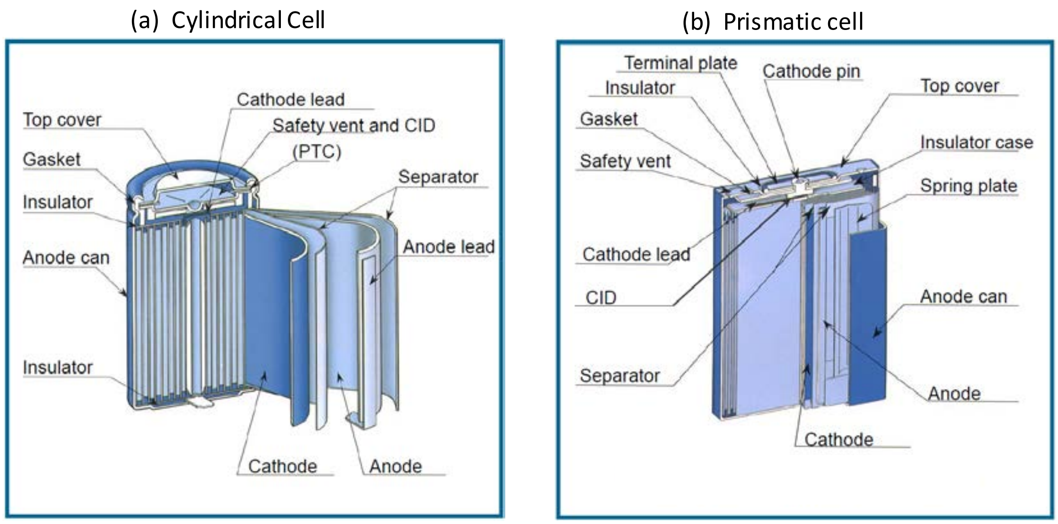
The Vehicle Technologies Office (VTO) of the U.S. Department of Energy (DOE) concluded that at a battery system cost of $100/kWh, an EV's per-mile operating cost will be comparable to that of an internal-combustion engine vehicle (Vehicle Technologies Office 2018). This $100/kWh target is generally considered to be the threshold beyond which EVs will become more cost effective than gas-powered vehicles. Many industry and government assessments have attempted to estimate when this threshold could be met. Some analysts estimate the threshold will be crossed in around 2026 (Watanabe 2017), while others predict that even in the most optimistic conditions, it won't occur until the early 2030s (Jaduan 2017). In 2018, Tesla has reported that it expected that its battery packs would reach the $100/kWh in 2020 (Musk 2018).

Despite their limited range and high purchase prices, EVs are rapidly gaining in popularity. The cumulative number of fully electric vehicles and plug-in hybrid-electric vehicles sold worldwide has risen from fewer than 500,000 units in 2013 to over 3 million in 2017, with over a million of these vehicles sold in 2017 alone (IEA 2018). Single-year sales are projected to rise to 10 million passenger vehicles in 2025, and 28 million in 2030 (McKerracher 2019). These EV sales projections directly translate into lithium-ion battery production projections that dwarf current production levels: by 2028, global Li-ion battery production is expected to reach 1200–1600 GWh, roughly 15 times the 2016 levels mentioned above (Tsiropoulos 2018).

B. Lithium-Ion Battery Overview

A battery cell is the smallest unit in a battery system that produces usable electrical power. A cell is made up of five key components: the cathode, anode, current collectors, electrolyte, and separator. The cathode and anode are the electrodes upon which the cell's electrochemistry occurs. The electrolyte is a medium that allows lithium ions to shuttle between the anode and cathode, and the separator is a barrier that prevents the anode from contacting the cathode while allowing ions to pass through. Last, electrons flow through the current collectors and to the outside circuit. No single component can produce power; rather, it is the cell that forms the basic electrochemical unit that converts stored chemical energy into usable electrical energy. Li-ion battery cell formats that are of most interest in EV applications are *cylindrical cells* and *prismatic cells*.[6] Cylindrical cells have the shape of a right circular cylinder; prismatic cells have a rectangular cuboid shape. Figure 1 is a schematic of cylindrical and prismatic cells.

[6] Pouch cells are also commonly used in electronics and other small-format, portable applications. These are similar to prismatic cells, but are contained in a soft-sided pouch as opposed to a rigid structure.



Source: Hall (n.d.).

Figure 1. Schematic of (a) Cylindrical Cell and (b) Prismatic Cell. From (Howell and Duong n.d.)

Within an EV, cells are typically grouped together into modules, and modules are grouped into packs. These packs would be analogous to a gas engine's gas tank. Battery packs will have battery-management systems built into them that control the charging and discharging of the cells, maintain the battery's temperature within acceptable bounds, and perform other functions. The functions that the battery-management system serves are critical to preserving the operating life and safety of the battery.

While many chemistries can be used in making a rechargeable battery, lithium-based batteries are compelling because lithium is very reactive, which allows it to store considerable energy when combined with other elements, and it is has a low mass (it is the third lightest element and the lightest metal). These properties allow it to store large amounts of energy in a lightweight system that can be used as a portable power source. The energy-per-weight metric is called *specific energy*, and it is typically measured in Wh/kg.[7]

Current commercial production of lithium-ion batteries uses a diversity of cathode chemistries. Choice of cathode plays a key role in determining the specific energy, cost, power, safety, and other performance metrics of the battery. The following are the most common cathode chemistries:

- Lithium cobalt oxide (LCO): $LiCoO_2$.
- Lithium manganese oxide (LMO): $LiMn_2O_4$.

[7] Whenever discussing specific energy of a battery, it should be made clear whether the specific energy is for the battery cell, battery pack, or the theoretical energy available from the basic electrodes (without other cell components or other packaging). In this report, we use the term *specific energy* for energy per unit mass (e.g., Wh/kg), and we use the term *energy density* for energy per unit volume (e.g., Wh/L).

- Lithium iron phosphate (LFP): $LiFePO_4$.
- Lithium nickel manganese cobalt oxide (NMC): $LiNi_xMn_yCo_zO_2$, (x + y + z = 1).
- Lithium nickel cobalt aluminum oxide (NCA): $LiNi_xCo_yAl_zO_2$, (x + y + z = 1).

Table 1 lists the basic properties of these cathode materials. Note that NMC and NCA have reduced cobalt content relative to the related LCO structure. Many EV battery makers are moving toward these reduced-cobalt-content cathodes because cobalt is not an abundant element in Earth's crust. In commercial cells, these cathodes are typically paired with a graphite anode. However, a significant push to update the anode composition and structure exists in the battery R&D community.

As can be seen in Table 1, the different battery types have distinct properties, and advances in battery chemistry, electrode materials, and electrolytes will yield batteries with improved properties for EVs, such as specific energy, battery life, safety, and power characteristics. The U.S. Government provides substantial financial support for R&D of each aspect of battery technology, including advanced manufacturing processes. In particular, the VTO within the DOE funded $101 million of battery R&D in fiscal year (FY) 2018 (Vehicle Technologies Office 2018). Other government agencies also participate in funding basic and applied research in battery R&D, including the Department of Defense (DoD), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and other offices within DOE. U.S. Government funding supports the phase of technology development with the highest uncertainty and risk, with the aim of facilitating transitions of technology first into industrial R&D and finally into the commercial marketplace. This R&D ecosystem is the first stage in the global pipeline for ever-improving battery performance.

C. The Lithium-Ion Battery Global Supply Chain and Goals of this Study

Batteries, and EV batteries in particular, are the final product of a long chain of steps shown schematically in Figure 2: mining, refining, manufacturing cell components, manufacturing battery cells, assembly into battery packs, integrating the battery packs into EVs, EV sales, and finally recycling or reuse of EV batteries. The first half of the supply chain is fairly generalizable as the battery cells produced in the fourth step can be used for a variety of applications, ranging from consumer electronics to electric vehicles. In many cases, distinct companies perform the work of each step. Therefore, the EV battery landscape is built on partnerships between the companies that mine, refine, and manufacture cell components, battery cells, battery packs, and EVs.

Table 1. Lithium-Ion Battery Common Cathode Chemistries and Their Properties

Cathode Material	Typical Specific Capacity (mAh/g)†	Voltage Against Carbon Anode (V)	Co-Based Specific Energy (Wh/g Co)*	Other Notes
$LiCoO_2$ (LCO)	145	3.8	0.9	First-generation cathode material, not typically used in EVs
$LiMn_2O_4$ (LMO)	130	3.7	NA	Good power performance, poor cycle life, low specific energy
$LiFePO_4$ (LFP)	165	3.3	NA	Good power performance and safety characteristics, low specific energy
$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC111)	160	3.7	3	High specific energy, good thermal stability compared with NCA. More reactive** than low-Ni materials.
$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622)				
$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811)	200	3.7	6	
	200	3.7	12	
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)	200	3.7	8	High specific energy, better capacity retention and power performance than NMC811. More reactive** than low-Ni materials.

† Note that the specific capacity listed here applies to just the cathode material and is given in mAh/g. The product of the specific capacity and voltage yields the energy per gram for that cathode material.

* Computed based on formula unit, voltage, and specific capacity listed in the table.

** In general, Ni-rich cathode materials exhibit greater reactivity to moisture and electrolytes than Ni-poor materials, which translates to increased complexity in manufacturing and/or final packaging (Schmuch et al. 2018).

Table References: Battery specific capacity and voltage sources for LCO, NCA, LFP: (Nitta et al. 2015). Specific capacity and voltage for NMC-111: (Schmuch et al. 2018). Specific capacity and voltage for LMO: (Liu, Li, and Li 2018). Specific capacity for NMC622 and NMC811 is based on the high end of what was observed experimentally by (Xia et al. 2018), also consistent with (Schmuch et al. 2018).

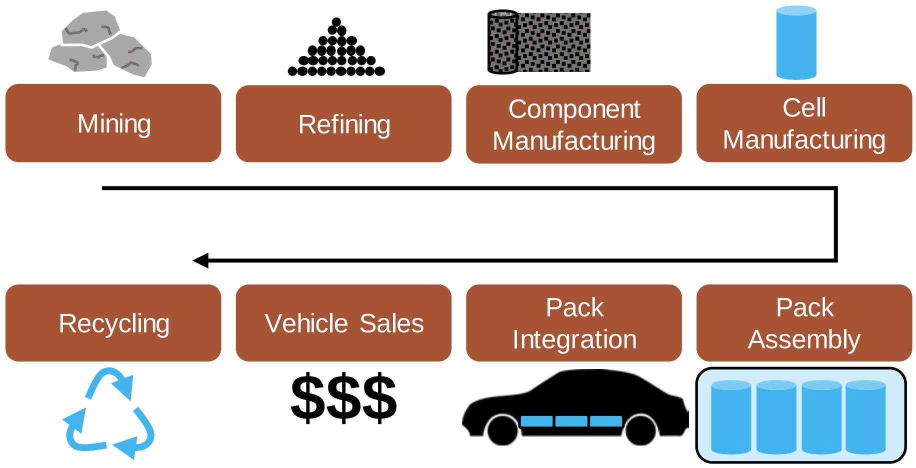


Figure 2. Schematic of the Battery Supply Chain

This report attempts to provide a snapshot of what the EV supply chain looks like today and identifies the strengths and weaknesses of U.S. corporations and research groups in this key piece of the global economy. Although it is challenging to paint a complete picture of this sector, in Chapter 2 we highlight the major entities in the current supply chain, provide examples of supply partnerships, and assess the current contribution of domestic companies in each step. In Chapter 3, we highlight current Li-ion battery R&D efforts being funded in the United States, and we consider how current legislation is affecting the channeling of these R&D investments into the U.S. industrial base. The health of battery R&D and the utilization of these advances by U.S. companies are critical considerations, since battery R&D has traditionally been a strength of the United States.

Last, we point out that EV battery technology is rapidly changing and deserves a periodic reassessment given this pace of change and its importance to the economy.

2. The Electric Vehicle Battery Supply Chain

As Figure 2 shows, the electric vehicle battery supply chain is composed of eight steps: mining, refining, manufacturing of cell components, manufacturing of battery cells, assembly into battery packs, integration of the battery packs into EVs, EV sales, and recycling or reuse of EV batteries. In this chapter, we outline the prominent technologies and the major players for each step of the supply chain, making an effort to catalogue the activities of U.S. companies within each step.[8] In addition, we highlight the role that different types of international partnerships play in the EV supply chain and consider the ramifications that such supply chains have for the United States.

A. Raw and Processed Materials

The first two steps in the battery supply chain are mining and refining. We define *mining* as the extraction of raw minerals from the ground and *refining* as the processing and purification that transforms the raw materials into high-purity chemicals. Key elements typically used in lithium-ion batteries are lithium, cobalt, carbon (graphite form), nickel, and manganese. There are concerns about the ability of the global production of battery-quality lithium, cobalt, and graphite to meet the growing demand for EVs. In response to concerns about insufficient raw materials supply, several EV companies have signed contracts directly with mining/refining companies. For example, Ganfeng Lithium Co., a Chinese lithium refining company, has contracts with Tesla and LG Chem, two major players in EV batteries, to supply substantial portions of their lithium needs (Stringer 2018). Some battery makers or carmakers are even purchasing stakes in lithium mines (Reuters 2019; Toyota Tsusho Corporation 2018). These contracts give the EV companies assured access to lithium or cobalt, but in practice these raw materials must pass through a number of other companies and processing steps before they make it into a car.

In addition to the global supply concerns, the United States included lithium, cobalt, and graphite in its most recently published list of critical minerals of importance for national and economic security, in part due to their use in lithium-ion batteries (Department of the Interior 2018).[9] Because of the extent to which this topic has been discussed elsewhere, this report will only briefly mention the major concerns associated with raw

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8 In this report, we do not address EV sales or reuse of EV batteries and only briefly address recycling of EV batteries.

9 This report does not intend to summarize the raw material reserves for batteries that may exist in a given country.

material mining and refining (Olivetti et al. 2017; Azevedo et al. 2018; Moores 2019). The main risks associated with lithium, cobalt, and graphite production are presented below. Although a diversified field of countries is currently mining lithium (dominated by Australia, Chile, and Argentina), the world's lithium-refining capacity is concentrated in China. Cobalt is mostly mined in the Democratic Republic of Congo, and there are serious concerns about human rights and child labor violations in those mining operations. Similar to lithium, most cobalt is refined in China. Natural graphite is abundant worldwide; however, processing of natural graphite into battery-grade spherical graphite is to date only performed at commercial scale in China. Synthetic graphite, produced from non-graphitic carbon sources such as petroleum coke, is also used in batteries as will be discussed in the anode section below. Synthetic graphite, however, is more expensive to produce than spherical graphite processed from natural graphite (Battery University n.d.a).

Although there are domestic reserves of lithium, cobalt, and graphite, there is little to no domestic production of these raw and refined battery materials. Several new ventures, if successful, could grow the U.S. domestic mining and refining capacity for lithium or graphite. Five companies have begun developing U.S. lithium mining projects, four of which are developing novel lithium-extraction methods (Scheyder 2019). Still, the United States lacks large-scale, domestic lithium-refining capacity, which would require additional investments and infrastructure. U.S.-based Albermarle Corp. is one of the largest producers of lithium worldwide, but it has largely invested in mining and refining projects in South America and Australia (Albermarle n.d.). Other efforts are focused on domestic cobalt mining and refining in Idaho (First Cobalt n.d.; Jervois n.d.) and graphite mining and processing in Alaska (Graphite One, Inc. n.d.) and Alabama (Westwater Resources n.d.). Some U.S.-based companies are also exploring recycling end-of-life EV batteries into refined battery materials, as an alternate feedstock to new mining of minerals (RecycLiCo, 2019; Kolodny 2018). Many of these mining, refining, and recycling projects are still in a pilot phase, and some are still seeking funding. Even of those that are operational, none have the capacity to meet a substantial portion of global demand or to compete with the currently very low prices for lithium and cobalt.

B. Lithium-Ion Battery Components

A lithium-ion battery is composed of two electrodes (the cathode and the anode), an electrolyte, a separator, and electrical current collectors that connect the electrochemical cell to an external circuit containing the load to be powered. The electrolyte and separator occupy the space between the two electrodes (see Figure 1). The design and choice of cathode, anode, separator, and electrolyte largely dictate the performance characteristics of the complete battery cell.

The characteristics of the cathode and anode pair are fundamental to determining the performance of a particular battery. For example, an increase in the amount of energy the electrode pair can store (the specific or volumetric capacity) or the discharge potential (voltage) of the pair will increase the amount of energy that can be stored by a battery, which translates to a longer driving range for the EV. In addition to the specific energy stored by a battery, properties like the specific power, safety, life span, and cost, among others, characterize a battery's performance. Typically, battery characteristics are influenced by other cell components in addition to the electrodes. For example, a battery's power capability (the rate at which energy can be released) is related to a number of factors, including the crystal structure and geometry of the electrodes, the conductivity of the electrolyte, the structure of the separator, and what kinds of coatings and electrolyte additives exist in the cell to facilitate easy charge transfer at the electrode-electrolyte interface. Another important cell property, cell safety, is related to the flammability of the electrolyte, the reactivity/stability of the electrodes, and the overall packaging scheme used to isolate one cell from another and prevent thermal runaway.

EV manufacturers must also consider the costs of different cell components, because the cost of the battery pack ultimately drives the cost of EVs. Battery makers are increasingly seeking cathode materials with lower cobalt content because of both price volatility and humanitarian and political concerns. Unsurprisingly, there is no single, one-size-fits-all cathode or anode material; rather, there are trade-offs between these desirable battery properties.

As stated previously, the goal of this report is not to exhaustively define the landscape of battery technologies and manufacturers, but rather to understand who the major players are in each step of the supply chain. Table 2 lists several major manufacturers of the common cathode and anode materials, and of battery cell makers that use those component chemistries. These lists of manufacturers are non-exhaustive, but capture many of the dominant producers. This table does not reflect anything about the supplier/consumer relationship between component manufacturers and cell makers. Several of the component manufacturers make several types of materials, for example, manufacturer Nichia makes LCO, LMO and NMC cathode materials.

1. Cathode

The cathode materials used in EV batteries today are far from standardized. The most common cathode materials for lithium-ion batteries are $LiMO_2$ materials, where the transition metal M can be nickel, cobalt, manganese, aluminum or combinations of those elements. Several performance metrics for these common battery cathode materials are listed in Table 1.

In 1980, the first lithium-transition metal oxide cathode material, $LiCoO_2$ (LCO), was demonstrated in a lithium-ion battery, a discovery which was awarded the 2019 Nobel Prize in Chemistry (Nobel Prize n.d.). While LCO is still commonly used in consumer electronics, it is typically not used in EVs due to low specific capacity. $LiMn_2O_4$ (LMO) was one of the first cathode materials used for EV batteries because it has good power performance and thermal stability. Despite LMO's lower specific capacity than many other cathode materials, it has remained in use today because it contains no Co; however, LMO is used almost exclusively in blends with higher specific capacity cathodes such as NMC ($LiNi_xMn_yCo_zO_2$) or NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) (Schmuch et al. 2018).

Table 2. Major Battery Component and Cell Manufacturers

Material	Cathode or Anode	Manufacturer	Cell makers*
LCO	Cathode	Umicore, L&F, Nichia, Beijing Easpring Material Tech	Not typically used for EVs
LMO	Cathode	L&F, Nichia, BASF Toda, Beijing Easpring, Tosoh	Li Energy Japan, Samsung SDI, AESC, LG Chem
LFP	Cathode	Johnson Matthey	A123, CATL, BYD
NMC	Cathode	Umicore, L&F, BASF Toda, Beijing Easpring, Reshine, Nichia	Toshiba, Panasonic/Sanyo, Li-Tec, SK Innovation, LG Chem, CATL
NCA	Cathode	Sumitomo, BASF Toda, Beijing Easpring, Ecopro	Panasonic
Natural Graphite	Anode	BTR New Energy Materials, JFE Chemical Corp., Mitsubishi Chemical, LuiMao Graphite, Shanshan Technology	Unknown
Synthetic Graphite	Anode	Hitachi Chemical, Kureha, JFE Chemical Corp., Nippon Carbon Co., Ltd., Mitsubishi Chemical, Showa Denko	Unknown
Si-doped C or SiO-doped C	Anode	Unknown	Panasonic

Caveats about this table: These lists of manufacturers are non-exhaustive, though the companies listed here are some of the major producers of each material. Also, this table does not reflect anything about the supplier/consumer relationship between component manufacturers and cell makers. Finally, we were unable to find disclosure from cell makers on the form of graphite they use in their batteries, thus the designation of unknown.

Information on battery cell makers and EV end users (except BYD e6) comes from (Schmuch et al. 2018). Use of LMO by BYD e6 from (Liu, Li, and Li 2018). Cells containing "LMO" cathodes typically actually use a combination of LMO and either or both NMC and NCA (Schmuch et al. 2018). Manufacturers of cathode and anode materials were identified from (Beard and Reddy 2019), and specific materials manufactured were confirmed through product listings available on company websites, news articles, and press releases. Umicore: (Umicore 2017), L&F: (Cision PR Web 2012), Nichia: (Nichia 2019), Beijing Easpring: (Argus 2018; Global Energy Metals Corp 2019), BASF Toda: (BASF 2015), Tosoh (maker of MnO_2 for LMO): (Tosoh 2019), Johnson Matthey: (Johnson Matthey 2019), Reshine: (BASF 2018), Sumitomo: (Reuters 2018), Ecopro: (Ecopro BM 2019), LuiMao, Shanshan, BTR, and BAIC: (Benchmark Mineral

Intelligence 2017), Mitsubishi Chemical: (Mitsubishi Chemical 2019), JFE Chemical Corp: (JFE Chemical Corporation 2019), Nippon Carbon Co., Ltd.: (Nippon Carbon Co., Ltd 2019), Showa Denko: (Showa Denko 2019).

NMC ($LiNi_xMn_yCo_zO_2$) is one of the most common cathode materials, though the ratio of Ni:Mn:Co has been gradually shifting from 1:1:1 to 5:3:2 to 6:2:2 to 8:1:1 in an effort to reduce the amount of Co required. As the Ni content in NMC increases, the specific capacity increases from 160 $mAhg^{-1}$ to 200 $mAhg^{-1}$, which further contributes to the adoption of NMC cathodes in many major EV models (Schmuch et al. 2018; Blomgren 2017; Anderman 2016). NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), another high-performance cathode, is used in all of Tesla's EVs. NCA has similar density to NMC811 but greater power and better capacity retention; NMC has superior thermal stability (Schmuch et al. 2018). The high Ni content in NMC811 and NCA make them both more reactive to moisture and electrolytes than lower Ni cathodes, which adds complexity to the component and cell manufacturing and packaging processes, as well as additional safety concerns (Schmuch et al. 2018).

$LiFePO_4$ (LFP) is a Co-free cathode material that has excellent safety and power performance, but a relatively low specific capacity. For electric buses or trucks that require a larger battery than a typical passenger car, undergo frequent stops and starts, and sometimes require very high power draws, the safety of LFP has made it the cathode of choice for many companies.

A recent analysis reported the percentage of market share in tons[10] for each cathode material used in lithium-ion batteries for all applications, including EVs as well as consumer electronics. The report found that in 2018 NMC made for 41% of the cathode market, followed by LFP at 34%, LCO at 11%, NCA at 9%, and LMO at 5% (Pillot 2019). According to the Benchmark Minerals Cathode Market Assessment, only 5% of battery manufacturing is currently targeting NMC811 (Benchmark Mineral Intelligence 2019a). Despite the diversity in cathode chemistry, over 60% of cathodes were manufactured in China, the remainder being largely produced in Japan and South Korea (Andrew Miller 2019; Inagaki 2018). The only domestic commercial manufacturer of cathodes we identified is BASF Toda, which operates two plants, one in Michigan and one in Ohio, to manufacture NMC and NCA (Toda America n.d.; BASF 2017). Although ownership of this company is Japanese and German, these American factories contribute local jobs and domestic cathode production know-how.

[10] EV batteries are orders of magnitude more massive than lithium-ion batteries for consumer electronics. When considering the meaning of these numbers for market share, they represent not the total number of batteries that use this cathode material, but instead the total mass of cathode material used in all the batteries with this type of cathode material.

2. Anode

Nearly all of today's commercial lithium-ion batteries use graphite as an anode material. Graphite is composed of layers of carbon atoms that lithium ions move in and out of during charging and discharging. There are several forms of graphite that can be used as anode materials: natural graphite, spherical graphite, and synthetic graphite. Natural graphite is the least expensive of these options, although it still undergoes some purification and processing post-mining (Schmuch et al. 2018). Natural graphite has been shown to yield worse performance (parasitic heat flow) than other graphites (Glazier 2017). One option to improve the performance of natural graphite is to transform it into spherical graphite, which has been shown to yield improved rate capacity (how well a material can charge or discharge at high rates) and coulombic efficiency (the amount of usable electricity gotten out of the battery for a given amount of input electricity) (Yoshio 2004). However, it requires about 2 tons of natural flake graphite to produce about 1 ton of spherical graphite, which has contributed to the exclusive production of commercial spherical graphite in China, where inexpensive natural flake graphite is available (Benchmark Minerals Intelligence 2016). Synthetic graphite is produced by heating a carbon precursor, such as coke, to extremely high temperatures (>2500 ℃), yielding extremely ordered and high-purity graphite. Synthetic graphite outperforms natural graphite as an anode material, but is significantly more expensive due to the energy-intensive processes (Schmuch et al. 2018). More recently, battery makers have begun to use anodes made from carbon mixed with silicon (often in the form of SiO_x), which increases the specific capacity and energy density compared with pure graphite (Wu et al. 2019; Schmuch et al. 2018; Blomgren 2017; Anderman 2016). Development of novel anode materials is an active area of research, and there are significant domestic R&D efforts in this area, as will be discussed in Chapter 3.

Cell makers rarely seem to reveal what types of graphite they use in their batteries, but reports suggest that the anode market is split at ~60% synthetic graphite and ~36% natural graphite (Mayyas 2018).[11] As of 2018, most commercial production of battery anode materials was concentrated in China; Shenzhen BTR New Energy Material alone accounted for 70% of global production (MassifCapital 2019). According to a Benchmark Mineral Intelligence (2016) report, in 2016, spherical graphite, which is produced exclusively in China, makes up 65% of the anode market. Most of the remaining 30% is concentrated in Japan and South Korea (MassifCaptial 2019; Roskill 2018). The United States has some domestic manufacturing capacity for synthetic graphite, and domestic and international companies are investing in new commercial production facilities to manufacture spherical graphite in the United States (Roskill 2019; Pyrotek n.d.; NovoCarbon n.d.; Syrah Resources, n.d.).

[11] The referenced report does not indicate what materials constitute the remaining 4% of LIB anodes.

3. Electrolytes and Separators

Electrolytes and separators are also key components of Li-ion batteries. Electrolytes are typically composed of Li-salts dissolved in organic solvents with various proprietary additives that enhance the performance of the battery (Schmuch et al. 2018). Major electrolyte manufacturers include Mitsubishi Chemical (Japan), Panax Etec (South Korea), Ube (Japan), Shanshan Tech (China), Capchem (China), Jinhui (China), and Zhangjiagang Guotai-Huang (China) (Pillot 2015). With such liquid electrolytes, separators must be used to prevent contact between the positive and negative electrodes of the battery. Lithium-ion battery separators today typically use microporous polymer membranes or nonwoven mats, sometimes coated with ceramic material (Schmuch et al. 2018). Major manufacturers of separators for Li-ion batteries include Asahi Kasei (Japan), Cangzhou Mingzhu Plastic (China), Celgard (United States), and Dreamweaver (United States), though other companies such as Du Pont (United States), LG Chem (South Korea), Targray (Canada), Entek (United States), and Lydall Performance Materials (United States) also sell separators (Technavio 2017; Lagadec, Zahn, and Wood 2018). While both separators and electrolytes are linked to the petrochemical industry through their use of organic materials (solvents, polymer precursors, etc.), electrolytes are also tied to the Li supply chain due to its use of specialty Li salts (Schmuch et al. 2018). U.S. companies have a major role in the supply of separators (e.g., Celgard), but a minimal role in supplying electrolytes (Sandor 2017). There are recent examples of electrolyte manufacturing business moving out of the United States. For example, in 2012, German chemical company BASF acquired U.S.-owned electrolyte producer Novolyte Technologies (Advanced Science News 2012). But in 2018 BASF Corporation sold its entire electrolyte manufacturing business to Capchem, which had plans to move production to China (Ouyang Kai 2018).

C. Battery Cells

Cylindrical cells are designated by a five-digit number describing their size, where the first two digits represent the battery's diameter in millimeters, and the last three digits represent the battery's height in tenths of millimeters. In the recent past, the most commonly used Li-ion cylindrical cell in EV applications (and also laptops) was the 18650, which contains roughly 10 Wh of energy, enough to illuminate a 10-watt light bulb for 1 hour.[12] There has been a recent push to use the 21700 cell in EVs, as manufacturers claim that the cell has a higher specific energy and lower cost than the 18650. Tesla, for example, recently moved from the 18650 format to the 21700.[13] Prismatic cells, on the other hand, are produced in whatever size and aspect ratio is appropriate for their application. Nissan selected prismatic cells for its Leaf EV for the first several model years of that vehicle.

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[12] At 18 mm in diameter and 65 mm in height, it is roughly twice the volume of a 14 mm diameter by 50 mm tall AA alkaline cell.

[13] Tesla refers to these as 2170 cells.

Large-scale production of battery cells for EV applications, as we know it today, was nonexistent just over a decade ago. The first commercially available Li-ion EV emerged in the late 2000s, when Tesla began to sell its Roadster and Nissan announced the Leaf EV. These two pioneering efforts took different approaches. Tesla sourced its 18650 Li-cells from outside manufacturers, as these cells were already widely produced for the laptop market (Berdichevsky et al. 2006). Nissan developed its own prismatic cell design at its R&D labs in Japan and produced them at its own factories in Japan, the United States, and the UK.

Bloomberg New Energy Finance provided a snapshot of the manufacturing capacity of the top Li-ion cell manufacturers in 2017 (Curry 2017), which is shown in Figure 3. Table 3 shows the headquarters and manufacturing locations for the top-12 manufacturers by total cell capacity. While this is a global industry, Asian manufacturers dominate the space. The headquarters of all of the top-12 manufacturers are in Asia, although the manufacturing locations are more spread out and include Asia, the United States, and, to a lesser extent, Europe. It is commonly thought that the battery manufacturing for Tesla is U.S.-owned, given Tesla's renowned battery "Gigafactory"[14] in Sparks, Nevada. But the Gigafactory is a joint effort with Panasonic, where Panasonic manufactures the cells and Tesla integrates them into battery packs and produces the battery-management systems for their vehicles. Consequently, Tesla's battery cells are a Panasonic product.

[14] The Gigafactory name was first used by Tesla to signal that its Sparks, Nevada, factory is producing over a GWh of batteries per year; however, the term "gigafactory" is now becoming part of the general lexicon of the battery sector.

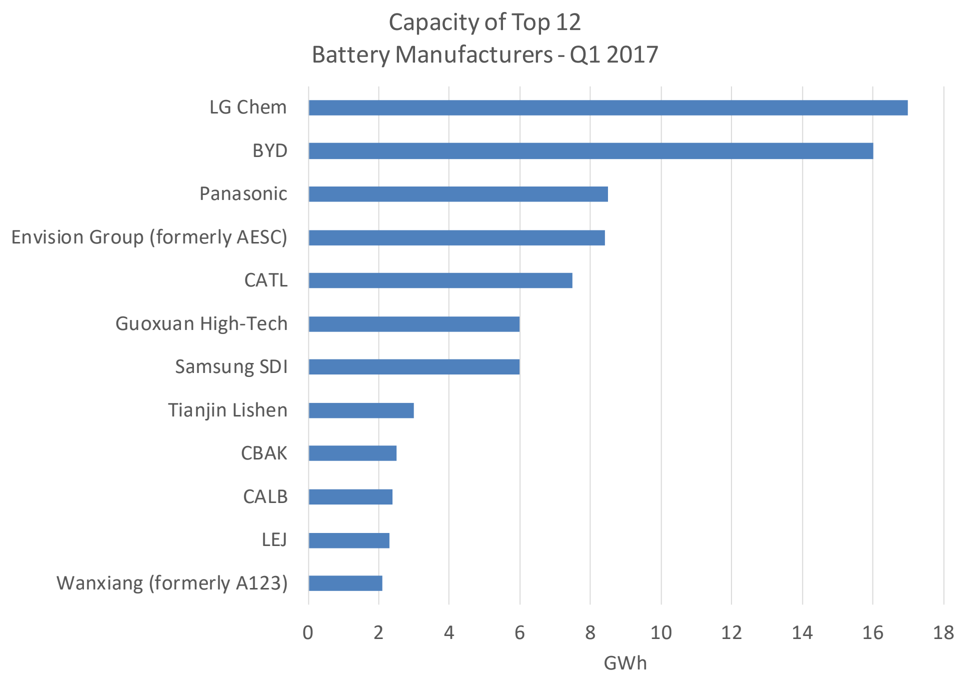


Figure 3. Capacity of the Top-12 Li-ion Battery Manufacturers as of 2017. An additional 22 GWh were produced by smaller manufacturers, for a total of just under 104 GWh. For more details, see Curry (2017).

Table 3. Headquarters and Manufacturing Locations of the Top 12 Li-ion Battery Manufacturers Identified in Figure 3

Company	**Headquarters Location**	**Manufacutring Locations (2019)**
LG Chem	South Korea	Souh Korea, Poland, US, China
BYD	China	China
Panasonic	Japan	US, Japan, China
Envision Group (formerly AESC)	China (formerly Japan)	US, Japan, UK
CATL	China	China
Guoxuan High-Tech	China	China
Samsung SDI	South Korea	South Korea, Hungary, China
Tianjin Lishen	China	China
CBAK	China	China
CALB	China	China
LEJ	Japan	Japan
Wanxiang (formerly A123)	China (formerly US)	China, US

Note: The manufacturing locations, which were gathered from information in the press and public statements by the battery companies, are current (2019) locations, and may be somewhat different than their 2017 status.

Lithium-ion battery production is forecast to grow rapidly for the next decade. Recent assessments of 2020 cell production levels estimated the overall output to rise to almost 350 GWh (Tsiropoulos 2018; Eckhouse 2018). This capacity would be a threefold increase over the 2017 output. Individual companies shown in Figure 3 have shared their plans for battery capacity expansion in the 2020 timeframe, which is summarized for the top-four battery makers in Figure 4 (Eckhouse 2018; Yamazaki and Panchadar 2019).[15] The average increase of the planned 2020 output over the 2017 levels for these four manufacturers is

[15] The Panasonic forecast applies to its U.S. manufacturing plant; its worldwide output may exceed this estimate.

about a factor of 5.2, well in excess of the forecast industry-wide 3× increase. In addition, there are new corporate efforts to enter the space. For example, SK Innovation, a leading petrochemical, refining, and chemical company from South Korea, has aggressive plans to become a major cell supplier (Dawson 2019). These may be indications that the worldwide capacity forecast of 350 GWh is an underestimate for 2020.

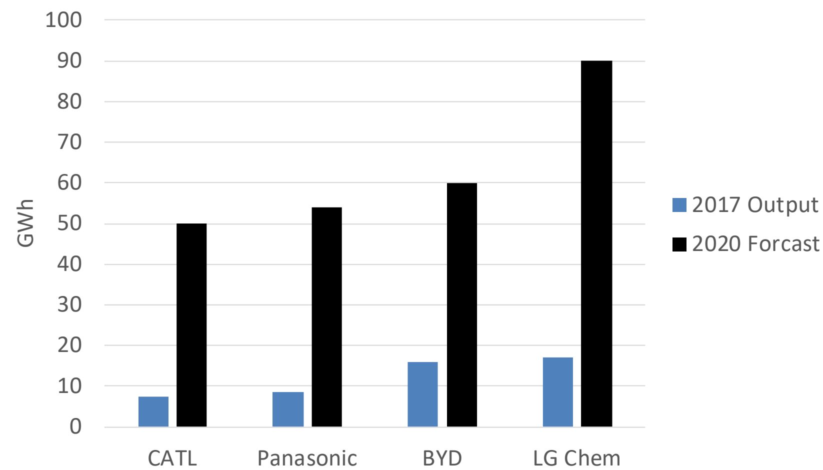


Figure 4. Forecast 2020 Battery Capacity Output by Some Major Manufacturers

Some recent activity in Europe suggests there will be significant sources of European-based cell manufacturing in the coming decade, both European and foreign owned (Reuters Factbox 2018). Despite this progress, the lack of cell manufacturing in Europe to date has alarmed some EU member governments, spurring them to bolster a viable battery manufacturing base. Germany reserved $1.2 billion for this task and has gotten buy-in from industry (Nienaber 2018). France followed suit and announced a $790 million investment of its own (Rose 2019). More recently, Germany and France announced that they are coordinating their efforts and expect a total of about $6 billion in investment, including contributions from industrial partners (Keating 2019). Overall, there seems to be a consensus in Europe that continued success in the automotive manufacturing sector will rely on success in the battery cell manufacturing sector.

There is less movement in the United States toward developing a viable cell-manufacturing base, from either the government or corporate sectors. In fact, some feel that it is not feasible for a U.S.-owned company to produce current state-of-the-art cells, but rather that the most expedient path for success in the future will be to capitalize on the next-generation battery cell (Schreffler 2018). Despite this, there are indications that U.S. companies will attempt to enter cell manufacturing. Tesla, for example, may be considering building its own cells to make it less dependent on Panasonic (Kolodny 2019). A consortium of companies recently announced a $130 million effort to create a GWh-scale plant in New York, backed by state and local tax incentives (New York State Governor's Office 2017). Overall, however, the United States has not coordinated its cell production on the scale that Europe has over the past year.

D. Battery Packs

The battery pack is a group of cells packaged into one unit, typically to achieve higher power and/or current loads. In most cases, batteries are first assembled into "modules" with a fixed number of cells, and then the modules are assembled into packs. Battery packs tend to be custom designed for each application, meaning different EV models likely have drastically different battery packs. For example, the Telsa Model 3's battery pack contains 7,104 cylindrical battery cells, while the Chevy Bolt's battery pack has 288 prismatic cells, and the Nissan Leaf's battery pack has 192 pouch cells (Morris 2019). The battery-management system is responsible for managing the safety and functionality of these hundreds or thousands of battery cells. The battery-management system is composed of electronics and software that monitor the health and safety of the battery pack and control charging and discharging, usually at a cell level (Battery University n.d.b). The manufacturing of the battery pack and its integration with a battery-management system is sometimes performed by the automaker and sometimes by the cell maker (Coffin and Horowitz 2018; Lebedeva et al. 2016).

Once battery cells have been assembled into battery packs, they typically weigh more than 1000 pounds, and there are numerous national and international regulations governing their safety requirements during transport (Huo 2017). Therefore, battery pack assembly tends to be co-located near vehicle assembly plants (Coffin 2018). For example, the early models of the Chevy Bolt, which is assembled in Michigan, used batteries produced by LG Chem that were shipped from its South Korea factories and then assembled into packs in a factory in Michigan. Beginning in 2018, LG Chem began producing batteries for the Chevy Bolt in Michigan as well, so that cell, pack, and vehicle assembly operations for the Chevy Bolt are all co-located (Evarts 2018). In this example, LG Chem, a South Korean-based company, invested in cell and pack manufacturing within the United States because of the proximity advantages of co-locating near market demand. For similar reasons, many battery manufacturers and automakers have invested in facilities in China, where the market demand is currently highest. The partnerships between cell manufacturers, pack manufacturers, and automakers vary widely, as will be discussed in the next section.

E. Partnership Models within EV Battery Supply Chains: Four Case Studies

The EV battery supply chains are far from uniform. Many of today's supply chains rely heavily on partnerships that are constantly evolving. Some automakers have supply chains that are more vertically integrated within a single company or country, while others are highly diversified and global. This section contains four brief case studies of the major EV battery cell makers, BYD, Tesla/Panasonic, LG Chem, and CATL, highlighting important aspects of their supply-chain partnerships.

1. BYD

The most vertically integrated supply chain we know of today is that of BYD, Build Your Dreams, a Chinese battery maker and automaker. BYD, the first Chinese company to make lithium-ion batteries, began in 1995 as a battery maker. BYD manufactured batteries at a lower cost than its Japanese competitors due to low-cost, high-quality labor available in China, which it favored over robotic automation (Quan 2018). Within 5 years, BYD became a worldwide leader in manufacturing of batteries for cellphones (Liu 2013).

In 2003, BYD Auto was formed when the company acquired an automaker and began to build its first electric vehicles using its own batteries. BYD is vertically integrated over most of the steps of conventional EV supply chain, making its own cell components, battery cells, battery packs, and vehicles. BYD states that this vertical integration saves customers 20%–30% by eliminating the communication and coordination that ordinarily occurs between supply partners (Quan et al. 2018). Further, BYD has partnered with a local company to build its own lithium mining and processing facilities (Tabeta and Takano 2018; China Daily 2016). BYD has also worked toward integrating a whole host of other elements related to the manufacture of EVs. BYD houses its own Central Research Institute, which conducts R&D on batteries, electronics, and automobiles. By one report, more than half the devices used in the manufacturing process were designed by BYD, rather than purchased or designed by other companies (Liu 2013). For example, the controls of an EV require an obscure electronic switch, called an insulated-gate bipolar transistor (IGBT). BYD built its own factory, so as demand for EVs soars, BYD has remained insulated from shortages in supply (Ball 2019a).

In 2017, BYD was number one in worldwide electric vehicle sales, ahead of BAIC, a Chinese state-owned EV maker; Tesla; and BMW (Fehrenbacher 2018). Today, BYD is becoming an increasingly international company, although 87% of its revenue still comes from sales within China (BYD 2018). BYD currently has partnerships with a number of global automakers, such as Daimler AG and Toyota, to build new EV brands for the Chinese market (Automotive News Europe 2018; Toyota 2019). BYD is also expanding into global sales, largely of electric bus fleets across the world, including in the Netherlands, Germany, and the United States (Campbell and Tian 2019). In addition, BYD is expanding its battery-cell-manufacturing capacity and is said to be in early talks regarding supplying batteries to other automakers like Audi (Bloomberg 2019b).

2. Tesla/Panasonic

The battery supply chain for Tesla, the most well-known U.S. EV automaker today, is based on a strong partnership with a single Japanese battery maker, Panasonic. For the Model X and S, batteries are shipped from Panasonic's Japanese production facilities, but for the Model 3, battery production lines were built within Tesla's Gigafactory in Nevada. Regardless of the battery's origin, all Tesla battery packs are assembled and integrated with the battery-management systems in the Nevada Gigafactory. The battery packs are then shipped to Freemont, CA, where the cars are assembled.

The Tesla/Panasonic partnership and co-location of production facilities offers many of the same benefits of a vertically integrated supply chain, even though Panasonic is technically the battery maker for Tesla EVs. Bringing battery manufacturing in house helped the two companies jointly design and engineer batteries for the Model 3 with a form factor and size selected for optimal performance (Tesla 2017). As a result of this collaborative design and manufacturing, Tesla/Panasonic have produced battery cells that cost at least 20% less than those of other major battery manufacturers, like LG Chem or CATL (Whiffin 2018). According to the analysis by UBS, in November of 2018, a Tesla battery cell cost \$111/kWh compared with \$148/kWh for an LG Chem battery cell (Whiffin 2018). As pointed out previously, Tesla estimated that its pack-level cost would drop below \$100/kWh in 2020 (Musk 2018). It is also important to note that Tesla/Panasonic is one of the only EV battery makers using an NCA cathode.

Tesla aims to fully vertically integrate its automotive assembly, and some have said that over 5,000 components (around 80%) are made in house (Morris 2017). In addition, Tesla recently established its own battery research facilities and has acquired two different energy storage technology startups, so in the far term, it seems that Tesla aims to take a more direct role in developing battery and battery component intellectual property (IP) and potentially produce its own batteries (Kolodny 2019).

As Tesla plans to expand sales and therefore production internationally, it seems to be departing from its sole-source battery contract with Panasonic. Tesla is currently building Gigafactory 3 in Shanghai, which is expected to begin production of Model 3 cars by the end of 2019. While the initial production may use Panasonic-produced batteries, some sources have reported that Tesla will turn to LG Chem or CATL to supply batteries for Gigafactory 3 (Lambert 2019).

3. LG Chem

LG Chem is the largest South Korean chemical company and a part of the parent LG Corporation (Nikkei Asian Review n.d.). LG Chem had the highest lithium ion battery production capacity, 51 GWh, of any battery manufacturer worldwide in 2018 (Benchmark Mineral Intelligence 2019b). LG Chem, however, is a diversified chemical company; only

22% of LG Chem's revenue coming from its EV battery production and sales in 2018 (Kane 2019b).

The quality of LG Chem batteries have made them a desirable choice for American, European, Korean, and Japanese automakers. Currently, LG Chem supplies batteries to Volkswagen, GM, Ford, Renault, Nissan, Hyundai, Kia, Geely, and others (Bohlsen 2019). To support all those markets, LG Chem currently operates five battery-manufacturing plants, one each in South Korea, the United States, and Poland, and two in China.

In particular, LG Chem has been a leader in high Ni, low Co battery chemistries, such as NMC 622 and NMC 811, and is reportedly moving toward using an NMCA chemistry (Lima 2018). Likely part of the reason LG Chem has been able to quickly adopt and manufacture new battery chemistries is that it is a vertically integrated chemical company that produces its own cell components, battery cells, and battery packs. In addition, LG Chem operates its own battery research center, which performed R&D on battery component materials such as the electrodes, separators and electrolytes, battery cells, and battery packs/battery-management systems for electric vehicles and other energy storage applications (LG Chem n.d.).

4. CATL

Contemporary Amperex Technology Co., Limited (CATL) is China's largest battery maker and in 2018 had the second largest battery-production capacity worldwide (Benchmark Mineral Intelligence 2019b). CATL was formed in 2011 as an electric vehicle battery spinoff from Amperex Technology Co. (ATL), which manufactured lithium-ion batteries for a number of other consumer electronics applications.

CATL's business model, like LG Chem's, relies on supplying batteries to a large number of domestic and international automakers. CATL currently supplies batteries to Volkswagen, Hyundai, Toyota, Honda, BMW, and others, including supplying more than 40% of all batteries that go into EVs in China. Though CATL's downstream supply chain is more globally diversified, its upstream supply chain is concentrated in China, such that 88% of all source materials and cell components come from other Chinese companies (Lin 2019). CATL has also begun buying stakes of lithium and cobalt mines to ensure its supply of these critical minerals (Fang 2018).

CATL currently manufactures battery cells, battery packs, and battery-management systems, as well as recycling technology. CATL largely produces two different battery chemistries, NMC for electric cars and LFP for electric buses. Before spinning off from ATL, the company made some investments in its own battery R&D, though much of the business strategy relied on the acquisition of technology licenses from the United States (Rathi 2019). Now focused on EV batteries, CATL invests considerably into its own R&D, spending 11% of its revenue on research in 2017 (Rathi 2019). This R&D has allowed

CATL to develop a cell-to-pack battery platform, which improves manufacturing efficiency and lowers costs by allowing cells to be integrated into battery packs directly without first clustering cells into battery modules (Xinhua 2019).

F. The Role of Government Policies in Driving Supply-Chain Partnerships

As described above, there are a diversity of partnership models between the battery cell makers and automakers. While we have only highlighted four such examples, all the current EV supply chains fall somewhere on this spectrum of fully vertically integrated to fully outsourced and diversified. For U.S. and European automakers, the decision to purchase batteries from a supplier like LG Chem or to develop their own battery technology (even if in partnership with a battery maker), like Tesla/Panasonic, is commercially driven, because there are no national domestic industrial policies. These automakers will source batteries based on the cost, efficiency, safety, and other needs for their electric vehicles.

For Chinese automakers, industrial policy has played a large role in shaping the Chinese EV supply-chain landscape. The Chinese government has invested nearly $60 billion over the past decade to aid in the creation of national supply and demand across the whole EV supply chain (Kennedy 2018). In addition to policies that encourage consumer and fleet adoption of electric vehicles and policies, one particular policy of interest has promoted the success of Chinese battery makers, like CATL. Since 2015, the Chinese government has provided substantial subsidies to automakers that use batteries made by domestic companies, which provided considerable advantage to companies like CATL. For the past several years, foreign battery makers—even those with factories in China—were not eligible for these subsidies. Analysts have suggested that this subsidy policy is responsible for propelling CATL to become a global leader in the production of EV batteries (Dickinson 2018). As of July 2019, China eliminated this “white list” policy and is phasing out many of its other EV subsidies, but at this point, Chinese battery makers like CATL have enough of a head start to compete internationally (Huang 2019).

G. Key Takeaways

- The market for EV batteries is growing rapidly, and many companies are taking strategic action to ensure their place in this industry.
- Mining and refining occurs globally but with significant concentration in China or Congo for certain materials. The United States has a presence in some aspects of mining but not in others.
- Battery component manufacturing, especially electrode manufacturing, is mostly done outside the United States.

- All the major cell manufacturer are currently Asian. Cell manufacturing and assembly often occurs near the auto assembly lines, however, so cell manufacturing is more global.
- EV battery companies run the gamut between fully vertical and fully diversified—each structure has its own advantages and disadvantages.
- Domestic industrial policies affect dominance in the market, as is evidenced by CATL’s growth.

3. The Domestic Battery Applied R&D Enterprise

The U.S. Government invests many millions of dollars each year in battery research and development. This investment includes direct research grants to academic research groups, national labs, and small businesses, as well as high-profile government-funded centers and initiatives that fund broad battery technology development. For example, the Joint Center for Energy Storage Research (JCESR) was founded in 2012 with a 5-year funding award of $24 million per year (Van Noorden 2014), focusing on developing novel battery technology to enable both high-energy-density vehicle batteries and inexpensive grid-scale energy storage. JCESR was recently renewed for an additional 5-year term at the same annual funding level (Harmon 2018). In 2019, the U.S. Department of Energy announced a new lithium-ion battery recycling R&D center, ReCell, which will receive $15 million annually for 3 years (Kunz 2019). Other important sources of government funding in electrochemical energy storage research are Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) programs. Four major government agencies (DoD, DOE, NSF, and NASA) have collectively invested increasing amounts of funding in Li-ion battery technology since FY2015.[16]

Research investment in batteries is not restricted to a single battery chemistry or battery component, but rather covers many technological aspects of batteries, from safety systems to novel battery materials. Basic and applied research funding spurs innovation in battery science and manufacturing that ultimately forms the foundation of startup companies that attempt to transfer technology to the commercial space. SBIR and STTR funding is meant to help support that difficult transition. In this section, we analyze this domestic battery research and innovation ecosystem in order to understand its longer-term outcomes, focusing on investment in the technology-transition phase. We first analyze SBIR and STTR investment in battery technology, identifying key technology areas and trends in investment since 2015. We then discuss the next stage of investment, when companies seek to raise funds from venture capital firms, focusing on a group of companies trying to commercialize novel anode materials for Li-ion batteries. Finally, we consider the federal legislative framework that governs transfer and manufacturing of technology based on IP developed with government support. The goal of the chapter is to illustrate the current

[16] About $10 million of SBIR/STTR funds was invested in Li-ion battery technology in FY2015, and that number has increased annually, reaching nearly $17 million in FY2018. Based on data collected from SBIR.gov.

domestic climate for battery technologies seeking commercial transition and help identify opportunities for the United States to better capitalize on early-stage technology-development investment.

A. SBIR and STTR Programs

The SBIR and STTR website (sbir.gov) provides data on funded projects, including funding agency, project abstract, award year, and funding amount. We obtained a list of SBIR and STTR projects returned for the keyword "lithium battery" from FY2015 to FY2018 and analyzed each project's abstract to categorize by battery chemistry of interest and specific battery technology focus.[17] Table 4 lists some key technologies that DoD, DOE, NSF, and NASA have funded through SBIR and STTR programs since 2015. It is clear from the table that SBIR and STTR investment has been diverse, covering novel materials, novel battery architectures, manufacturing methods, and even raw-material resource extraction. Different technologies promise different advantages in terms of battery technology; some have the potential to increase the energy or power density of the battery, and others could improve safety or lower cost. While all these goals are relevant to the electric vehicle market, it is rare to find a technology that can achieve all of them at once. Advancing batteries on each of these performance metrics will take a mix of technologies, including novel materials and manufacturing methods, engineered architectures, and improved battery monitoring and control.

Figure 5 aggregates some key results from the SBIR/STTR data. Figure 5(a) shows funding division by agency for programs focusing on Li-ion battery chemistry. The total SBIR/STTR funding for Li-ion battery programs has been increasing since 2015, the largest contribution coming from DoD, followed by DOE, NSF, and NASA. Figure 5(b) shows several of the key technology areas that have been funded by the SBIR/STTR program by year, including two major chemistries (Li-sulfur and solid-state Li-ion), two major battery components (the anode and the battery-management system), and mid-stage (manufacturing methods and scale-up) vs. end-stage (recycling and mining) manufacturing aspects. It is clear from the figure that a substantial increase in investment in battery manufacturing technology has occurred since 2015, including novel manufacturing methods and technology scale-up. Likewise, research into developing battery anodes

[17] Focus technology areas were broken down, as applicable, by component of the battery (e.g., cathode, anode, battery-management system, electrolyte) or by manufacturing aspect (e.g., manufacturing method, scale-up, recycling, mining). Note that the search term "lithium battery" returned some results where the technology focus was an alternative energy storage technology that was only being compared to Li-ion batteries. Such alternative technologies included non-Li-ion battery chemistries and the occasional fuel cell, radioactive isotope, or combustion engine project. For Figure 5(a), only those programs that were actually focused on Li-ion battery chemistry were included. For Figure 5(b), some projects looking at alternative battery chemistries were also included. About 10% of the funding returned for this search term went to programs focused on designing and building a battery for a specific application (e.g., missile propulsion) rather than advancing battery technology.

(including novel materials, novel manufacturing methods, and novel anode architectures) has also been increasing. Solid-state Li-ion batteries have seen fairly steady interest since 2015, while battery-management systems saw an increase in funding in 2016. The non-Li-ion chemistry that has received the most SBIR/STTR support has been Li-sulfur, including solid-state Li-sulfur batteries. Note that Figure 5(b) does not cover every technology area that has received significant SBIR/STTR investment, but instead focuses on a few that illustrate trends relevant to our discussion in this report.

Table 4. Advantages and Disadvantages of Key SBIR and STTR-Funded Technologies FY2015–FY2018

Technology	Potential Advantages	Challenges and Limitations
Novel anodes (e.g., Si-C composites, Li-metal)	Improved energy or power density	Manufacturing, cycle life, safety (for Li-metal)
Low-Co cathodes	Decreased dependence on critical materials, cost	Manufacturing, scale-up, safety, cycle life
Nanostructured electrodes	Power density, cycle life	Manufacturing, cost
Battery recycling	Decreased dependence on critical materials	Cost, business case
Novel separators	Safety	Cost
Novel liquid electrolytes	Safety, cycle life	Cost, manufacturing
Coatings and additives	Power density, cycle life	Cost
Li-Sulfur	Specific energy, cost, resource abundance, safety	Manufacturing, cycle life, power density, electrolytes
Li-Air	Energy density	Power density, cycle life, low-cost catalysts
Solid-state Li-ion	Safety, energy density, calendar life	Power density, cycle life, manufacturing
Battery-management systems and failure detection	Safety, cost savings, extending battery life	Flexibility for different battery types and configurations, reliability
Manufacturing methods	Cost, final battery performance or architecture	Requires substantial initial capital infusion
Source material extraction	Critical materials, cost	Competition

Sources for this table include sbir.gov and several review articles on battery technologies: (Nitta et al. 2015; Schmuch et al. 2018; Choi and Aurbach 2016).

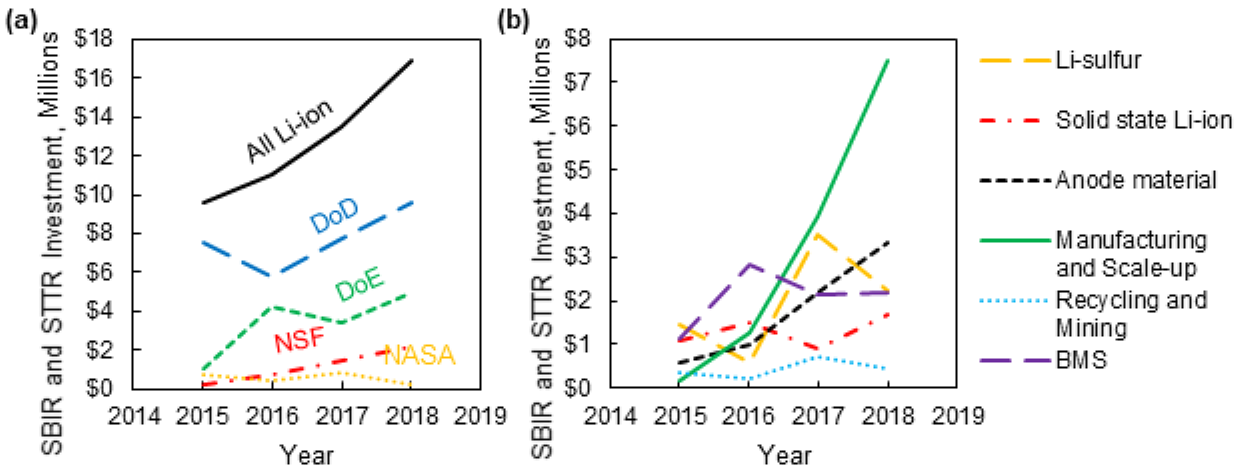


Figure 5. SBIR and STTR Funding for Projects with Keyword "Lithium Battery" from FY2015 to FY2018, DoD, DOE, NSF, and NASA. These charts show the SBIR and STTR funding dollars by (a) funding agency (Li-ion chemistry only) and (b) battery technology area, including non-Li-ion battery chemistry for FY2015–FY2018. A search of the sbir.gov award database for DoD, DOE, NSF, and NASA with keyword "lithium battery" returned 214 results totaling $80.1 million for this range of fiscal years. Abstracts for each project were reviewed and coded by keywords describing the research focus, including battery chemistry and technology component. In (a), only programs focused on Li-ion battery technology are included, including solid-state Li-ion battery programs. In (b), some programs did not focus on Li-ion batteries, instead focusing on other chemistries, such as Li-sulfur or Li-air.

B. Battery Startup Companies in the United States

Battery startup companies spin out from U.S. universities every year with the goal of commercializing novel technology. Many of these companies start out with some kind of government funding, but eventually need to raise capital from other sources. Venture capital can come from domestic or international sources, as well as from investment arms of large companies such as Toyota or LG Chem. For this report, we wanted to get a snapshot of where that investment comes from when startups attempt to scale up their technology. To develop that picture, we first identify some key technologies driving battery startup companies in the United States.

Nanalyze (2017) listed 13 battery startup companies that were gaining notoriety. Of those companies, 10 were originally located in the United States. Five of the ten (Enevate, Amprius, Solid Energy, ActaCell, and OneD) were working on innovative battery anodes, along with one of the British companies (Nexeon). An additional company (Prieto Battery) was working on "3D Li-ion battery technology" that would involve a complete restructuring of the battery architecture, including the electrodes. Table 5 lists the technological focus of the 10 U.S. companies.

Table 5. U.S.-Originated Companies Identified by Nanalyze (2017)

Company Name	State	Technology
Boston Power	MA	Long-lasting batteries
Enevate	CA	Si composite anode
Amprius	CA	Si nanowire & Si composite anodes
Solid Energy	MA	Li anode
ActaCell	TX	Nanocomposite anode and Mg-spinel cathode materials
Cadenza Innovation	MA	Battery packaging solution
Ionic Materials	MA	Polymer electrolyte
Prieto Battery	CO	3D Li-ion battery structure
QuantumScape	CA	Solid-state batteries for electric vehicles
OneD	CA	Si composite anode

JCESR produced three spinoff companies after its first 5 years of funding (Crabtree 2019): Blue Current (a company specializing in solid-state electrolytes), Sepion (a company specializing in size-selective polymer membranes for Li-sulfur batteries), and Form Energy (a company focused on air-breathing aqueous sulfur batteries for grid storage applications). Of the various novel battery chemistries currently being explored to replace Li-ion, Li-S has generated positive expectations for the near term (Peng et al. 2017; Choi and Aurbach 2016; Van Noorden 2014), despite challenges that remain with cycle life and volumetric energy density. This technology is at an earlier readiness level than Si-C composite anodes, but has the potential to build on advances made in developing Li-metal anodes or solid-state Li-ion battery technology.

Although this discussion has not come close to covering every battery startup company currently operating in the United States, it shows an emphasis on three emerging battery technologies: novel anode materials, solid-state Li-ion batteries, and Li-Sulfur batteries. Of these technologies, improved anode materials appears closest to market success, in part because this technology requires a minimal change in the larger battery manufacturing infrastructure (Choi and Aurbach 2016; Li et al. 2017).

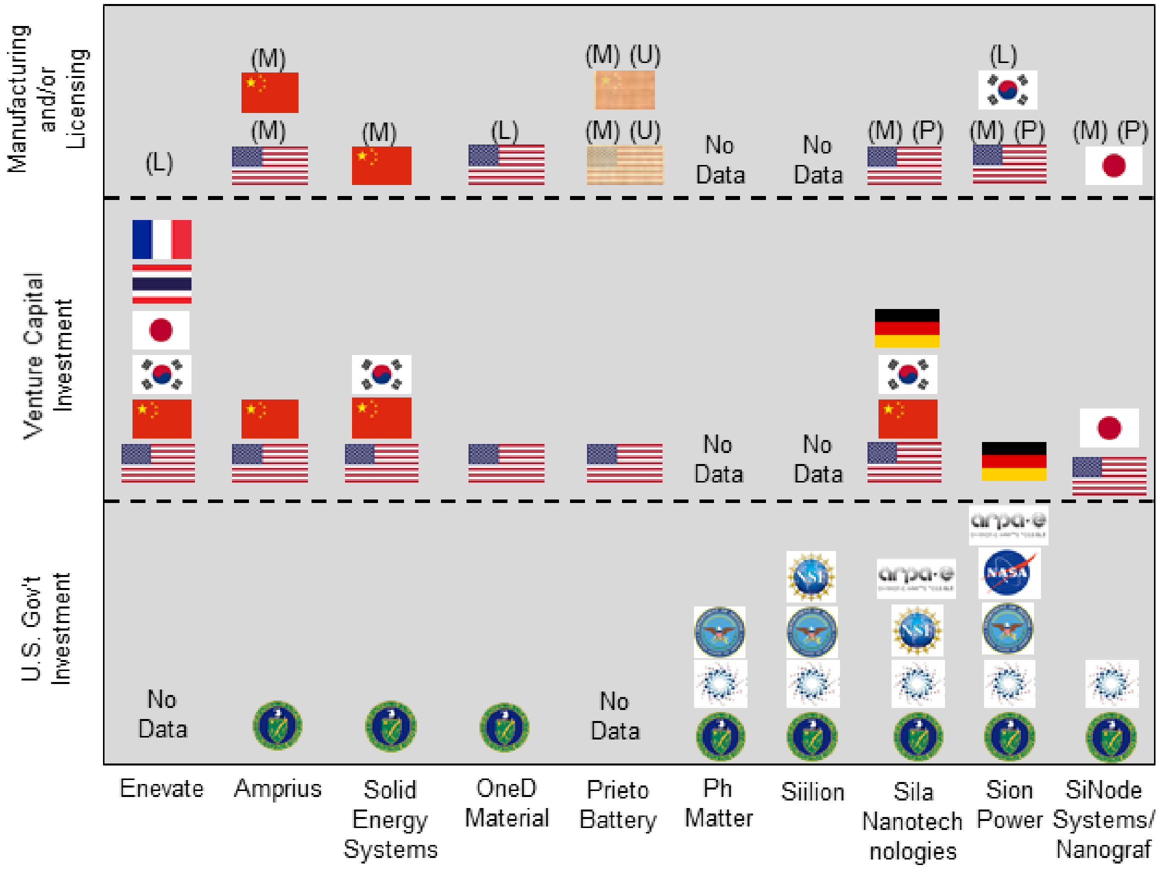
C. Anode Material Case Study

Novel anode materials are likely to be the next major advancement in Li-ion batteries, and U.S. research in this technology has produced several notable startup companies. For these reasons, we chose to focus on this technology area to understand the forces that drive startups to make investment and location decisions in the critical stages of technology transfer and manufacturing scale-up.

Along with the migration to Ni-rich cathode materials, novel anodes are likely one of the nearest term technological advances that will occur for Li-ion batteries (Choi and Aurbach 2016; Li et al. 2017; Schmuch et al. 2018). Today's commercial Li-ion batteries almost exclusively use graphite as the anode,[18] but a change of this material to a Si or a Si-carbon composite has the potential to increase battery capacity and increase the range of electric vehicles. Numerous Si-C composite anode structures have been explored in recent years, as researchers seek to improve the cycle life and power capabilities of these structures by overcoming challenges with volume change during cycling and poor Si conductivity (Dou et al. 2019). Some of the most promising Si-composite anode technologies have spun out into startup companies such as those listed in Nanalyze (2017). Li-metal anodes have also seen significant interest in recent years. Li-anodes, like Si-anodes, have the advantage of higher capacity than graphite anodes, but struggle to achieve long cycle lives. Whereas Si-anodes face mechanical degradation due to substantial volume change during cycling, Li-anodes struggle with dendrite formation during repeated cycling, a serious safety risk. In fact, one reason that solid-state Li-ion batteries are also under intense R&D is the possibility that a solid electrolyte could prevent Li-metal anodes from growing dendrites that short-circuit the battery, simultaneously improving battery safety and increasing energy density by enabling this higher capacity anode.

Based on Nanalyze (2017), the SBIR.gov data, and data available from ARPA-E, we identified 10 U.S.-based startup companies focused on developing novel anode technology. These companies are working on a range of approaches, including various Si-C-composite and nanostructured Si anodes (Enevate, Amprius, OneD Materials, PH Matter, Siilion, Sila Nanotechnologies, and SiNode Systems), Li anodes (Solid Energy, Sion Power), and novel battery architecture (Prieto Battery). Sion Power was initially founded to develop Li-S technology, but transitioned to focus on Li-metal batteries. To the extent possible for each of these 10 companies, we identified government funding sources (including SBIR and STTR grants, ARPA-E grants, grants from the DOE's Vehicle Technologies Office, and Clean Energy Business Plan Competition awards), venture capital sources, manufacturing facilities, and licensing deals. Figure 6 graphically summarizes this information.

[18] Some commercial Li-ion batteries do use small amounts of Si in the anode today, usually as SiO_x (Schmuch et al. 2018).



Sources: Enevate: (Bloomberg 2019a; Enevate 2019), Amprius: (Vehicle Technologies Office 2018, 2012; Amprius 2019; Ball 2019b), Solid Energy Systems: (U.S. Department of Energy 2012; Ball 2019b; Bullis 2013), OneD Material: (Vehicle Technologies Office 2015; Nanalyze 2017; Green Car Congress 2015; OneD Material LLC 2019), Prieto Battery: (Prieto Battery 2017, 2015; Prieto Batttery 2016), PH Matter, Siilion, Sila Nanotechnologies, Sion Power, and SiNode Systems: SBIR.gov, Sila Nanotechnologies: (Vehicle Technologies Office 2015; Wesoff 2019; ARPA-E 2010a), Sion Power: (ARPA-E 2010b; Vehicle Technologies Office 2012; Off Grid Energy Independence 2012; Sion Power Corporation 2018; Sion Power 2016), SiNode Systems/NanoGraf: (Vehicle Technologies Office 2018; Davis 2018; Wnuk 2019; Lott 2013).

Figure 6. Sources of U.S. Government Investment, Countries of Venture Capital Investment, and Countries of Manufacturing Facilities (M) and Licensing (L) for 10 U.S. Startups Focused on Novel Anode Technology. Manufacturing facilities that have been planned or announced are denoted (P), and manufacturing facilities for which there is uncertain information are denoted by (U). Specifically, Prieto battery has a manufacturing partnership with a U.S. company with manufacturing facilities in both the United States and China, but it is unclear if this partnership has progressed beyond R&D (Prieto Battery 2017). Enevate has a stated strategy of licensing its technology, but no information was found on specific licensees (Bloomberg 2019). This chart is built on positive data only; it is possible that some funding sources, investors, facilities, and licensing deals were missed. Note that PH Matter also received SBIR funding from NSF and NASA at various points, but not for battery technology.

It was not possible to collect exhaustive lists of government funding sources, investor locations, manufacturing locations, or license agreements for every company. The data shown in the figure are based on news articles, company websites, and U.S. Government data-reporting resources (sbir.gov, arpa-e.energy.gov, and the DOE's Vehicle Technologies Office Annual Progress Reports) for which positive identification of these groups was possible. Where no group was identified, "No data" is listed.

Several observations are apparent from the figure. At least 8 of the 10 companies received initial investment from 1 or more U.S. Government sources, funding levels ranging from small prizes from the Clean Energy Business Plan Competition ($100,000 each for SolidEnergy and SiNode Systems/Nanograf) to multi-million-dollar grants from ARPA-E (e.g., $3.2 million for Sila Nanotechnologies, $4.3 million for Sion Power). Note that in addition to the Clean Energy Business Plan prize, SiNode Systems also received $1.15 million funding from SBIR grants in 2013–2014 and $800,000 from the DOE Vehicle Technologies Office in a cost-shared award with the US Advanced Battery Consortium from 2016 to 2018.

Foreign investors were identified for six of the eight companies for which any venture capital investment information could be found. The most common foreign investment partner was China, followed by South Korea, and then Japan and Germany. It was not possible to identify the scale of investment in most cases, but there were several examples of foreign companies dominating investment news. For example, the most recent investment round conducted by Amprius raised $30 million, entirely from Chinese investors (Ball 2019b). Likewise, SiNode recently rebranded as NanoGraf corporation and now plans to set up "production facilities in Japan" with a $4.5 million investment from JNC (Davis 2018). Finally, BASF, a German company, invested $50 million in Sion Power in 2012 (Off Grid Energy Independence 2012), gaining a substantial equity stake in that company early in the technology-development process.

Sila Nanotechnologies and Enevate present particularly instructive examples of foreign and domestic investment patterns. Daimler AG (a German company) recently led a $170 million investment round in Sila Nanotechnologies (Wesoff 2019). The exact quantity of Daimler's contribution to that total is unknown; the same article listed nine other investors, including China's CATL, South Korea's Samsung, and Germany's Siemens, as well as several American venture capital firms. Similarly, Enevate lists nine investors on its website, including the investment arms of South Korea's Samsung and LG Chem, France's Renault Nissan Mitsubishi (RNM), and Japan's Sumitomo Corporation. Enevate also recently announced investment from Bangchak, a Thai energy company (Bloomberg 2019a). Like Sila Nanotechnologies, U.S. investment in Enevate consists of venture capital firms. These examples highlight the differences in the kinds of investment that battery startup companies can receive from foreign and domestic sources. Whereas domestic investors are often venture capital firms such as can be found on Sand Hill Road, foreign companies often invest with technological partnership potential, representing battery materials suppliers (e.g., BASF, Sumitomo Corporation), battery cell manufacturers (e.g., CATL, Samsung, LG Chem), auto-parts manufacturers (JNC), or automakers (Daimler, RNM). In addition, investment from foreign venture capital firms has been accepted by many of the 10 companies in Figure 6. Domestic investors with any potential for technology partnership mainly fall into the battery end-user category. For example, Prieto Battery has received funding from Intel and Stanley Black & Decker,[19] and the U.S. Advanced Battery Consortium (USABC, composed of automakers Fiat-Chrysler, Ford, and GM) has participated in cost-sharing contracts to fund Amprius, SiNode Systems, and (announced July 2019) NanoGraf (Vehicle Technologies Office 2018; USCAR 2019; Prieto Battery 2015; Prieto Batttery 2016). The United States has very few domestically owned and operated manufacturers of battery materials or battery cells, Kokam and Eaglepicher being rare exceptions.[20] Both these companies produce batteries on a small scale and cater to specialized end users, such as the U.S. military, rather than focusing on the EV or consumer electronics markets.[21] Strategic investment from potential technology partners influences where companies build manufacturing facilities and find customers for their products. This analysis suggests that for battery technologies, this type of investment is sorely limited in the United States.

To emphasize this point, consider the manufacturing and licensing information available in Figure 6. Manufacturing information was less available than investment and government funding information. At least 1 existing or planned manufacturing facility[22] was identified for 5 of the 10 companies. U.S. manufacturing locations were identified for four[23] of those five companies, while foreign manufacturing facilities were identified for three of those five. One company (Amprius) has manufacturing in both the United States and China, with the larger scale facility located in China (Ball 2019b). Note that all companies with manufacturing facilities currently, or planned to be, located abroad also

[19] In 2017, Prieto battery signed a memo of understanding to work on electroplating manufacturing with Moses Lake Industries, an American company with manufacturing facilities in U.S. and China (Prieto Battery 2017).

[20] Kokam was acquired by U.S. company SolarEdge in 2018 (SolarEdge 2018), but Kokam itself remains headquartered in South Korea. Kokam operates a 700 MWh cell production and assembly plant in Joplin, MO (Kokam 2019b). Therefore, Kokam is technically U.S.-owned and does operate manufacturing in the U.S., though it continues to have significant operations and assets overseas.

[21] Kokam has some stake in the EV market, however, and markets its technology on the company website for electric vehicles including trams, electric buses, and racecars (Kokam 2019a). As of 2010, Kokam had licensed Li-ion battery manufacturing technology to the Canadian auto-parts manufacturer Magna (Kokam 2019b). At that time, Magna was investing hundreds of millions of dollars in battery production (Abuelsamid 2010). As of July 2019, Magna had been selected to provide Chinese automaker BAIC with 180,000 electric vehicles annually, starting in 2020 (Kane 2019a).

[22] Figure 6 does not include R&D headquarters facilities among manufacturing locations. The ten companies in the figure are still U.S.-based, so they all maintain some form of headquarters facility, often with R&D capabilities, in the United States.

[23] Including OneD Material, which licensed its technology to Eaglepicher to be manufactured at an Eaglepicher facility in Missouri (Green Car Congress 2015).

received venture capital funding from a company in the corresponding country *and* government funding from the United States, though the magnitude of government funding varied substantially. Based on the lack of readily available information on investment in Prieto Battery, it seems likely that this company is at too early a technology-readiness stage to build large-scale manufacturing facilities beyond its headquarters. But Prieto Battery's recent partnership with Moses Lake Industries (a U.S. company with facilities in the United States and China) suggests that such scale-up may not be far away (Prieto Battery 2017). Sion Power is also early in its manufacturing effort, having broken ground on a new battery testing facility in Arizona in late 2018 (Sion Power Corporation 2018). SiNode Systems will be building facilities in Japan pursuant to its recent influx of capital from JNC (Davis 2018). Some startup companies are choosing to license their technology to more experienced manufacturers instead of building their own facilities. For example, OneD Material licensed its technology to the American company EaglePicher in 2015 with a plan to produce its SiNANOde material at EaglePicher's facility in Joplin, Missouri (Green Car Congress 2015). Similarly, Sion Power granted LG Chem a license to its technology in 2016 (Sion Power 2016).

Of the numerous battery technologies that have been the subject of basic and applied research in the United States in the past decade, novel anode technology is poised to be the next widespread change in the Li-ion battery. Today, the vast majority of Li-ion batteries use graphitic anodes, and the specific form of natural graphite used (spherical graphite) is refined exclusively in China.[24] However, anodes incorporating Si are seeing substantial success in the startup sector, and they have attracted investment from government, venture capital, and industry sources. Li-metal anodes are also under intense development, with applications envisioned in Li-S and solid-state Li-ion batteries. This change in the key material used for anodes should forecast a shift in Li-ion battery supply chains to a decreased need for graphite and an increased need for Si and/or Li. Not only a change in the raw material supply but also a change in the manufacturing techniques should be anticipated. Si-C composite anodes frequently require nanostructuring of some form, and Li-metal anodes are only viable if additives, coatings, and (most likely) solid electrolytes are available to manage the dendrite-formation problem, which suggests the need for new manufacturing technologies as well (Dou et al. 2019; Choi and Aurbach 2016; Li et al. 2017; Schmuch et al. 2018).

The anode technology industry is in now a place similar to where LFP cathode technology was before A123 went bankrupt and was acquired by Chinese company Wanxiang (Hals and Klayman 2013). If the United States wants to build a stake for itself in the battery cell or component manufacturing industry, anode technology presents a perfect opportunity. To capitalize on the substantial investment of the U.S. Government,

[24] Synthetic graphite is used in some batteries instead.

secure U.S. relevance in the Li-ion cell manufacturing industry, and diversify its supply chain for Li-ion battery anode materials, the United States should attempt to capture this emerging sector of the battery cell manufacturing industry and domestically develop this critical technology. Investments such as those undertaken by the USABC are perhaps a good model for encouraging that to happen, but these rely on cost-sharing with the U.S. Government.

Although not the focus of the anode material case study, solid-state batteries present a second area in which the United States has a real potential to develop a foothold in the battery industry. As described in Section 3.B, solid-state batteries are a battery technology area that has been generating substantial interest and investment. Solid-state batteries are of interest not only for electric vehicles, but also for small-scale devices such as wearable sensors (e.g., for soldier power). Similar to anode technology, solid-state batteries are an area where the United States has an opportunity to break into the battery component and cell manufacturing space.

D. The Role of Federal Legislation

Since many key battery innovations in the United States are created by universities and small businesses using U.S. Government R&D funds, it is worth briefly reviewing the legislation that governs federally funded research and the IP rights associated with that research and assessing the effectiveness of these policies in the context of battery research.

Before 1980, the ownership of inventions made with government funding was assigned to the Federal Government. By the late 1970s there was a consensus that this arrangement was a drag on the commercialization process of IP funded with government R&D grants, thereby limiting the public availability and associated economic benefits of the IP. In a move to spur innovation and commercialization of inventions, Senators Birch Bayh of Indiana and Robert Dole of Kansas cosponsored the Patent and Trademark Law Amendments Act, commonly called the Bayh-Dole Act, which Congress passed in 1980 (Bayh Dole Act 1980).

The Bayh-Dole Act entitles small businesses, universities, and nonprofits (typically called contractors) to retain ownership of inventions they make using government funds, although the government does retain rights to use the invention for government purposes. The shift from government ownership to contractor ownership for commercial purposes gives contractors considerable leeway to choose the fate of the IP.

If the contractor chooses to retain rights to its invention, it does have obligations. Contractors must disclose to the government any inventions they make using government funds, and they agree to file a patent application and state in the patent that the invention arose from government-sponsored work and that the government retains rights to the invention. When contractors grant exclusive licenses to use or sell the invention in the

United States, the manufacture of the inventions should be "substantially" in the United States, although in individual cases this requirement may be waived. The contractor also has reporting requirements to the government. If the contractor's obligations are not met, the government retains "march-in rights," where the exclusivity of the patent rights can be revoked, and other licenses to appropriate applicants may be granted by the government.[25]

The Bayh-Dole Act gives inventors a level of ownership over the IP developed using outside money that is not typically given in analogous circumstances. For example, corporate R&D labs that fund research normally require inventors to assign their patents back to the corporation. In the case of venture capital investments, the investors purchase a stake in the company's ownership, which is typically determined by the relative value of their investment versus the company's pre-investment valuation. On the other hand, under the auspices of the Bayh-Dole Act, contractors that retain rights to their invention do not have to give a financial stake back to the government, even though the government funds are typically the earliest and riskiest investments made in the invention-to-commercialization process.

The Bayh-Dole Act reconciles the magnanimity of the U.S. taxpayer by stating a preference for U.S. industry to manufacture inventions using U.S. labor. Specifically, it is stated that entities holding an exclusive right to sell the invention in the United States should "substantially" manufacture the invention in the United States. This preference for U.S. manufacture would apply, for example, to an invention created by a university that was licensed exclusively to a business for sale in the United States. If the contractor wishes to grant an exclusive license to an entity that would not manufacture the product in the United States, the contractor may apply for a waiver if the item's U.S. manufacture is not commercially feasible or if reasonable but unsuccessful attempts were made to find a manufacturer in the United States.[26]

As described previously, battery components are almost exclusively manufactured overseas, so any promising battery component technology company benefiting from Bayh-Dole provisions would, from the outset, have little choice but to base its manufacturing overseas. If advances were made in cell integration and manufacturing, there are major cell manufacturers located in the United States, but the parent companies at these facilities would be foreign.

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[25] As of 2016, Bayh-Dole march-in rights had never been exercised by the government. Apparently, only NIH has received petitions for the government to consider implementing march-in rights, but each case was denied (Thomas 2016).

[26] Note that if a contractor licenses the invention nonexclusively, the contractor would apparently be relieved of the requirement that the invention should be manufactured in the United States. We assume this is because a U.S. manufacturer could step in at any time, license the invention, and sell it in the United States. It does not, however, provide any level of assurance that this will happen, and we view this as a gap in the logic for the preference for U.S. industry.

There is a more important issue at play here that is not addressed in the Bayh-Dole regulations, namely the foreign purchase of startups benefitting from Bayh-Dole provisions. The case study highlighted in Section 3.C has shown that numerous battery startups have thrived in the United States in this critical emerging-technology area, often with substantial early investment from U.S. Government sources. Eventually, these startups seek venture capital investment. Although funding is available, and often secured from, foreign and domestic venture capital firms, investment partners that are battery component or cell manufacturing companies (as opposed to investors that are purely financial institutions) are almost exclusively foreign. When investment partners are foreign manufacturers, it logically follows that manufacturing and the associated technology know-how will ultimately migrate overseas, moving to places where investors can more easily provide capital.

In some cases foreign entities are not simply investment partners; rather, they outright purchase the U.S. startup and own the associated IP. This highlights a key gap in the Bayh-Dole Act, namely that it does not address the foreign purchase of U.S. companies developing IP funded by the U.S. Government, thereby allowing U.S. taxpayer-funded R&D to benefit the competitiveness and labor force of foreign companies. Although the foreign purchase of U.S. startups may have been a rare event when the act was first conceived in 1980, it is now commonplace.

In this scenario, although the foreign purchase of a U.S. company would benefit the foreign buyer, it seems logical that Bayh-Dole obligations of the U.S. company would nevertheless pass through to the foreign buyer. But ensuring compliance would be complicated because the U.S. Government would now be required to monitor a foreign company to verify that the Bayh-Dole obligations are met. As has been pointed out (GAO 2015), ensuring that the United States sees the appropriate return on investment for its R&D dollars requires accurate record keeping and company tracking, which is a challenge even when dealing with U.S. companies. In any case, the government has avoided exercising its march-in rights, even when requested to consider the action. This light-touch approach effectively cedes the benefits of U.S. investments to foreign companies when they purchase U.S. Government–funded startups.

Given that the path from research to product development is complex and increasingly involves foreign investment and ownership transactions, it seems that the time is right for a rethinking of the Bayh-Dole Act. While we have focused on EV battery technology in this report, the same holds true in other fast-paced, lucrative technology areas. Attempting to close gaps within the current Bayh-Dole framework may not be enough. Indeed, a rethinking and rewriting of the act—with special attention to giving the taxpayers' return on investment—should be considered.

E. Key Takeaways

Investment by U.S. Government in battery technology has produced many viable startup companies with valuable IP in areas such as anode manufacturing and solid-state batteries. However, because of the lack of domestic cell and component manufacturers, overseas investment in these home-grown technologies is almost inevitable. Although initial startup funds may be raised from domestic venture capital firms, such groups rarely have the expertise and resources to assist startups in developing manufacturing capabilities at scale. There are very few experienced battery cell or component manufacturers in the United States, and Federal regulations do not effectively encourage companies to set up domestic manufacturing facilities or preserve domestic control of IP. When novel battery technology achieves the readiness level at which scale-up is logical and necessary, increased foreign investment occurs, and IP can migrate overseas along with the actual manufacturing efforts.

Li-ion battery manufacturing is a global industry, and we do not believe it is wise or practical to try to develop a fully domestic electric vehicle battery supply chain. Rather, the United States should try to carve out footholds in emerging technology areas for which manufacturing methods are not yet established and for which the United States has an IP advantage due to the productive domestic innovation ecosystem. Novel anode technologies and solid-state batteries are two areas that meet that description, and in which the United States may be able to build a niche for itself in the rapidly growing Li-ion battery industry.

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Abbreviations

ATL	Amperex Technology Co.
CATL	Contemporary Amperex Technology Co., Limited
DoD	Department of Defense
DOE	Department of Energy
DRC	Democratic Republic of Congo
EV	electric vehicle
FY	fiscal year
IGBT	insulated-gate bipolar transistor
IP	intellectual property
JCESR	Joint Center for Energy Storage Research
LCO	lithium cobalt oxide
LEP	lithium iron phosphate
LMO	lithium manganese oxide
NASA	National Aeronautics and Space Administration
NCA	lithium nickel cobalt aluminum oxide
NMC	lithium nickel manganese cobalt oxide
NSF	National Science Foundation
R&D	research and development
RNM	Renault Nissan Mitsubishi
SBIR	Small Business Innovative Research
STTR	Small Business Technology Transfer
VTO	Vehicle Technologies Office

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14. ABSTRACT

In the next decade, demand for high-energy-density batteries is expected to boom, driven by the rapidly expanding market for electric vehicles. This report explores the current state of the electric vehicle battery supply chain and domestic research enterprise to identify weaknesses in the U.S. infrastructure for producing this critical technology. This analysis draws upon a collection of openly available sources to analyze the interconnected global supply chains for electric vehicle batteries, projected future battery manufacturing scale, and the domestic battery innovation ecosystem. We highlight the opportunity for the United States to build critical expertise in emerging battery manufacturing technologies that could enable us to cement a foothold in an industry that we have otherwise failed to penetrate.

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