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Lithium-Ion Battery Materials for Electric Vehicles and their Global Value Chains

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Abstract

Lithium, cobalt, nickel, and graphite are integral materials in the composition of lithium-ion batteries (LIBs) for electric vehicles. This paper is one of a five-part series of working papers that maps out the global value chains for these four key materials. The analysis concludes that the unrefined product value chain (mining/extraction) is geographically diverse amongst the four key materials, while the refining value chain that precedes the final product manufacturing (LIBs) is clustered across Asia, especially in China.

U.S. International Trade Commission

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Introduction

Lithium-ion batteries (LIBs) are a type of rechargeable battery and have a relatively short history.[1] The technology was developed by a U.S. company, Exxon, in the 1970s and was introduced commercially in 1991 by a Japanese company, Sony (Blomgren 2016). Due to their effectiveness and efficiency in storing and transmitting electricity, as well as consistent technological advancement, LIBs are used in many modern applications, including smartphones, laptops, and electric vehicles (EVs).

LIBs have significant potential environmental benefits. To reduce transportation-related carbon dioxide (CO_2) emissions and their contribution to climate change, for instance, some analysts recommend widespread adoption of LIB powered EVs. EV LIBs are manufactured by integrating several key materials, especially lithium, cobalt, nickel, and graphite. As these materials are globally dispersed, secure and long-term access is critically important to the manufacture of EV LIBs and for expanding the EV market. Accordingly, these four materials' complex and differentiated global value chains (GVCs) have garnered extensive interest.

This paper is one of a five-part series of working papers that map out the GVCs for lithium, cobalt, nickel, and graphite that are used in LIBs for EVs. The intent of the working paper series is to better understand the value that is added from the materials' mining/extraction and refining/processing in preparation for EV LIB assembly. This paper provides a holistic GVC analysis of all four materials; the other four working papers provide in-depth and separate studies on each of the individual four materials.[2]

The paper begins by summarizing basic GVC concepts. The second section discusses factors impacting demand for EVs and their LIBs. The third section summarizes LIB technologies, including configurations related to the four key LIB materials. The fourth section discusses the international trade flows of the four key materials. The fifth section offers some conclusions.[3]

Section 1: Global Value Chains

GVC analysis examines the value added,[4] from conception to end use, to a good or service. The focal point of GVCs is recognition that intermediate goods are an important element in international commerce (Krugman 1979). Evidence emerged that the simple theory of comparative advantage is inadequate to explain the complexity of international trade. The physical separation of production processes across borders—*fragmentation*—is now commonplace (Arndt and Kierzkowski 2001). Porter (1985) expanded on this analysis by Krugman and others by presenting five core value chain activities, namely inbound logistics; operations; outbound logistics; marketing and sales; and services to the customer. Gereffi and Fernandez-Stark (2011) defined GVCs as "the full range of activities that firms and workers perform to bring a product from its conception to end use and beyond."

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[1] For additional information on how lithium-ion batteries work, see USDOE 2017, "How Does a Lithium-Ion Battery Work?," https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work.

[2] Published and forthcoming working papers by USITC staff (Guberman, LaRocca, Matthews, and Tsuji) in the Natural Resources and Energy Division of the Office of Industries, on the global value chain for four key materials (nickel, lithium, cobalt, and graphite, respectively) used in the production of lithium-ion batteries.

[3] Several appendixes also are included that present supplemental information on the global EV market, government programs to support EV sales, and trade data measurements for the four materials.

[4] Samuelson and Nordhaus (2010, 675) have defined value added as "[t]he difference between the value of goods produced and the cost of materials and supplies used in producing them."

LIB GVCs

GVC analysis of LIBs is important for several reasons. LIBs incorporate multiple materials, unlike, for instance, lead-acid batteries that primarily incorporate lead. Moreover, raw LIB materials are substantially transformed and increase in value along the path to being installed into LIBs. The movement of LIB materials for eventual integration into LIBs requires the crossing of several country borders and thus can be fragmented.

Prior literature discussed manufacturing supply chains for LIBs across key economies (Sandor et al. 2017), some mapped the manufacturing that takes place within the United States (Lowe et al. 2010), and others analyzed the supply and use of some of the key materials, such as cobalt and lithium (Foss et al. 2016). This series of working papers adds to existing knowledge by reviewing the four key LIB materials' GVCs, especially mining/extraction and refining/processing, as well as measuring their value as they are traded across borders.

Section 2: EV and LIB Market Demand

EVs are potential substitutes for the currently dominant internal combustion engine (ICE) powered motor vehicles. Since transportation is a significant source of CO_2 emissions, consumers can substitute EVs for ICE vehicles to reduce their contribution of these emissions and other pollutants. EVs are, however, generally more expensive for consumers than ICE vehicles, and demand is further restrained by the time it takes to charge an EV, a limited charging station infrastructure, and low oil prices.

Global Market Demand[5]

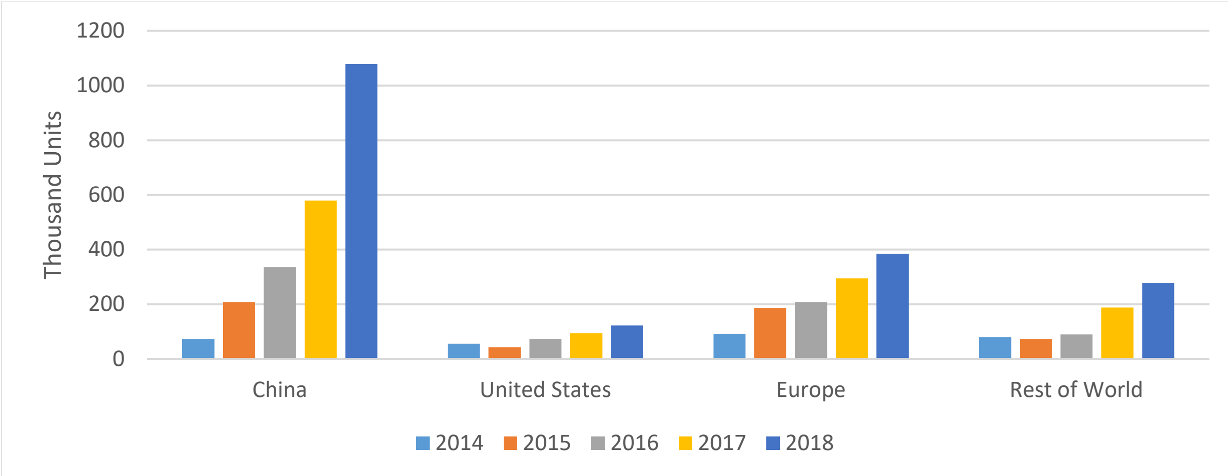
Demand for LIBs—and their four key materials—is derived directly from the demand for the EVs that they power.[6] The global fleet of EVs surpassed 5.1 million in 2018; over 2 million EVs were sold in 2018, up from 0.3 million in 2014 and a few thousand in 2010 (IEA 2019b; Hertzke et al. 2019). Although sales have thus grown in recent years, EVs represented less than 0.5 percent of the global passenger vehicle fleet in 2019 (Kah 2019).

China is the world's largest EV market with nearly 1.1 million EVs sold in 2018 (IEA 2019b). The United States and EU have experienced slower sales growth and had sales of 361 thousand and 320 thousand EVs respectively in 2018 (Figure 1).

[5] Additional information is provided in Appendix A, Global EV Market.

[6] In addition to EVs, LIBs are used in many other electronic devices (such as cell phones and laptops) and storage systems (such as utilities and data centers). Although EVs are currently a small share of the LIB market, some sources project an increasing share of LIBs will be used in the transportation sector (Mann 2019).

Figure 1 EV sales, by region

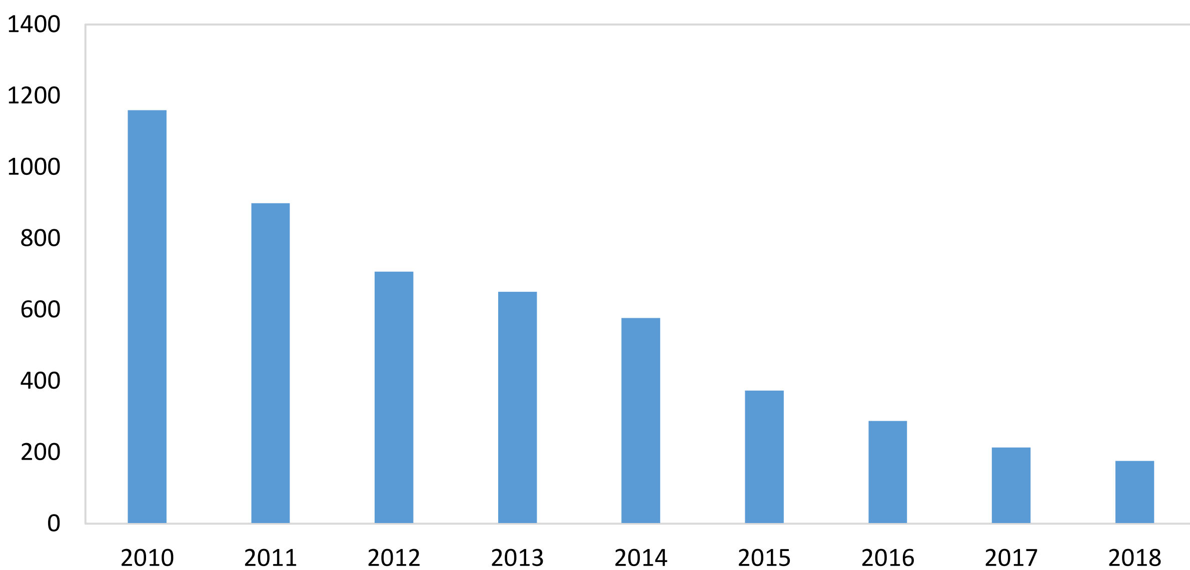


Sources: IEA 2019, "Global EV Outlook 2019."

EV Cost

Although EV prices have decreased in recent years, EVs are generally still more expensive than comparable ICE vehicles. Progress towards cost parity convergence largely reflects cost reductions by means of newer battery technologies as well as the application of government incentives. One source estimates that LIB prices have dropped from $1,160 to $176 per kilowatt-hour, an 85 percent drop, in the last two decades, making EVs more affordable (Figure 2).

Figure 2 LIB pack[a] price, volume-weighted average



Source: Goldie-Scot 2019, "A Behind the Scenes Take on Lithium-Ion Battery Prices."
[a] The basic LIB unit is the "cell" that contains the electrodes, separator, and electrolyte. The battery pack is a collection of cells and accessories. BloombergNEF surveys produced LIB prices. The survey responses include a wide range of battery types, which are weighted based on volumes sold.

LIB prices directly impact the total cost of EV ownership (IEA 2018) as the battery cell accounts for 25 percent of a typical EV's overall manufacturing costs (CTI Symposium, n.d.). In some models, such as the Tesla Model 3, the LIB constitutes as much as one-third of the EV's cost (Ma and Thomas 2019). According to Coffin and Horowitz (2018), the choice of LIB is the key differentiator between EV manufacturers. In addition, estimates show that most (70 percent) of the value added through the LIB value chain is accounted for by making the cells, compared to only 15 percent in assembly, and 10 percent in the electrical and mechanical components (Canis 2013).

The LIBs that power EVs use several different material formulations and technological advances in battery chemistry that are delivering substantial cost reductions (IEA 2019b). Depending on the chemistry, lithium-ion battery costs are sensitive to lithium, cobalt, nickel, and graphite prices; the availability of these key materials could put upward pressure on LIB prices (Hertzke et al. 2019). Although there may be short-term fluctuations, many industry observers speculate that battery prices will continue to decrease (BloombergNEF 2019). Certain industry experts further speculate that falling battery prices in most market segments (with wide variation between vehicle segments and geographies) will motivate price parity between ICE vehicles and EVs by the mid-2020s (IEA 2019b).

Growth in the number of battery producers led to overcapacity in recent years, which is another of the drivers for the decrease in LIB prices. However, a variety of firms—Tesla (U.S.), BYD (China), CATL (China), LG Chem (Korea), Samsung SDI (Korea), SK Innovation (Korea), and Panasonic (Japan)—are increasing their investment in battery production, implying confidence in increasing demand for LIBs. In addition, the EV segments in BMW, Daimler, and Volkswagen have shown interest in acquiring a secure supply of LIBs (IEA 2019b).

Government Support Reduces Cost

As one option for countering cost competitiveness obstacles, some national and local governments have implemented tax credits to reduce EV purchase prices and make them more competitive with comparable ICE vehicles (IEA 2019b).[7] Government support is a crucial factor in technology adoption; governments have used tax credits as well as other policies (such as fuel economy standards and building EV charging station infrastructure) to make EVs more cost competitive (IEA 2019b). The goal of these policies is to induce automakers to produce more EVs and consumers to buy more of them (Baik et al. 2019). Government policy can support not only EV manufacturing capacity, but also can develop the LIB technology value chain; these investments have externalities beyond EVs, since cost reductions in LIBs have multiple applications (IEA 2019b).

Growth of the Chinese EV market has been driven by generous government incentives.[8] Similarly, Norway's world leading EV market share of 46 percent in 2018 reflects its government's wide range of incentives (IEA 2019b).[9] In contrast, the United States has provided far fewer incentives for potential EV

[7] For more information on incentives for EV purchases at the U.S. federal level and state level, see the U.S. Department of Energy's Alternative Fuels Data Center at https://afdc.energy.gov/laws/.
[8] China's subsidy program reportedly encourages automakers to sell EVs below manufacturing costs (Moss 2019; Barrett 2019). See Appendix B, Government Programs.
[9] Norway's EV incentive policies have included, but are not limited to, no purchase or import taxes, exemption from 25percent VAT on purchase, no annual road tax, no charges on toll roads or ferries, and free municipal parking. See Norsk elbilforning, n.d.

purchasers. In addition, the United States has not raised its national gasoline tax since 1993, which has helped to keep fuel prices low, motivating slower EV market growth.

Evidence suggests that, despite optimistic forecasts from some industry experts, global EV growth will not accelerate over the short-term for several reasons (Butler 2019). The growth in gasoline powered SUVs and Crossover Utility Vehicles (CUVs) exceeds the growth of EVs in the United States and many other countries (IEA 2019a). The United States is in the process of weakening future domestic vehicle fuel efficiency standards. China has recently reduced subsidies for EVs, which are anticipated to weaken EV growth, and thus alter downward previous predictions. In addition, low oil prices have strengthened the attractiveness of ICE vehicles to cost conscious consumers (Hook 2019).

Range and Charging Infrastructure

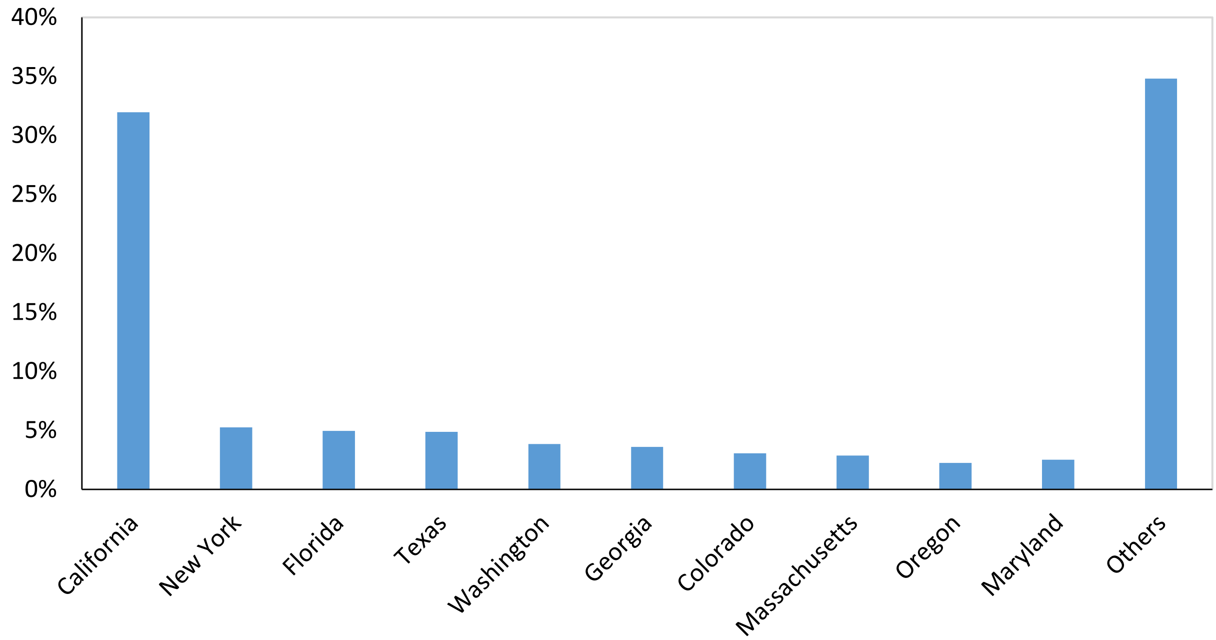
Recent years have brought innovation and improvements to driving range limitations and charging times. Although EVs have had shorter ranges (per full charge) than comparable ICE vehicles (per full tank of gas) (Coffin and Horowitz 2018),[10] several models now offer driving ranges of over 200 miles. Tesla's Model S, for instance, offers a maximum range of 370 miles and the mid-range of the more affordable Tesla Model 3 offers a maximum range of 320 miles. Although EV charging time is still considerably longer than filling up an ICE vehicle tank with gasoline, Level 3 charging (the fastest EV charging) can complete a battery charge (from empty to full) in approximately 30 minutes.

A comprehensive charging network would also likely motivate greater EV adoption. At the time of writing, there are globally over 600,000 public charging stations and this number continues to grow, albeit slowly. Currently, this includes a scattered infrastructure of ultra-fast chargers, wireless chargers, and battery swapping arrangements. In 2018, roughly three quarters of the public charging outlets were in China (48 percent) and Europe (30 percent) (BloombergNEF 2019). Norway launched a program in 2017 to provide at least two fast charging stations every 50 km on its main roads.[11] There are now more than 10 thousand public fast charging points in Norway (Norsk elbilforening, n.d.).

The United States has about 10 percent of the global supply of charging stations (BloombergNEF 2019).[12] Although there are 70,000 public EV charging outlets in the United States, they are unevenly distributed and miniscule compared to gasoline filling stations. The top 10 states account for 65 percent of all EV charging outlets, with California alone accounting for 32 percent of these outlets (Figure 3).[13]

[10] In addition, technological innovations are increasing the longevity of LIBs used in EVs. Tesla has recently filed patents on new battery chemistry (to improve the NMC chemistry) to make it last over 1-milion miles in an EV (Lambert 2019).
[11] This project is almost complete, with the exceptions of Finnmark and Lofoten.
[12] The IEA estimates that the electricity used to charge the EVs on the road in 2018 emitted 41 million tons of carbon-dioxide equivalent (Mt CO2-eq). Compared to equivalent ICE vehicles, this saved 36 Mt CO2-eq (IEA 2019).
[13] The top ten states for public EV outlets are California (22,193), New York (3,648), Florida (3,445), Texas (3,380), Washington (2,665), Georgia (2,492), Colorado (2,125), Massachusetts (1,997), Oregon (1,565), and Maryland (1,750).

Figure 3 U.S. States with the most EV charging stations



Source: U.S. Department of Energy, https://afdc.energy.gov/stations/states (accessed October 27, 2018).

Section 3: Lithium-ion Battery Types

LIBs have four major components: *cathode* (positive electrode), *anode* (negative electrode), *electrolyte*, and *separator*. The electrolyte carries lithium ions back and forth between the anode and cathode via the separator. Of the four materials examined in this paper, lithium, cobalt, and nickel are used in the cathode, and graphite is used in the anode (USDOE 2017).

Common LIB Types

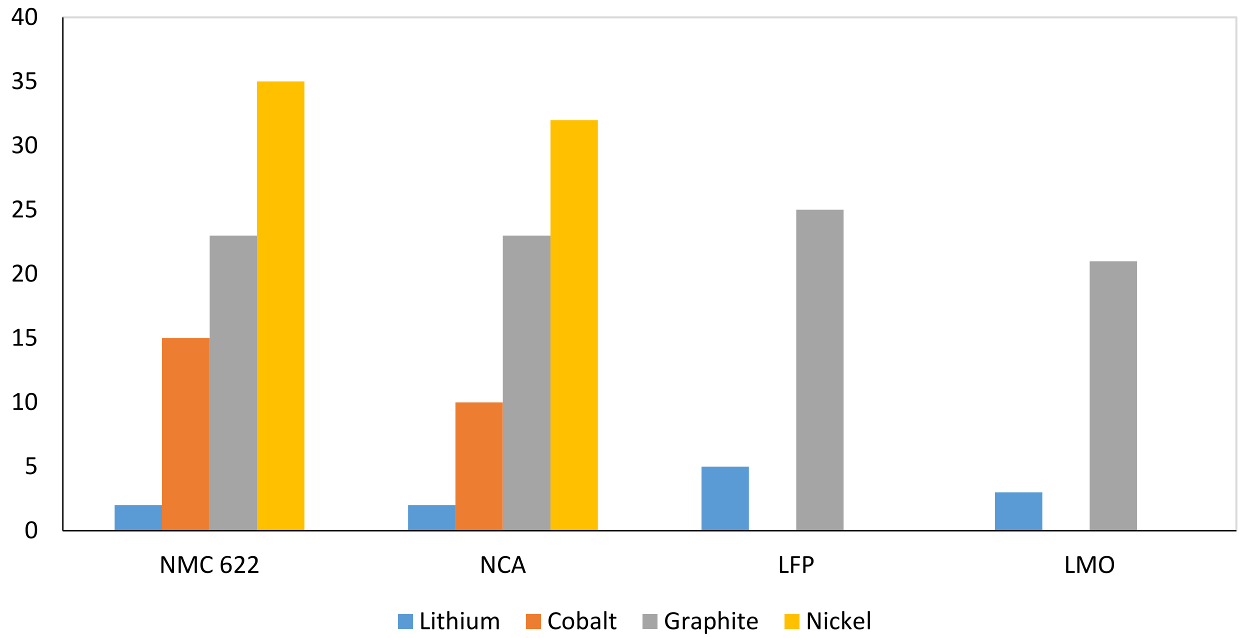
There are several different LIB types, primarily determined by the proportion of their integrated materials. Table 1 reflects four of the most common LIB types at the present time. Figure 4 presents an estimate of the proportion of the four key materials in the four LIB types listed in Table 1. The cost of the different LIBs depends on the battery chemistry, design, and manufacturing process (Nelson et al. 2012).

Table 1 LIB types

Name	Chemical term	Short name	EV models and other uses
Lithium Manganese Oxide	$LiMn_2O_4$	LMO or Li-manganese	EVs (e.g. Nissan Leaf), power tools, medical devices, electric powertrains
Lithium Nickel Manganese Cobalt Oxide	$LiNiMnCoO_2$	NMC	EVs (e.g. Chevy Bolt, BMW i3), E-bikes, medical devices, other
Lithium Iron Phosphate	$LiFePO_4$	LFP or Li-Phosphate	Energy storage
Lithium Nickel Cobalt Aluminum Oxide	$LiNiCoAlO_2$	NCA or Li-aluminum	EVs (e.g Tesla), other

Sources: Battery University, n.d., "BU-205: Types of Lithium-Ion."; Battery University, n.d, "BU-306: What is the Function of the Separator?"; Battery University, n.d., "BU-307: How Does Electrolyte Work?"

Figure 4 Key material share of common LIB compositions, by weight



Source: Argonne National Laboratory, 2018 and staff calculations.

LIB Key Materials GVCs

The key LIB component materials are intermediate goods that participate in separate supply chain paths until integration into a battery. LIBs and their component materials have complex supply chains and thus participants—such as miners, refiners, battery manufacturers, and end product (e.g., EVs) manufacturers—have formed strategic alliances to promote supply chain efficiency and value chain competitiveness (Jussani et al. 2017). LIB materials can reenter individual paths if they are later separated from spent batteries for recycling and reuse. Like all GVCs, LIB material GVCs can be divided into segments or phases. The literature has some differentiation in the LIB GVC phases (The Boston Consulting Group 2010; Lebedeva, Di Persio, and Boon-Brett 2016), but generally they include sourcing (mining/extraction); processing/refining; cell manufacturing; battery pack manufacturing; installation in an EV; and recycling.

The scope of this paper includes the GVCs of the raw materials that are mined/extracted and then refined/processed to a specific composition. Afterward, processed materials are used to manufacture electrodes, cells, and other components for assembly in battery packs before installation in EVs.

LIB Materials Sourcing

Sourcing individual LIB materials generally begins with mining/extraction. Because LIB materials have a wide global diversity of origin, accessing them can pose varying geopolitical challenges. Drawing from U.S. Geological Survey 2018 data on the four key LIB materials, Table 2 summarizes the countries with the largest mining production. The table also shows U.S. production, which is tiny.

Table 2 LIB materials mining production, 2018

LIB material ores and concentrates	Countries with largest mining production (share of global total)	U.S. mining production (share of global total)
Lithium	Australia (60 percent), Chile (19 percent), China (9 percent), Argentina (7 percent)	Withheld to avoid disclosing company proprietary information; staff estimates less than 1 percent
Cobalt	Democratic Republic of Congo (64 percent), Cuba (4 percent), Russia (4 percent), Australia (3 percent)	Less than 0.5 percent
Graphite (natural)	China (68 percent), Brazil (10 percent), India (4 percent)	0 percent
Nickel	Indonesia (24 percent), Philippines (15 percent), Russia (9 percent)	Less than 1 percent

Source: U.S. Geological Survey, Mineral Commodity Summaries, February 2019.

Lithium is the material that gives the LIB its name and is chiefly responsible for impacting the battery's characteristic low weight and electrochemical reactivity. Lithium, a metal, is primarily extracted from two major sources, brine lake deposits and pegmatite ores (a type of igneous rock). Chile is the dominant source of lithium from brine and Australia is the dominant source of lithium from rock (pegmatites). Although the United States does not mine much raw lithium domestically, a U.S. company, Albemarle, is one of the largest miners of lithium, mostly from resources in Chile. The lithium sourcing landscape can change very quickly—for instance, Rio Tinto, an Anglo-Australian conglomerate, announced in October 2019 that it had discovered a potentially large source of lithium in California (Sanderson 2019). Unlike other LIB cell materials, particularly cobalt, lithium has generally not faced political instability risks.[14]

Cobalt is the material used in common LIB cathodes that provides thermal stability and high energy density for batteries; its use enables the LIB to not overheat or catch fire and can store and transfer more energy relative to other materials being used (such as nickel). Cobalt, a metal, is primarily obtained as a by-product of copper or nickel mining. The Democratic Republic of Congo (DRC) is the dominant source of raw cobalt. There are a few other countries that also have cobalt resources, particularly Australia, which has the second largest reserves after the DRC. The United States has a negligible amount of cobalt resources (Slack et al. 2017). Because of the DRC's ongoing political instability, as well as poor labor conditions, sourcing cobalt faces significant geopolitical challenges. Accordingly, some companies are reportedly attempting to eliminate or reduce the amount of cobalt used in LIBs. Cobalt

[14] For more background on lithium and its GVCs, see LaRocca (forthcoming).

has competing demand for use in jet engine turbines, stainless steel fabrication, and medical prosthetics.[15]

Nickel is the material used in common LIB cathodes to economically—reflecting its lower prices relative to other materials used (such as cobalt)—increase energy density and storage capacity. Nickel, a metal, is generally mined from two types of ore deposits, near-surface laterite deposits and underground sulfide deposits. Most of the nickel produced from laterite deposits is used for the production of stainless steel, while nickel products derived from sulfide deposits are used in a range of applications including cathodes for LIBs.[16] In 2018, Indonesia and the Philippines were the leading global producers of nickel ores and concentrates; however almost all of this nickel mine production, which was from their vast laterite deposits, was exported to China for use in stainless steel production.[17] Australia, Canada, Russia, and Finland were the leading producers of nickel ores and concentrates from sulfide deposits in 2018.[18] The United States has minimal reserves of nickel and little prospect to become a significant producer. The largest competing demand for nickel is for use in stainless steel manufacturing.[19]

Graphite is the material used in LIB anodes to steady the discharge rate of electrons. Graphite, a non-metal and a type of pure carbon, is primarily extracted from carbonaceous sedimentary rocks. It can also be produced in synthetic form by treating amorphous carbons with high temperatures. Graphite is the only non-metal that can conduct electricity. Both natural graphite and synthetic graphite can be used in the LIB anode. China, Brazil, and India are currently the largest producers of natural graphite. Turkey, with the world's largest reserves of natural graphite, has great potential to become a large graphite producer (Robinson, Jr., Hammarstrom, and Olson 2017). The United States has limited natural graphite resources but is the world's largest producer and exporter of petroleum coke for artificial graphite. China, Japan, and the United States are the world's largest exporters of artificial graphite. Obtaining graphite for EV LIBs does not currently pose difficult geopolitical obstacles.[20]

LIB Materials Processing and Refining

After their sourcing, the raw materials must be processed and refined before they can be used in LIBs. The refinement of these four key LIB materials is largely an Asian story, and specifically China. Lithium is processed and refined into intermediary forms, especially lithium carbonate, lithium hydroxide, lithium chloride, and lithium metal. These intermediate forms of lithium function as LIB inputs. China is the largest importer of unprocessed lithium, which it then transforms into processed or refined lithium. It is believed that China consumes most of the refined lithium that it produces in the country's downstream

[15] For more background on cobalt and its GVCs, see Matthews (2020).
[16] Nickel ores and concentrates are processed into two different classes of primary nickel products: high-grade nickel (class 1) predominantly produced from sulfide deposits and suitable for use LIBs and lower grade nickel (class 2) produced from laterites deposits and only used in stainless steel.
[17] In some cases, nickel is smelted and refined in the same country that it is mined and in other cases the nickel ore is exported for processing.
[18] The nickel supply chain as well as the production processes employed can vary significantly. In some cases, nickel is smelted and refined in the country where it is mined, however, in other cases nickel mine production is exported for processing in other countries.
[19] For more background on nickel and its GVCs, see Guberman (forthcoming).
[20] For more background on graphite and its GVCs, see Tsuji (forthcoming).

LIB manufacturing. However, China does export some of the transformed product to other countries that manufacture LIBs, particularly South Korea and Japan (LaRocca, forthcoming).

China is the leading producer of refined cobalt with Finland a distant second. China imports most of the raw cobalt ore that it uses as feedstock from the DRC whereas Finland imports it from both Russia and the DRC. The United States does not currently have production of refined cobalt of any significance (Cobalt Institute, n.d.; Matthews 2020).

The leading overall producers of primary nickel products[21] were China, Indonesia, Japan, Russia, and Canada. A relatively small portion of total primary nickel production is refined further into nickel sulfate, the chemical compound that is used in cathodes for LIBs. This upgrading process primarily occurred in China, Japan, and South Korea (Guberman, forthcoming).

Graphite also undergoes processing and refining before it is ready for use in a LIB. With most natural graphite intended for use in LIBs being produced in China, it is either refined in China or exported for refinement, particularly to Japan and Korea. For synthetic graphite, exports from China primarily go to other Asian countries for processing and refining; similarly, U.S. exports of synthetic graphite also are primarily destined for Asia for processing and refining (Tsuji, forthcoming).

Resource Availability, Depletion Risks, and Sustainability

LIB material extraction/mining and refining/processing are directly linked to resource availability, depletion, and sustainability. Like any natural resource, LIB materials supplies are finite. Assessments of LIB material resource and reserve volumes lack consensus **(**Egbue and Long 2011) and are difficult to calculate (Chagnes and Światowska 2015), particularly because estimates of economically recoverable reserves have been increasing over time (Gruber et al. 2011). For instance, the U.S. Geological Survey global estimates of lithium reserves increased from 4.1 million metric tons in 2009 (USGS 2009) to 14.0 million in 2018 (USGS 2019), which is a 241.5 percent increase in just nine years.

Although supply has thus far generally outstripped demand for LIB materials—which generally corresponds to adequate resource and reserve volumes, as well as steady or declining prices—if efforts to curb transport-related CO_2 emissions accelerate, demand will increase substantially. A large rise in automotive LIB demand will augment concerns about scarcity, resource depletion, sustainability, and higher prices of the required materials. Like the concept of *peak oil*, *peak lithium* or *peak cobalt* could be a concern.[22]

Although many analysts are optimistic about LIB materials availability, the myriad assumptions that need to be made, combined with incomplete information, reportedly provide unreliable forecasts (Olivetti et al. 2017; Gruber et al. 2011). In particular, the uncertainty regarding LIB growth scenarios temper forecasts (Verma et al. 2016).

To manage, guide, and protect the long-term sustainability of LIB materials, Ali et al. (2017) contend that good governance and effective regulations are needed at national and international levels. To guard

[21] Includes ferronickel, nickel pig iron, nickel chemicals, and nickel metal.
[22] The term "peak oil" indicates the highest possible global oil production level (Campbell and Laherrère 1998).

against supply shocks and volatile prices, one recommendation is stockpiling LIB materials, which has been called a 'metal bank' (Bardi et al. 2016). This is like what has been done with the stockpiling of petroleum with strategic oil reserves, which aims to provide stability in times of sharp price volatility. Canadian company Cobalt 27 Capital Corp is an example of a business that focuses on stockpiling cobalt (Burton 2018).

Another approach to offsetting LIB resource depletion and raw materials supply shortages is recycling, which would also counteract the growing waste streams of used batteries. Based on data related to LIBs used in portable equipment—as few EV LIBs have reached their end-of-life—research suggests that approximately 95 percent of LIBs are currently landfilled (Heelan et al. 2016). Soon there will be more many more spent EV LIBs to be landfilled or recycled.

Recycling LIBs poses collection, technological, and economic challenges. Generally, the objective will be to collect automotive LIBs before they are dumped in landfills, although there could also be recovery of LIBs through "landfill mining" (Krook et al. 2018). In addition, the processes for separating the distinct materials from a LIB are complicated, expensive, and pose environmental problems (Boyden, Soo, and Doolan 2016). Choices of which materials to prioritize for separation and reuse is necessary based on availability, cost, and ease of separating from the battery (Peiró et al. 2013). The profit motive is currently lacking because securing raw materials is cheaper than recycling and thus governments likely will need to provide the appropriate incentives (Mayyas, Steward, and Mann 2019).

In all regions, increasing attention is being given to vertical integration in the LIB industry from material extraction, mining and refining, battery materials, cell production, battery systems, reuse, and recycling. The United States is lagging in upstream capacity; although the United States has some domestic lithium deposits, it has very little capacity in mining and refining of any of the key raw materials.

China has recently worked toward vertical integration of its capacity (BloombergNEF 2019; Ma and Thomas 2019). The rest of Asia (mainly South Korea and Japan) represent another 21 percent of the market. China also manufactures most of the key components—anodes (65.7 percent), electrolytes (64.3 percent), separators (44.8 percent), and cathodes (39.0 percent) (Ma and Thomas 2019). The EU, however, has adopted measures in its May 2018 *Strategic Action Plan for Batteries* to support synergies between government and industrial interests to build a LIB value chain in Europe (European Commission 2019).

Section 4: International Trade Flows

With the growing importance of intermediate goods that cross borders many times before integration in a final good, a double-counting problem arose in measuring international trade when using conventional statistical techniques. Looking merely at export and import data without considering the value-added was misleading at best and inaccurate at worst. In considering this problem, economists developed inter-country input-output (ICIO) models to quantitatively measure value-added trade (Jones, Demirkaya, and Bethmann 2019). This new trade statistics methodology is called Trade in Value-added (TiVA) and, among the most widely-used TiVA tools, is the OECD-WTO TiVA database "which provide(s) a measure of international interdependencies through the construction of global input-output tables that show how producers in one country provide goods and/or services to producers and consumers in others" (Ahmad et al. 2017).

Although the TiVA is a powerful tool to evaluate GVCs, its focus is at a higher level of industry aggregation than the more granular level required to examine the individual key materials that compose EV LIBs.[23] In addition, the OECD-WTO TiVA database does not include relevant countries (such as the Democratic Republic of Congo, which is central to trade in raw cobalt) for trade in these materials. Finally, these data are only available up to 2015 and do not reflect the more recent dynamic shifts in the EV LIB marketplace. Additional indicators based on trade data are widely used to evaluate the integration of certain countries in fragmented GVCs and to capture activity that is more recent.

Trade data are widely used to evaluate the integration of certain countries in fragmented GVCs (Ahmad et al. 2017). The comparison of trade in the key materials show where certain countries reside in LIB GVCs and where intermediate products' value is added in the process.

Several trade-data based indicators are available that reveal the importance of certain direct export and import partners at the upstream intermediate product-level—from extraction to refining—as products progress through the EV LIB value chain. The comparison of trade in the *intermediate* goods (the key materials) rather than exclusively the *final* goods (EV LIBs), highlight where certain countries reside in the GVC and the intermediate goods' value added in the process.

Although generating a rough estimate, the HS trade data can provide timely insights with product and trading partner disaggregation and comparability. The ability to identify trade in intermediate products provides valuable information on how countries integrate into and are positioned within GVCs.[24]

The trade-data based indicators, however, do have shortcomings. For example, although Harmonized System (HS) trade data capture the flow of goods between countries, the HS categories can be broader—include a wider range of related products—than the precise intermediate good of interest.[25] These data do not reveal the industry of origin or end-use of goods[26] and do not contain firm-level detail. In addition, if goods of interest are domestically consumed, rather than exported, these trade data will not capture the further movement of the intermediate good. The main shortcoming of indicators using gross trade statistics is their inability to quantify the value added contributed by countries in the GVC.

Key LIB Materials Trade Flows

We use trade data to generate several indicators—the most commonly used GVC measures based on international trade statistics—about trade involving the four key LIB materials and the main trade partners (Ahmad et al. 2017). We use three measures: Coverage Ratio, Revealed Comparative Advantage (RCA), and Grubel-Lloyd Index. Descriptions of these measures and information on their design and interpretation are presented in Table 3.[27]

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[23] For additional information about TiVA, see OECD, n.d., "What Can the TiVA Database Tell Us?," oecd.org/sti/ind/whatcantivadatabasetellus.htm.

[24] We provide a broad analysis of the outcomes on each of the key materials. The working papers that focus on each of the key materials provide a more in-depth treatment of the LIB global value chain.

[25] The HS is a standardized system for classifying goods that are traded internationally.

[26] For example, the products may feed multiple industries and not merely the manufacture of LIBs.

[27] For additional information on these measures and their calculations, see Ahmad et al. 2017, 14–16.

Table 3 GVC indicators based on international trade statistics

Indicator	Design	Interpretation
Coverage Ratio: a broad measure of a country's position in GVC.	Ratio of a country's intermediate goods imports to its exports.	Countries located at the beginning of the production chain (upstream) tend to export more and import fewer intermediates. This results in a relatively low value. Conversely, higher values indicate that a country is downstream; they tend to export fewer and import more intermediate goods.
Revealed Comparative Advantage (RCA) index: a measure of the intensity with which a country exports a product.	Share of exports of intermediate good in a country relative to world exports of the intermediate good.	Values greater than unity reveals a country's comparative commodity advantage, exporting more than its "fair" share. Conversely, if values are less than unity, the country has a comparative disadvantage.
Grubel-Lloyd Index (GL):[a] serves as a proxy of a country's insertion in GVCs. It is the most widely used intra-industry (key material in this use) trade measure.	Relates absolute net exports of an intermediate good with total trade (sum of exports and imports) of the same good.	The index takes on values between one and zero. At one the country exports as much of the good as it imports; as the score approaches one there is high intra-material trade. Conversely, if the value is zero (or approaching zero), the country either only exports or imports the intermediate good (a low level of intra-material trade). Lower percentages are likely outcomes for countries that either exports or only imports the material.

Source: Ahmad et al. 2017.

[a] We use this measure on the trade of each key LIB material at the HS-6 subheading.

Interpretation of these indicators requires caution, as with any measure. For example, a coverage ratio's shortcoming is that it does not reflect economic scale and there are limits to its international comparisons. For example, a country that imports a large share of intermediate goods for use in its domestic market and has few intermediate exports will have a higher ratio than another country with higher intermediate exports. Also, if the products go back-and-forth across borders some double counting may occur in measures that combine imports and exports for the GVC phases (as the products move from unrefined, processed and refined).[28] As noted earlier, in the absence of available alternatives (e.g., TiVA) at the material-level, we use the most widely used and accepted gross trade data indicators, but they are unable to provide *value added* by country in the GVC; any attribution of value gained by a country in the GVC in the following analysis should be cautiously considered and not be construed as TiVA (*trade in value-added*) equivalent.

Overall, the following trade data and GVC measure results confirm the descriptive analysis above. The outcomes are provided for the main trading countries, as appropriate for each of the key materials. This analysis illustrates that the unprocessed (upstream) product value chain is diverse amongst the four key materials, but the (downstream) refining (for use in manufacturing products, such as LIBs) is heavily concentrated across countries in Asia—mostly in China.[29]

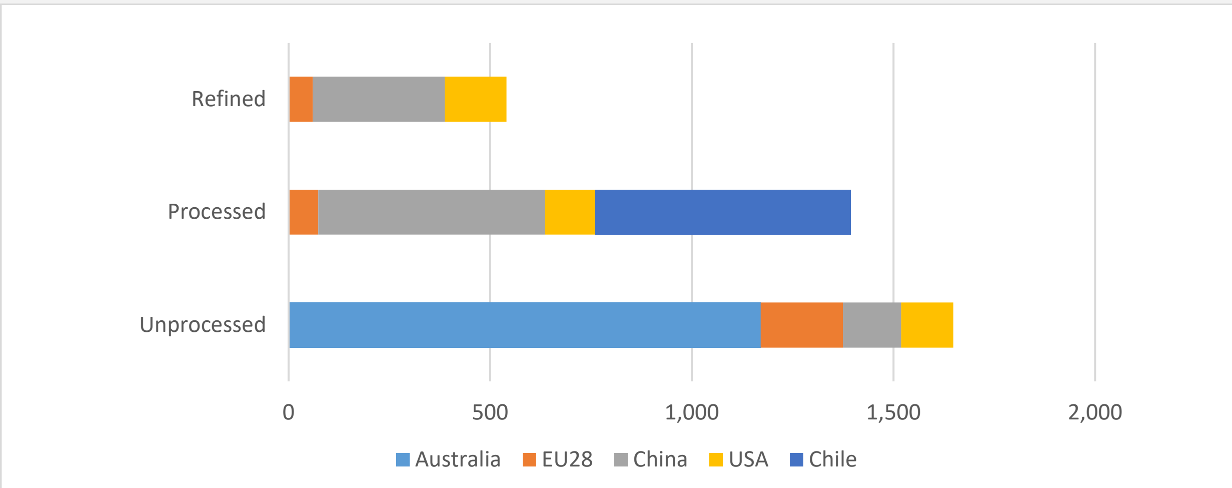
[28] For example, if a country imports the raw product and then exports the refined product, those materials are counted twice when adding them to calculate total trade for that material.

[29] As they relate to this analysis, the upstream GVC phase includes sourcing (such as mining and extraction) and any transitional material processing prior to refining; the downstream phase includes refining.

Lithium[30]

Six different Harmonized System (HS) 6-digit numbers capture trade for the three relevant forms of lithium: unprocessed (HS 2530.90), processed (HS 2836.91 and 2825.20), and refined (HS 2805.19, 2827.39, and 2826.90).[31] The 2018 global export unit price for unprocessed lithium from Australia was $0.34 per kilogram and the processed lithium export unit price from Chile was $13.37.[32] There are two unique lithium value chains (Figures 5 and 6); unprocessed and processed products are exported either from Chile into South Korea and Japan or exported from Australia to China for processing, refinement, and battery manufacturing.[33] Since China controls most of the global processing for lithium that is used in LIBs, it is therefore capturing most of the increase in value as the intermediate goods progress through the GVC.

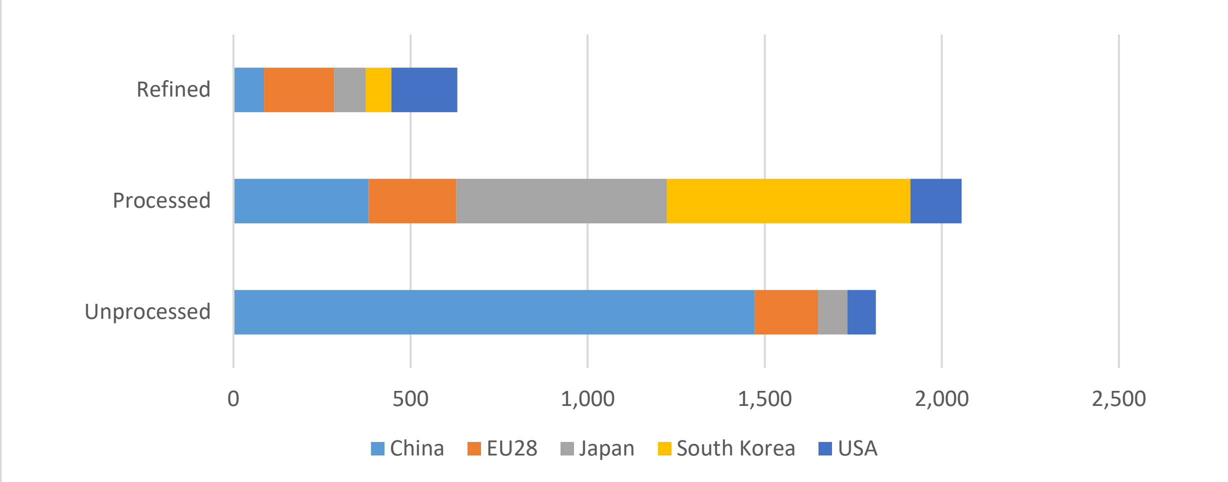
Figure 5 Lithium exports, selected countries, 2018, $ millions



Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019. Unprocessed lithium (HS 2530.90), processed lithium (HS 2836.91 and 2825.20), and refined lithium (HS 2805.19, 2827.39, and 2826.90). Some export figures are based on "mirror data," which are derived using export statistics from partner countries' import data.

[30] For a detailed analysis on trade in lithium, see LaRocca, forthcoming.
[31] The HS codes examined do not exclusively pertain to lithium compounds used in EVs. According to IHS Markit's Global Trade Atlas, the most recent year with a world export total is 2013, at $5.9 billion.
[32] The price difference between Australian and Chilean ores may be due to relative lithium content, with the Chilean ores tending to be much more lithium dense. IHS Markit, Global Trade Atlas, accessed January 12, 2020.
[33] China's exports to the United States are a relevant share of bilateral trade of refined lithium, however, these are not recognized as those used in LIBs; the unit price per kilogram in 2018 of products in HS 2805.19 were $61.28, HS 2826.90 were $4.33, and HS 2827.39 were $4.26. In addition, China's global export unit prices per kilogram in 2018 of products in HS 2805.19 were $40.49, HS 2826.90 were $2.08, and HS 2827.39 were $0.94 (IHS Markit, Global Trade Atlas, accessed January 12, 2020).

Figure 6 Lithium imports, selected countries, 2018, $ millions



Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019. Unprocessed lithium (HS 2530.90), processed lithium (HS 2836.91 and 2825.20), and refined lithium (HS 2805.19, 2827.39, and 2826.90).

The coverage ratio presented in Table 4 confirms that Australia and Chile have advantages upstream and are involved in producing unrefined materials. Australia's advantage is in unprocessed lithium and Chile's is in processed lithium. Japan, Korea, China and the United States are relatively downstream in the production process. Japan and Korea import moderately large values of both processed and refined lithium. The GL scores confirm the high intra-material trade in the United States and China. The United States has relatively low production levels of unrefined lithium (upstream) and moderate values downstream throughout the GVC. China heavily imports unprocessed lithium and exports refined lithium, but it is involved throughout the GVC. China dominates global processing and as a leader in manufacturing LIBs it consumes—rather than exports—most of its refined products. In 2018 China exported very little relative of its imports of unprocessed lithium: it exported almost half of the processed lithium it imported and exported much more than it imported of refined lithium, by value (Figures 5 and 6). However, lithium trade is not substantial to the overall trade of any of these countries.

Table 4 Lithium measures, selected countries, 2018[a]

Country	Coverage ratio: Imports to refined exports (percent)	Lithium exports to all goods exports (percent)	Lithium imports to all goods imports (percent)	Lithium trade to all goods trade (percent)	Grubel-Lloyd Index	Revealed comparative advantage
Australia	1.8	0.5	0.0	0.2	0.0	24.6
Chile	0.4	1.4	0.0	0.7	0.0	75.9
China	162.7	0.0	0.1	0.1	0.8	2.5
Japan	1,649.9	0.0	0.1	0.1	0.1	0.3
Korea, Republic of	1,458.9	0.0	0.2	0.1	0.1	0.5
United States	79.4	0.0	0.0	0.0	0.9	1.3

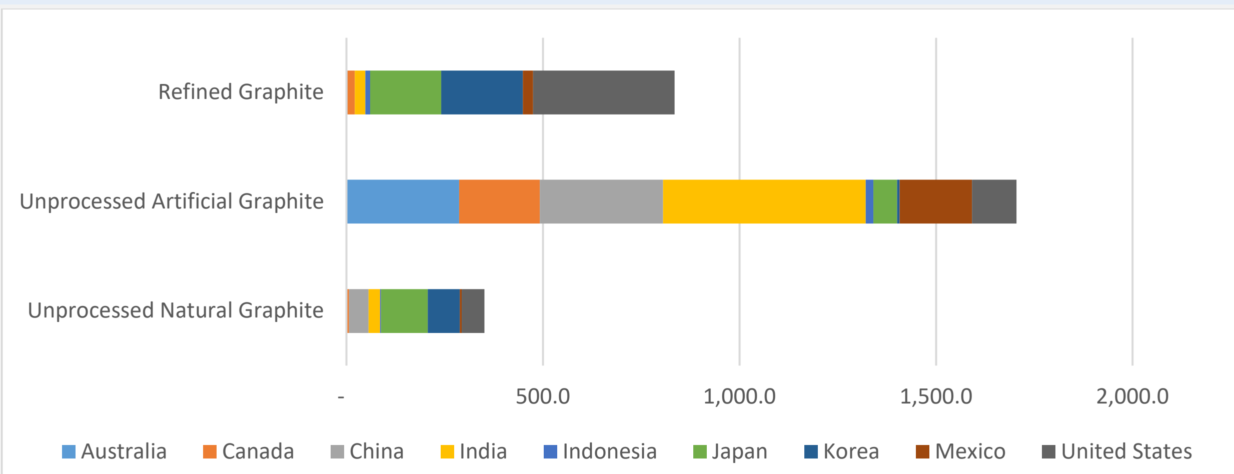
Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.
[a] Additional calculations on the individual phases of lithium trade data are in Appendix C (tables C.1 to C.3).

Graphite[34]

Four HS-6 numbers capture trade for the three relevant forms of graphite: natural unprocessed (HS 2504.10), unprocessed material input (HS 2713.12, petroleum coke, the primary feedstock used for making artificial graphite), and refined (HS 3801.10 and 8545.19).[35] The leading graphite mining country in 2018 was China (67.7 percent) (Olson 2019).[36] The leading petroleum coke producer in 2016[37] was the United States (48.3 percent, with 60,458 thousand metric tons) at 1.8 times more than the combined production of the two next largest competitors, China and India (UN Statistics Division, 2016). These production shares are supported by the 2018 trade data (Figures 7 and 8), wherein the United States was the largest exporter of unprocessed artificial graphite (petroleum coke) and China was the largest exporter of unprocessed natural graphite. China and Japan are the largest exporters of refined graphite. The largest importer of unprocessed natural graphite is Japan, India imports the most unprocessed artificial graphite, and the United States imports the most refined graphite.

China's global export unit price of natural unprocessed graphite per kilogram in 2018 was $1.46 and the U.S. global export unit price of petroleum coke per kilogram in 2018 was $0.56, while China's global export unit price of refined graphite per kilogram was $0.82 and Japan's was $8.39.[38] Value is added as the material is refined, however, there is a wide variety of graphite qualities that are being shipped to several importers with both LIB and EV manufacturing locations (China, Japan, United States, and South Korea).

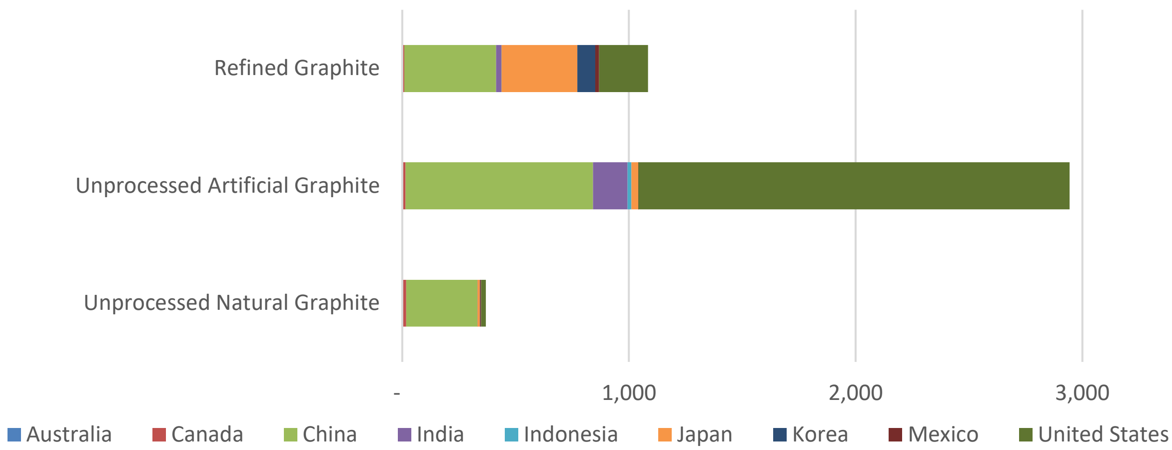
Figure 7 Graphite imports, selected countries, 2018, $ millions



Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019. Natural unprocessed graphite (HS 2504.10), unprocessed artificial graphite (HS 2713.12, petroleum coke), and refined graphite (HS 3801.10 and 8545.19).

[34] For a detailed analysis on trade in graphite, see Tsuji, forthcoming.
[35] The HS-6 codes examined do not exclusively pertain to graphite used in EV anodes. According to IHS Markit's Global Trade Atlas, the most recent year with a world export total is 2013, at $18.5 billion.
[36] Global mine output in 2018 was 930,000 metric tons. The second largest producer in 2018 was Brazil, with 10.2 percent share.
[37] This is the most recent year that these data are available.
[38] IHS Markit, Global Trade Atlas, accessed January 12, 2020.

Figure 8 Graphite exports, selected countries, 2018, $ millions



Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019. Natural unprocessed graphite (HS 2504.10), unprocessed artificial graphite (HS 2713.12, petroleum coke), and refined graphite (HS 3801.10 and 8545.19).

The scores on Table 5 are somewhat unclear about graphite trade for the United States, China, and Australia, and illustrate the need for analysis to go beyond just the indicator scores. The United States and China coverage ratios are in the lower range, which indicates that these countries are leaders, but are not exclusive as product sources worldwide. The U.S. advantage is in artificial graphite, while China's advantage is in natural graphite. However, both countries import large quantities of graphite in different stages. For example, the United States and China accounted for much of all graphite trade in 2018, by value (Figures 9 and 10). In particular, the United States accounted for a large share of raw artificial graphite exports and a relatively moderate amount of refined graphite imports and exports. China accounted for most of the raw graphite exports and a relatively moderate amount of raw artificial graphite imports as well as a moderate amount of refined graphite imports and exports. These two countries are involved in graphite trade at each step along the GVC.

Australia's coverage ratio score reveals its much larger imports relative to exports of graphite in each stage[39]; the GL indicates low intra-material trade. Additionally, 98.6 percent of Australia's graphite trade (by value) in 2018 was in imports of artificial graphite to replace domestic production and for domestic use. As Australia's domestic production of refined petroleum products declined[40] in recent years, so did its production of petroleum coke (EIA 2017; UNDESA 2015; UNDESA 2016).

Japan and Korea both participate along the GVC; they both import moderate amounts of natural graphite, by value. Japan also imports a moderate amount of refined graphite, but it exports almost twice that value. Overall, Japan imports close to the same amount of graphite as it exports. South Korea exports a moderate amount of refined graphite, but it imports over two-and-a-half times that value. Collectively, Korea's coverage ratio shows that it imports four-times as much graphite as it exports.

[39] Australia's 2018 total graphite imports were $290.9 million and its total graphite exports were $0.3 million.
[40] This can be attributed to closures or idling of petroleum refineries due to tighter refining (profit) margins, high labor and production costs, stricter environmental regulation of motor fuels, previously higher costs of imported crude oil, and rising imports of refined petroleum products as Australia's petroleum refining sector is small-scale and technologically outdated compared to the more technologically advanced refineries in Asia.

Although both countries manufacture LIBs, these trade value proportions reflect the nature of the countries' resources and LIB manufacturing structures.[41]

Table 5 Graphite measures, selected countries, 2018[a]

Country	Coverage ratio: imports to exports (percent)	Graphite exports to all goods exports (percent)	Graphite imports to all goods imports (percent)	Graphite trade to all goods trade (percent)	Grubel-Lloyd Index	Revealed comparative advantage
Australia	115,553.2	0.0	0.1	0.1	0.0	0.0
Canada	569.3	0.0	0.0	0.0	0.3	0.6
China	37.2	0.1	0.0	0.0	0.5	3.8
India	324.3	0.1	0.1	0.1	0.5	3.3
Indonesia	203.4	0.0	0.0	0.0	0.7	0.6
Japan	96.5	0.1	0.0	0.0	1.0	3.1
Korea, Republic of	368.5	0.0	0.1	0.0	0.4	0.8
Mexico	903.0	0.0	0.0	0.0	0.2	0.3
United States	24.9	0.1	0.0	0.1	0.4	7.9

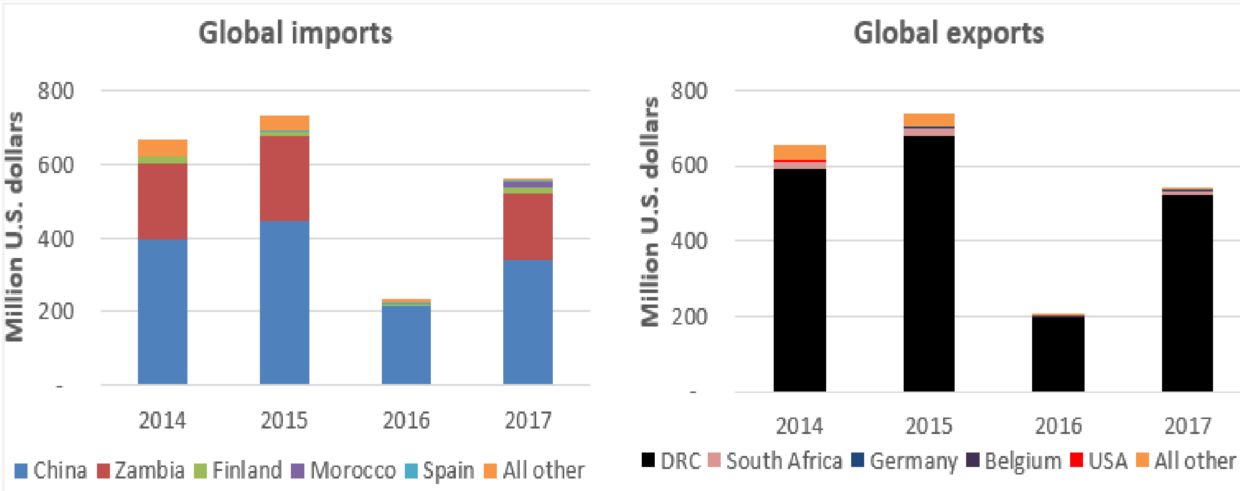
Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.
[a] Additional calculations on the individual phases of graphite trade data are in Appendix C (tables C.4 to C.6).

Cobalt[42]

Three HS-6 numbers capture trade for the two relevant forms of cobalt: unrefined (HS 2605.00) and refined (HS 2822.00 and 8105.20).[43] The trade data on unrefined cobalt confirms that most of it comes from DRC and goes to China for further processing (Figures 9 and 10). The trade in refined cobalt indicates more diversification;[44] however, China continues to be the largest import market. China, the largest importer of unrefined cobalt reported unit values per kilogram from DRC, the largest exporter, of $1.49 in 2016, $3.37 in 2017, and $4.36 in 2018. Global refined import unit prices per kilogram to China show similar volatility, of $5.36 in 2016, $9.62 in 2017, and $16.26 in 2018.[45] China's foreign ownership is mostly in the DRC, with influence on mines that are Chinese owned, which increases its effect on the cobalt GVC; China is capturing most of the value on cobalt before its use in LIB manufacture (Gulley, McCullough, and Shedd 2019).

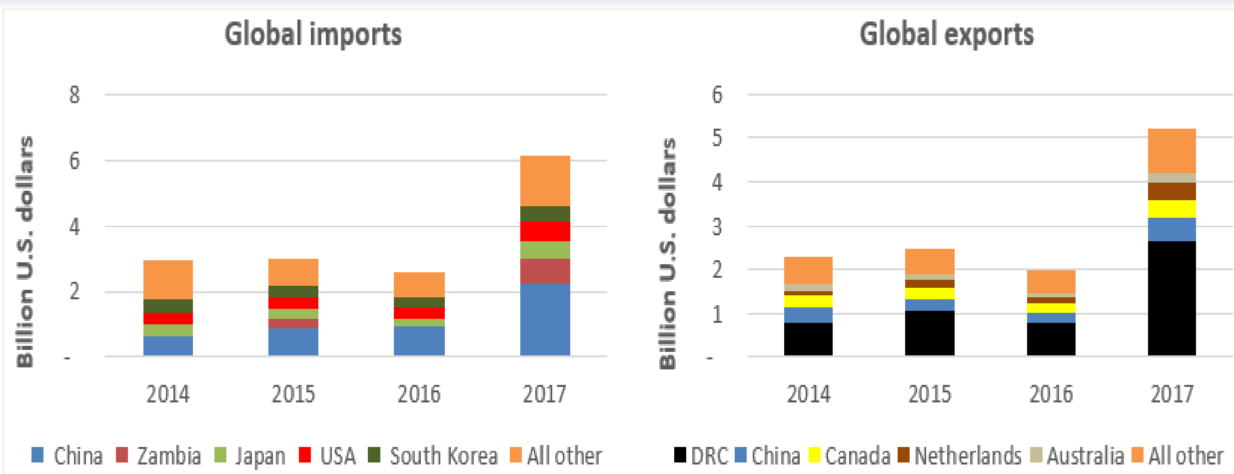
[41] Battery anode producers are dominated by China, Japan and Korea. Korea is a large producer of graphite, while Japan does not have active graphite mines.
[42] For a detailed analysis on trade in cobalt, see Matthews (2020).
[43] The HS codes examined do not exclusively pertain to cobalt used in EVs. According to IHS Markit's Global Trade Atlas, the most recent year with a world export total is 2017, at $3.8 billion.
[44] Netherlands is a warehousing hub, rather than a processor.
[45] IHS Markit, Global Trade Atlas, accessed January 12, 2020.

Figure 9 Unrefined cobalt (HS 2605.00) trade, 2014–17, $ millions



Source: IHS Markit, Global Trade Atlas, accessed March 5, 2020.
Note: Discrepancies in import and export values are likely due to reporting issues in the Global Trade Atlas. Export figures use "mirror data," which are derived using export statistics from partner countries' import data.

Figure 10 Refined cobalt (HS 2822.00 and 8105.20) trade, 2014–17, $ millions



Source: IHS Markit, Global Trade Atlas, accessed March 5, 2020.
Note: Discrepancies in import and export values are likely due to reporting issues in the Global Trade Atlas. Export figures use "mirror data," which are derived using export statistics from partner countries' import data.

DRC's coverage ratio and GL index in 2017[46] show that the DRC exports much more than it imports; DRC accounted for almost all global unrefined cobalt exports (Table 6 and Figure 9). The RCA score also reflects the DRC's position as the world's dominant producer and exporter of unrefined cobalt. China imported most of these products in 2017 and controls important stages of this GVC; many of the cobalt-related companies in DRC are Chinese-owned (Farchy and Warren 2018).

The scores for the United States and China reflect high levels of imports for final product manufacture; their imports far exceed exports**.** U.S. imports of unrefined cobalt and imports and exports of refined cobalt were much less than those of China. China imported a substantial amount of refined cobalt and

[46] The data to calculate DRC's RCA for 2018 are not available, so the RCA ratios for 2017 are provided.

had smaller exports; China's imports and exports of unrefined cobalt were much lower than those of refined (figures 9 and 10).

China also has substantial production capacity, as it accounted for over 60 percent of all global refined cobalt production in 2018 (Cobalt Institute, n.d.). Although capacity is growing in other areas with Chinese investments upstream in DRC, Chinese domestic firms are expected to remain the main suppliers of refined cobalt (downstream) and LIBs for the next few years (Patterson and Gold 2018). China is a leader in LIB manufacturing and consumes most of its domestic refined cobalt production.

Table 6 Cobalt measures, selected countries, 2017[a]

Country	Coverage ratio: imports to exports (percent)	Cobalt exports to all goods exports (percent)	Cobalt imports to all goods imports (percent)	Cobalt trade to all goods trade (percent)	Grubel-Lloyd Index	Revealed comparative advantage
China	492.4	0.0	0.1	0.1	0.3	3.4
Congo, Dem. Rep.	0.0	22.8	0.0	13.7	0.0	3,340.9
United States	598.3	0.0	0.0	0.0	0.3	0.9

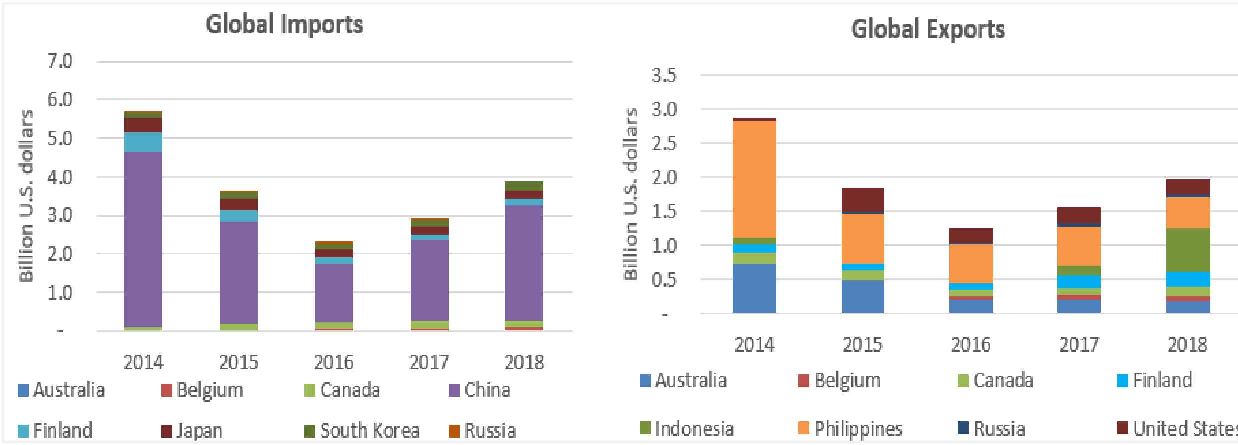
Source: IHS Markit, Global Trade Atlas, accessed March 4, 2020; USITC staff calculations.
[a] This is the most recent year where data are available for each of selected countries. Although Japan, South Korea, and Canada have some trade in cobalt, their relative share of global trade is insignificant relative to that of the DRC and China. Additional calculations on the individual phases of cobalt trade data are in Appendix C (tables C.7 and C.8).

Nickel[47]

Four HS-6 numbers capture trade for the two relevant forms of nickel: unprocessed (HS 2604.00) and refined (HS 7502.10, 7502.20, and 7504.00).[48] The trade data show that much of the unprocessed nickel is exported from Australia, Indonesia, Philippines, and the United States and is imported by China. However, since only the purest nickel ore (class 1, which has 99.8 percent or higher nickel content) is used in LIB manufacture, and most nickel is used in the manufacture of stainless steel, the countries that provide the higher nickel content (class 1) used in LIBs are typically Australia, Canada, Russia, and Finland.[49] Large shares of the refined nickel are exported from Canada and Russia—locations exporting class 1 nickel that would be suitable for use in LIBs—and imported into China, Japan, and South Korea—locations which are known to have LIB production facilities. The global unit import price per kilogram for the largest unprocessed importer, is relatively stable; China's import price per kilogram in both 2017 and 2018 was $0.06. By contrast, the unit values/kilogram for Chinese imports of refined nickel were $11.16 in 2017 and $13.94 in 2018. China not only imports most of the raw nickel, it also imports refined nickel; China controls most of the global processing for the nickel that is used in LIBs and is a leading LIB manufacturer and is therefore capturing most of the value.

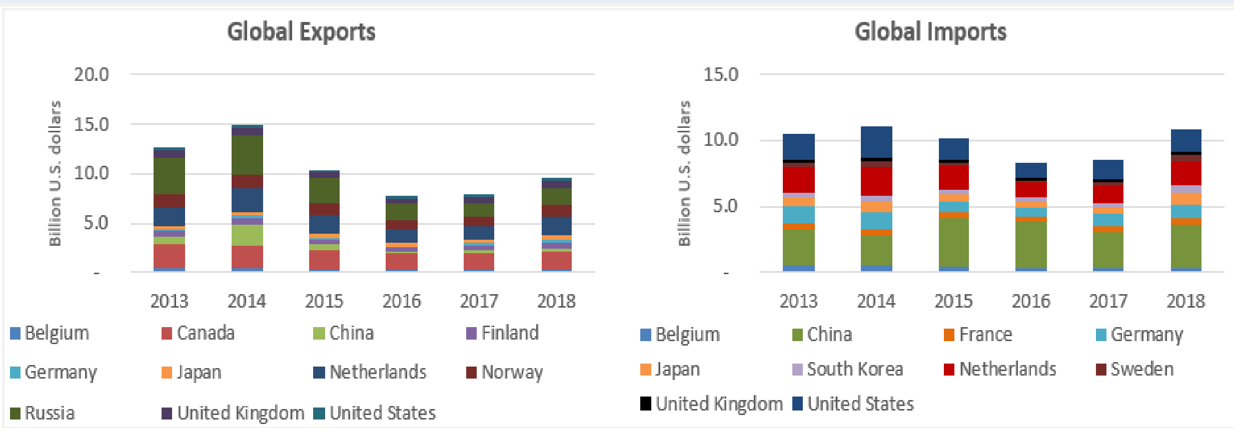
[47] For a detailed analysis on trade in nickel, see Guberman, forthcoming.
[48] The HS codes examined do not exclusively pertain to nickel used in EVs. According to IHS Markit's Global Trade Atlas, the most recent year with a world export total is 2017, at $17,957.4 million.
[49] The Netherlands is not a known producer but is the location of a London Metal Exchange warehouse.

Figure 11 Unprocessed nickel (HS 2604.00) trade, selected countries, 2014–18, $ billions



Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019.

Figure 12 Refined nickel (HS 7502.10, 7502.20, and 7504.00) trade, selected countries, 2014–18, $ billions



Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019.

Nickel trade data are difficult to parse as much of it is used in stainless steel and the Harmonized System does not differentiate between the type used for LIB and stainless-steel manufacture. The data presented in Table 7, however, confirm that Australia, Canada, Finland, Norway, and Russia are further upstream in the value chain for nickel than is China. Norway concentrates on nickel refining and exporting for use in other countries.

China imports about twenty-two times more nickel than it exports. The RCA shows that China imports large amounts of both unprocessed and refined nickel for domestic use; this corresponds with China's position as the world leader in the production of both LIBs and stainless steel.

Table 7 Nickel measures, selected countries, 2018[a]

Country	Coverage ratio: nickel imports to nickel exports (percent)	Nickel exports to all goods exports (percent)	Nickel imports to all goods imports (percent)	Nickel trade to all goods trade (percent)	Grubel-Lloyd Index	Revealed comparative advantage
Australia	6.4	0.3	0.0	0.2	0.1	9.6
Canada	11.8	0.5	0.1	0.3	0.2	14.0
China	2215.7	0.0	0.3	0.1	0.1	0.3
Finland	23.9	1.1	0.2	0.7	0.4	32.9
Norway	0.3	1.0	0.0	0.6	0.0	29.9
Russia	1.3	0.4	0.0	0.3	0.0	12.2
United States	322.0	0.0	0.1	0.1	0.5	1.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.
[a] Additional calculations on the individual phases of nickel trade data are in Appendix C (tables C.9 to C.10).

Section 5: Conclusion

Lithium-ion batteries, the "engine" for electric vehicles, have emerged as the central mechanism for reducing transportation-related carbon emissions. LIBs require four key materials, namely lithium, cobalt, nickel, and graphite. Because these materials are globally dispersed and face sourcing challenges in a setting of anticipated demand growth, comprehending their global value chains is vital.

This paper uses both descriptive analysis and quantitative trade-based indicators—Coverage Ratio, Revealed Comparative Advantage (RCA), and Grubel-Lloyd Index—to analyze the global value chains of the four key LIB materials. Both the quantitative and qualitative analysis results presented in this paper illustrate that the upstream product source value chain is diverse amongst the four key materials. The GVC downstream, however, is geographically located across countries in Asia, mostly in China. China has been increasing its global footprint, such as its increased ownership of upstream cobalt-related firms in DRC. China has also been enlarging its consumption of the four key LIB materials and its influence on the GVC has helped secure these materials for Chinese manufacturing of LIBs for insertion in EVs.

Currently, LIB materials availability will continue to be more than adequate if there is not a substantial increase in the proportion of EVs worldwide. If there is to be a rapid transition from ICE to EVs, however, stakeholders will need to expand LIB material resource availability and guard against depletion risks to ensure sustainability.

Appendix A: Global EV Market

The global EV market consists mostly of passenger vehicles; EVs are a small, but important, part of the global passenger vehicle market (Coffin and Horowitz 2018). The global electric vehicle fleet almost doubled in 2018, exceeding 5.1 million from 2 million in 2017. In 2018, 45 percent (2.3 million) of the world's EV fleet was in China, up from 37 percent in 2017. By comparison, Europe accounted for 24 percent[50] (1.2 million) and the United States accounted for 22 percent (1.1 million).

There are some commercial applications of EVs; buses currently dominate the global commercial EV market. Out of the global fleet of 425 thousand electric buses, China has 421 thousand electric buses (accounting for about 18 percent of its total bus fleet), Europe has 2,250, while the United States has 300. Other commercial vehicles—such as trucks—continue to be mostly ICE vehicles (BloombergNEF 2019). EVs for freight transport were mostly light-commercial vehicles (250 thousand in 2018), but the fleet also includes about 2,000 medium-sized trucks (IEA 2019).

Mobility services—taxis, ride-hailing and car-sharing fleets—are a growing segment and ride-hailing app use is on the rise globally; EVs account for 1.8 percent of the shared mobility fleet (BloombergNEF 2019). The largest ride-hailing market is in China with 10 billion rides in 2018, whereas the United States had less than 3 billion rides. China's mobility service providers include (such as BAIC Motor, SAIC Motor, GAC Motor, and Geely Auto) or have forged partnerships (such as Didi Chuxing) with automakers. However, profits have been hard to find in this segment. Daimler is withdrawing its Smart mini-cars (its car-sharing service is car2go) from China in favor of a joint venture with Geely to capture the premium ride-hailing segment (IHS Markit 2019).

China accounts for both a large share of global EV production and sales—60 percent of 2018 world-wide sales (BloombergNEF 2019). China's light EV sales climbed from 220 thousand units in 2015 to 1.1 million in 2018 (48 percent CAGR). Its penetration rate among light passenger vehicle sales grew from 0.9 percent to 3.9 percent in the same period. China has a large market for very small "city" vehicles; 90 percent of China's very small cars were EVs. Larger vehicles are also common; about one-third of China's EVs are sport-utility vehicles (SUVs) (IEA 2019). One source predicts that the Chinese market will not maintain the same robust growth beyond 2020 and may experience an overall market decline, reflecting the phase out of subsidies. With subsidies, small BEVs are at purchase-price parity with ICE vehicles and have a lower total-cost-of-ownership. However, the Chinese government is phasing out its EV-subsidy program by the end of 2020 and China's Corporate Average Fuel Consumption and New Energy Vehicles dual-credit scheme applies up to 2019 (Hertzke et al. 2019).

Comparatively, China's EV market is about three times larger than the markets for both Europe and the United States. Europe's EV sales were 385 thousand units in 2018 (320 thousand units are accounted for by EU countries), with mixed results at the country level. The EU's penetration rate among light passenger vehicle sales grew from 1 percent in 2015 to 1.8 percent in 2018. Although Europe has countries with the largest penetration of electric car sales, its 2018 growth rate (31 percent) from 2017 is lower than the global average.[51] By market share, Norway (which is not a member of the EU) is the

[50] The European Union countries accounted for 0.96 million of these vehicles.
[51] Europe's growth rate in 2017 from 2016 was 41 percent.

global leader, with EVs accounting for 46 percent of its new car sales in 2018.[52] By sales volume, Norway is followed by Germany, United Kingdom, and France. Some reports predict that Europe's EV market will continue to grow due to domestic automaker commitments and tightening fuel economy regulations (BloombergNEF 2019).

U.S. light EV sales grew from 115 thousand units in 2015 to 361 thousand in 2018 (33 percent CAGR). Its penetration rates grew from 0.7 percent in 2015 to 2.1 percent in 2018. The U.S. market almost doubled to 361 thousand EV units in 2018 from 200 thousand in 2017, which was faster than that global market growth rate. This was mainly on strong sales of Tesla's Model 3, which accounted for 134 thousand BEVs sold in 2018, reflecting a large backlog of orders and EV tax credits. However, the backlog is now exhausted and there is a proposed federal rule[53] that loosens fuel economy standards and removes California's state authority to set stricter vehicle emission standards under the Clean Air Act. (Hertzkeet al. 2019).

[52] Norway's share is more than double than that of Iceland (a very small market, by volume), which has the second-largest market share at 17-percent of its new car sales. Norway's EV fleet is—and has been for several years—the largest per capita in the world; EVs were one out of three vehicles sold in 2018 (Norway's total new passenger car sales were 147,929, relative to that of the United States with 17.3 million in 2018). Norway's public incentives make EV purchases competitive with ICE vehicles, including certain fee exemptions (such as purchase tax and 25 percent VAT) and tax reductions.

[53] The proposed federal rule rolls-back current fuel economy standards (set to hit an average of 54.5 miles per gallon for passenger cars and trucks by 2025) by freezing them at 2020 levels through 2026. USEPA. "The Safer Affordable Fuel Efficient (SAFE) Vehicles Proposed Rule for Model Years 2021–2026," https://www.epa.gov/regulations-emissions-vehicles-and-engines/safer-affordable-fuel-efficient-safe-vehicles-proposed, accessed February 28, 2020.

Appendix B: Government Programs

Some government programs related to EVs are at the national level, while others are implemented at local levels. The following discussion provides information on programs in China, EU, Norway, and the United States.

China

Government emissions regulations have provided incentives for EV investments by automakers. China's leadership on EVs in all market segments is reflected by its aggressive policy support (IEA 2019a). China reportedly spent $58 billion on direct and indirect subsidies through 2018, keeping EV prices artificially low (Moss 2019). China's New Energy Vehicle (NEV) mandate, which took effect in April 2018, has set a quota for the number of zero-emissions vehicles that automakers must sell and provides credit targets for those that exceed these quotas so that they can sell them to companies that do not make their quotas (Steer 2018). China has also tightened the average fuel economy for light-passenger vehicles (effective by 2025)[54] and restricted investments toward new ICE vehicle manufacturing plants (IEA 2019a; IHS Markit 2019). In addition, EVs must account for about 3–4 percent of Chinese automaker's 2019 production, with gradual annual increases (Moss 2019). Policy support to firms with the batteries with the best performance has consolidated battery manufacturers and stimulated technological innovation (IEA 2019).

Since 2013, China's subsidy program has encouraged automakers to sell more EVs, which lowered the EV purchase price below manufacturing costs (and below prices for similar ICE vehicles) to the point that the country is now the global leader. However, these subsidies produced excess capacity and in March 2019, the government announced a phase-out of blanket EV production subsidies in favor of performance-based subsidies (including incentives for increasing battery range). Consequently, EV sales dropped in 2019 (Moss 2019; Barrett 2019; Shepherd 2019).

European Union (28)

The EU's member states recently agreed to the Clean Vehicles Directive 2019/1161 (requires public procurement of electric buses) and the 2018 amendment to the Energy Performance Directive 2012/27 (minimum requirement for EV charging infrastructure in new and renovated buildings) (IEA 2019a). The EU also approved a carbon-dioxide reduction target of 37.5 percent (compared with 2021) in car emissions by 2030 (Baik et al. 2019).

In addition to its EU-wide policies, most EU members offer tax reductions or exemptions. There are twelve member states that also offer purchase incentives.[55] Only four member states do not offer any tax benefits or incentives on EV purchases and consequently have low EV market shares—Croatia (N/A), Estonia (0.5 percent), Lithuania (0.4 percent), and Poland (0.2 percent) (ACEA, 2019).

[54] China's automakers are required to comply with a corporate average fuel economy (CAFE) target that is a 42-percent reduction from the 2015 level.
[55] These countries are Austria, Belgium, Finland, France, Germany, Ireland, Italy, Romania, Slovenia, Spain, Sweden, and the United Kingdom.

Norway

Norway's EV market success reflects substantial incentives to promote zero-emission vehicle sales, including tax exemptions—purchase and import tax, 25–percent VAT, annual road tax—as well as many other benefits until 2021, such as 50-percent of road and ferry tolls, 50-percent parking fees (Norsk elbilforening., n.d.).

United States

The United States government and several states offer financial incentives, such as tax credits, to lower the purchase costs of EVs. The Internal Revenue Service (IRS) tax credit is for up to $7,500 per new EV purchase, which phases-out after 200,000 EVs have been sold.[56] Several locations have additional tax credits (such as Colorado, Louisiana, Maryland, and New York), some offer excise tax and inspection exemptions (District of Columbia and North Carolina), and others provide free access to the carpool lane and parking (Arizona, Hawaii, and California). However, other locations (such as Alabama) charge annual EV ownership fees in additional to registration fees to offset the cost of building infrastructure (e.g., charging stations) (USDOE, n.d.).

[56] Each automaker is eligible for $7,500 in tax credits for each EV it sells, up to 200,000 in sales. Six months after that amount of sales, the tax credit is halved ($3,750) and then six months later it is halved ($1,875) again and then it is reduced to zero.

Appendix C: Tables, Measures by Key Material

Table C.1 Unprocessed lithium trade measures, percent of value, 2018

Country	Coverage ratio: Unprocessed imports to unprocessed exports	Unprocessed exports to all lithium exports	Unprocessed imports to all lithium imports	Trade in unprocessed to all lithium trade	Unprocessed exports to all goods exports	Unprocessed imports to all goods imports	Trade in unprocessed to all goods trade
Argentina	49,980.1	0.0	44.5	9.5	0.0	0.0	0.0
Australia	1.1	99.6	62.4	99.0	0.5	0.0	0.2
Chile	280.7	0.1	45.8	0.3	0.0	0.0	0.0
China	1,015.7	12.4	77.5	52.7	0.0	0.1	0.0
Japan	827.4	22.6	11.3	12.0	0.0	0.0	0.0
Korea, Republic of	487.0	27.4	9.1	10.3	0.0	0.0	0.0
United States	62.2	32.1	25.2	29.0	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

Table C.2 Processed lithium trade measures, percent of value, 2018

Country	Coverage ratio: processed imports to processed exports	Processed exports to all lithium exports	Processed imports to all lithium imports	Trade in processed to all lithium trade	Processed exports to all goods exports	Processed imports to all goods imports	Trade in processed to all goods trade
Argentina	2.7	87.6	0.0	70.8	0.1	0.0	0.0
Australia	3,343.8	0.0	0.0	0.3	0.0	0.0	0.0
Chile	0.0	88.6	0.0	88.3	1.2	0.0	0.7
China	219.2	14.1	0.0	17.2	0.0	0.0	0.0
Japan	37,773.6	1.9	0.0	40.6	0.0	0.0	0.0
Korea, Republic of	2,418.0	34.2	0.1	55.3	0.0	0.1	0.0
United States	550.2	5.7	0.0	20.8	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

Table C.3 Refined lithium trade measures, percent of value, 2018

Country	Coverage ratio: refined imports to refined exports	Refined exports to all lithium exports	Refined imports to all lithium imports	Trade in refined to all lithium trade	Refined exports to all goods exports	Refined imports to all goods imports	Trade in refined to all goods trade
Argentina	102.4	12.4	46.8	19.7	0.0	0.0	0.0
Australia	111.4	0.4	23.2	0.8	0.0	0.0	0.0
Chile	1.8	11.3	50.5	11.5	0.2	0.0	0.1
China	7.8	73.5	3.5	30.1	0.0	0.0	0.0
Japan	997.9	75.5	45.7	47.4	0.0	0.0	0.0
Korea, Republic of	1,296.6	38.4	34.1	34.4	0.0	0.1	0.0
United States	44.9	62.1	35.1	50.2	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

Table C.4 Artificial graphite trade measures, percent of value, 2018

Country	Coverage ratio: unprocessed imports to unprocessed exports	Artificial graphite exports to all graphite exports	Unprocessed imports to all graphite imports	Trade in unprocessed to all graphite trade	Unprocessed exports to all goods exports	Unprocessed imports to all goods imports	Trade in unprocessed to all goods trade
Australia	n/a	n/a	98.7	98.6	n/a	0.1	0.1
Canada	1,441.4	35.4	89.6	81.5	0.0	0.0	0.0
China	37.9	53.5	54.4	53.7	0.0	0.0	0.0
India	338.6	86.4	90.2	89.3	0.0	0.1	0.1
Indonesia	118.8	98.9	57.8	71.3	0.0	0.0	0.0
Japan	198.1	8.2	16.8	12.4	0.0	0.0	0.0
Korea, Republic of	2,461.7	0.3	2.0	1.7	0.0	0.0	0.0
Mexico	23,497.5	3.3	85.9	77.7	0.0	0.0	0.0
United States	5.9	88.9	21.3	75.4	0.1	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

Table C.5 Natural graphite trade measures, percent of value, 2018

Country	Coverage ratio: Natural graphite imports to unprocessed exports	Natural graphite exports to all graphite exports	Natural graphite imports to all graphite imports	Trade in natural graphite to all graphite trade	Natural graphite exports to all goods exports	Natural graphite imports to all goods imports	Trade in natural graphite to all goods trade
Australia	43,584.7	1.0	0.4	0.4	0.0	0.0	0.0
Canada	30.5	42.3	2.3	8.2	0.0	0.0	0.0
China	15.9	20.4	8.7	17.2	0.0	0.0	0.0
India	9,462.1	0.2	5.1	3.9	0.0	0.0	0.0
Indonesia	n/a	0.0	7.6	5.1	0.0	0.0	0.0
Japan	1,275.9	2.5	33.0	17.5	0.0	0.0	0.0
Korea, Republic of	5,953.7	1.7	27.5	22.0	0.0	0.0	0.0
Mexico	93.9	21.8	2.3	4.2	0.0	0.0	0.0
United States	275.8	1.0	10.9	3.0	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

Table C.6 Refined graphite trade measures, percent of value, 2018

Country	Coverage ratio: Refined imports to refined exports	Refined exports to all graphite exports	Refined imports to all graphite imports	Trade in refined to all graphite trade	Refined exports to all goods exports	Refined imports to all goods imports	Trade in refined to all goods trade
Australia	1,089.1	99.0	0.9	1.0	0.0	0.0	0.0
Canada	208.2	22.3	8.2	10.3	0.0	0.0	0.0
China	52.5	26.2	36.9	29.1	0.0	0.0	0.0
India	112.8	13.4	4.7	6.7	0.0	0.0	0.0
Indonesia	6,446.5	1.1	34.6	23.6	0.0	0.0	0.0
Japan	54.3	89.3	50.2	70.1	0.0	0.0	0.0
Korea, Republic of	265.0	98.0	70.5	76.3	0.0	0.0	0.0
Mexico	142.5	74.9	11.8	18.1	0.0	0.0	0.0
United States	166.9	10.1	67.8	21.6	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

Table C.7 Unprocessed cobalt trade measures, percent of value, 2017

Country	Coverage ratio: Unprocessed imports to unprocessed exports	Unprocessed exports to all cobalt exports	Unprocessed imports to all cobalt imports	Trade in unprocessed to all cobalt trade	Unprocessed exports to all goods exports	Unprocessed imports to all goods imports	Trade in unprocessed to all goods trade
China	251,314.5	0.0	13.0	10.8	0.0	0.0	0.0
Congo, Dem. Rep.	0.0	16.5	22.8	16.5	3.8	0.0	2.3
United States	43.2	1.6	0.1	0.3	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed March 4, 2020; USITC staff calculations.

Table C.8 Refined cobalt trade measures, percent of value, 2017

Country	Coverage ratio: Refined imports to refined exports	Refined exports to all cobalt exports	Refined imports to all cobalt imports	Trade in refined to all cobalt trade	Refined exports to all goods exports	Refined imports to all goods imports	Trade in refined to all goods trade
China	428.4	100.0	87.0	89.2	0.0	0.1	0.1
Congo, Dem. Rep.	0.0	83.5	77.2	83.5	19.1	0.0	11.4
United States	607.2	98.4	99.9	99.7	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed March 4, 2020; USITC staff calculations.

Table C.9 Unprocessed nickel trade measures, percent of value, 2018

Country	Coverage ratio: Unprocessed imports to unprocessed exports	Unprocessed nickel exports to all nickel exports	Unprocessed nickel imports to all nickel imports	Trade in unprocessed to all nickel trade	Unprocessed exports to all goods exports	Unprocessed imports to all goods imports	Trade in unprocessed to all goods trade
Australia	0.0	24.1	0.0	22.7	0.1	0.0	0.0
Canada	140.8	6.6	78.3	14.1	0.0	0.0	0.0
China	13,651,694.6	0.0	47.6	45.5	0.0	0.1	0.1
Finland	87.9	26.6	98.0	40.4	0.3	0.2	0.3
Norway	0.0	0.1	0.0	0.1	0.0	0.0	0.0
Russia	0.0	2.1	0.0	2.1	0.0	0.0	0.0
United States	0.1	42.0	0.0	10.0	0.0	0.0	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

Table C.10 Refined nickel trade measures, percent of value, 2018

Country	Coverage ratio: Refined imports to refined exports	Refined nickel exports to all nickel exports	Refined nickel imports to all nickel imports	Trade in refined nickel to all nickel trade	Refined exports to all goods exports	Refined imports to all goods imports	Trade in refined to all goods trade
Australia	8.4	75.9	100.0	77.3	0.2	0.0	0.1
Canada	2.7	93.4	21.7	85.9	0.4	0.0	0.2
China	1,162.1	100.0	52.4	54.5	0.0	0.2	0.1
Finland	0.6	73.4	2.0	59.6	0.8	0.0	0.4
Norway	0.3	99.9	100.0	99.9	1.0	0.0	0.6
Russia	1.4	97.9	100.0	97.9	0.4	0.0	0.3
United States	555.0	58.0	100.0	90.0	0.0	0.1	0.0

Source: IHS Markit, Global Trade Atlas, accessed August 16, 2019; USITC staff calculations.

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