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Global Value Chains: Cobalt in Lithium-ion Batteries for Electric Vehicles

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Abstract

Cobalt is critically important to the cathode composition of lithium-ion batteries (LIB), which power electric vehicles. This paper examines the global value chain (GVC) for cobalt as part of a five-part series of working papers, that together, map out the global sources of mining, refining, and the value added for the key LIB raw materials. The results show that the unrefined (upstream) and refined (downstream) product value chains are dominated by two players—The Democratic Republic of Congo and China.

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Introduction

This article is one of a series of five working papers examining the global value chains (GVCs) for the key raw materials—cobalt, lithium, graphite, and nickel—that are critical to the composition of lithium-ion batteries (LIBs) that power electric vehicles (EVs).[1] In recent years, global trade in cobalt ores and refined cobalt products used in LIBs has increased, and global prices for these materials have been highly volatile. There have also been concerns regarding the security of cobalt supplies due to the political instability of the Democratic Republic of the Congo (DRC), the world's largest source of mined cobalt (HS 2605.00), as well as the concentration of global cobalt refining capacity in China. In general, cobalt ores mined in the DRC are transported to refineries in China and other countries where they are processed into refined cobalt (e.g., HS 2822.00, HS 8105.20). These refined chemicals are important materials used to manufacture the cathode material of LIBs, which are used to power EVs.[2]

This paper provides an overview of the global cobalt industry and the value added to cobalt as it moves through the global supply chain from its cobalt-bearing metal ore form to a refined product. The paper explains the product's attributes, sources, processing, and global market. In terms of organization, the paper first provides an overview of the role of cobalt in LIBs. The second section discusses the methods for mining and processing cobalt ores and concentrates (HS 2605.00) into refined products such as cobalt oxides and hydroxides (HS 2822.00) and unwrought cobalt (HS 8105.20). Two geographic case studies are then provided: one study is on the DRC, the largest source of cobalt ores and concentrates (HS 2605.00) and the second is on China, the world's largest producer of cobalt oxides and hydroxides (HS 2822.00) and refined cobalt (HS 8105.20). Finally, the last section discusses the global value chain indicators associated with trade in this intermediate good.

The main materials discussed throughout this paper are traded at the global Harmonized System (HS) 6-digit subheading level include cobalt ores and concentrates (HS 2605.00); referred to as "unrefined," cobalt oxides and hydroxides (HS 2822.00); and refined (i.e. unwrought) products of cobalt metallurgy (HS 8105.20). These two products (HS 2822.00 and 8105.20) are collectively referred to as "refined" (see table 1). While another refined cobalt product—cobalt sulfate—is widely used in the manufacturing of LIB cathodes, trade data for this product are not presented or discussed throughout this paper because

[1] This paper uses the terms "global value chain" (GVC) and "global supply chain." Global supply chains are similar to global value chains—and have some overlap—but are a slightly different concept. Supply chains generally entail a focus on logistics—moving the original material, through sourcing, refinement if necessary, and transport, to a final product that is delivered to the customer. Unlike global value chains, global supply chains do not entail analysis of the value added during the different stages of manufacture, but rather the path the product follows from inception to final delivery (Scott and Ireland, forthcoming). Forthcoming working papers by the USITC staff in the Natural Resources and Energy Division of the Office of Industries are related to the global value chains for three other key materials—lithium, nickel, and graphite—used in the production of lithium-ion batteries cell. An overview paper will introduce these materials and the global value chain for these products.

[2] In an electrocyclic cell, which includes batteries, the cathode is a positive (oxidizing) electrode that acquires electrons, in this case lithium-ions, through the external circuit and is reduced as part of the electrochemical reaction.

trade in this product is not measured or reported at the HS 6-digit level, the most detailed level at which global trade data is harmonized.[3]

Table 1 Cobalt products, by HS subheading and country source

Cobalt material	HS Subheading	Source(s)	Description
"Unrefined" Raw cobalt ores and concentrates	2605.00	DRC (Russia, Australia, Canada, and Cuba to a lesser extent)	Raw ores and concentrates obtained as a byproduct from nickel and copper mining operations
"Refined" cobalt oxides and hydroxides	2822.00	China (Belgium to a lesser extent)	Refined product processed from cobalt ores and concentrates
"Refined" Unwrought cobalt	8105.20	China (Finland, Belgium, and Canada to a lesser extent)	Refined cobalt product processed from cobalt ores and concentrates.

Source: IHS Markit, Global Trade Atlas (accessed September 24, 2019).
Note: Global trade data for cobalt sulfates, another form of refined cobalt, are not harmonized at the six-digit level. HTS 2833.29.1000 is the U.S. Harmonized Tariff Schedule statistical reporting number for U.S. imports of cobalt sulfate.

Electric Vehicle Lithium-Ion Batteries

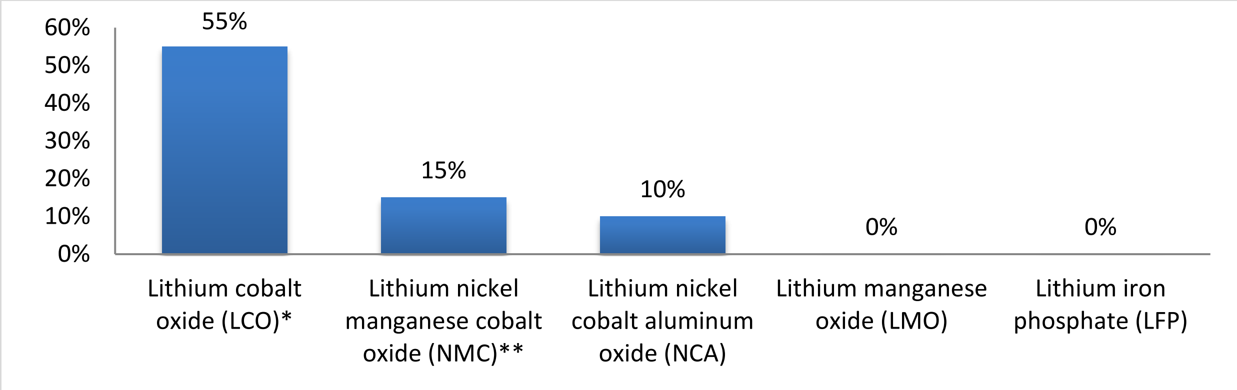
Lithium-ion batteries (LIBs) power electric vehicles (EVs) and nearly all consumer electronics. Consumers demand EVs for their potential to reduce carbon dioxide (CO_2) emissions and other pollutants released by conventional vehicles (with internal combustion engines, ICE). In addition, EV demand growth partly reflects LIB cost improvements in the global supply chain for key LIB materials, battery technology innovations, and government incentives to defray costs (Scott and Ireland, forthcoming).

Previous research has examined the importance of EV batteries (particularly LIBs) and their inputs, as well as the structure of the global EV battery supply chain. Coffin and Horowitz (2018) note the supply chain for EVs is similar to traditional internal combustion engine (ICE) passenger vehicles, however unlike ICE passenger vehicles which compete based on engine and transmission, EVs compete based on their battery types. The most common LIB composition for EVs is lithium-nickel-manganese-cobalt-oxide ("NMC"), however it should be noted that lithium-nickel-cobalt-aluminum oxide ("NCA") batteries are found in the best-selling EVs in the United States.[4] The difference between the LIBs is their composition (see figure 1) which contributes to variances in battery properties such as specific energy density comparing NMC and NCA. Research by DeCarlo and Matthews (2019) highlights the importance of cobalt as a material in both NMC and NCA batteries, as well as the global supply constraints for cobalt used in these battery types.[5] Both papers indicate that a projected rise in global demand for EVs and

[3] The United States Harmonized Tariff Schedule statistical reporting number for cobalt sulfate is 2833.29.1000. In 2018 and 2019, U.S. imports of cobalt sulfate totaled $17.2 million and $8.8 million, respectively, while U.S. imports of all products classified under HS 6-digit subheading 2833.29 totaled $193.2 million and $132.7 million, respectively. USITC DataWeb/USDOC (HTS subheading 2833.29 and 2833.29.1000; accessed May 15, 2020).
[4] Coffin, David, and Jeff Horowitz, "The Supply Chain for Electric Vehicle Batteries," December 2018, 3.
[5] DeCarlo, Samantha, and Daniel Matthews, "More Than a Pretty Color-The Renaissance of the Cobalt Industry," February 2019, 9.

their increasing share of the global automobile market will likely lead to a rise in demand for LIBs and their respective inputs (e.g. cobalt).[6]

Figure 1 Refined cobalt composition share in selected lithium-ion batteries, by volume, 2017



Source: Visual Capitalist, January 2017.
Notes: *LCO batteries have the highest concentration of cobalt, however they are not commonly used in EVs. **NMC batteries are commonly used in EVs and electric motorbikes.

Cobalt's Attributes and LIB Role

Cobalt is a metal valued for its hardness, resistance to corrosion, high energy density relative to other metals, and its ability to withstand high temperatures.[7] End uses for cobalt include a variety of commercial and industrial applications, including catalysts for the chemical and petrochemicals industries, superalloys for gas turbines and aerospace engines, batteries for electronic devices and vehicles (particularly EVs), and cemented carbides, among others.[8]

Cobalt is a key material used in one of the most widely recognized battery types—LIBs. According to one estimate, cobalt helps the battery retain about 80 percent of its power capacity after several thousand recharging cycles, thereby extending the standard lifetime of the battery.[9] This attribute is important for the EV manufacturing industry where there is a demand for lighter, more powerful batteries that can extend vehicle-driving range.[10]

[6] Coffin and Horowitz, "The Supply Chain for Electric Vehicle Batteries," December 2018, 16; DeCarlo and Matthews, "More Than a Pretty Color-The Renaissance of the Cobalt Industry," February 2019, 6-8, 17.
[7] Royal Society of Chemistry, "Periodic Table: Cobalt" (accessed September 5, 2018).
[8] Other end uses for cobalt include steel alloys, tool materials, pigments, magnets, and soaps. Battery University, "BU-310: How Does Cobalt Work in Li-ion?" accessed December 30, 2019; Shedd, "Cobalt Statistics and Information," July 25, 2018.
[9] Rajamanickam, "The Future of Electric Vehicles Lies in the Sourcing of Lithium and Cobalt for Batteries," August 1, 2018.
[10] Ramsey, "Energy Density of EV and Gasoline Powertrains will Converge," May 18, 2016.

There are several types of LIB chemistries, some of which do not use cobalt. Of the five major types of LIB cells listed in figure 1, NMC and NCA are the commonly used LIBs in EVs.[11] According to various industry sources, NMC batteries, particularly NMC-622, is the most common type of LIB used in EVs.[12]

Cobalt Refining Process

The primary mineral feedstocks of cobalt are copper-cobalt sulfide ore, cobalt-nickel sulfide concentrate, arsenide ore, and nickel-laterite ore—all of which use a different refining process to extract the cobalt from the ore (HS 2605.00).[13] Large industrial-scale miners and smaller artisanal miners in the DRC obtain cobalt from copper-cobalt sulfide ores (see figures 2 and 3). Copper-cobalt sulfide ores (HS 2605.00) are the most common source of cobalt ores; the refining process for these products begins by using a separation flotation process that creates air bubbles that carry mineral particles to the surface.[14] Refiners then use chemical reagents that attract cobalt to the bubbles—separating them from the copper. Certain miners complete these first steps of the refining process on site or near the mine; together, these processes result in an unrefined cobalt concentrate (HS 2605.00).[15] Unrefined cobalt concentrate is further refined into cobalt metal (e.g. HS 8105.20) and chemicals (e.g. HS 2822.00) using a pyrometallurgical or hydrometallurgical extractive process.[16] This step in the refining process takes place in regions other than where the original mining occurred, usually China, and to a lesser extent, Finland (see page 11). Once it undergoes a pyrometallurgical or hydrometallurgical extractive process, the refined cobalt (e.g., HS 2822.00, HS 8105.20) is then used in the production of battery precursor materials (i.e. cathodes) in China, Japan, and South Korea, for LIBs in electric vehicles and other applications (figures 2 and 3).

[11] While lithium-cobalt oxide (LCO) batteries have the highest share of cobalt in the cathode (up to 55 percent), these batteries are more common in smart phones, laptops, and cameras. DeCarlo and Matthews, "More Than a Pretty Color-The Renaissance of the Cobalt Industry," February 2019, 5.

[12] In NMC-622 lithium ion batteries, nickel makes up 60 percent of the active material, while manganese and cobalt make up 20 percent of the active material. Kay, "6 Lithium-ion Battery Types," July 23, 2018.

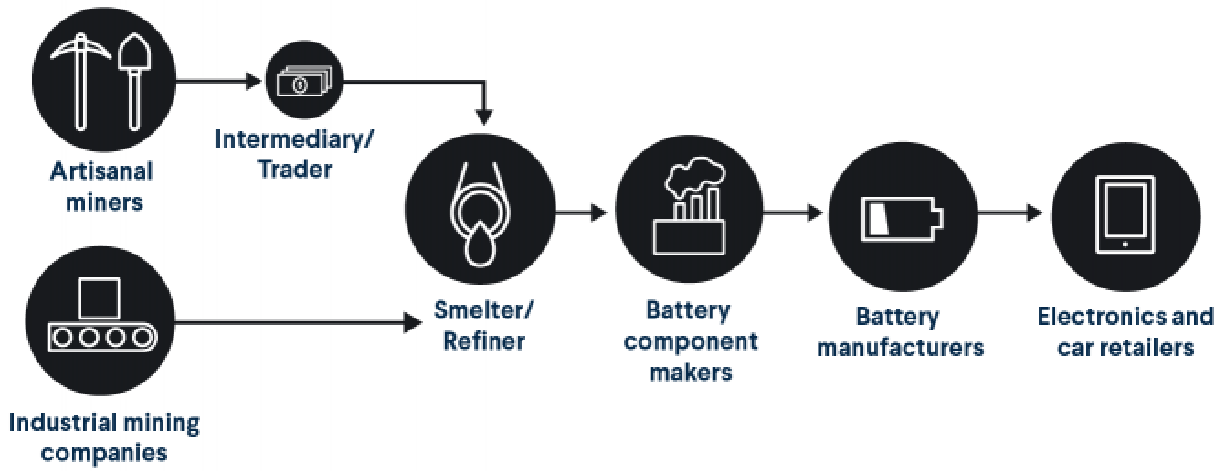
[13] Historically, cobalt has been mined as a secondary product in the mining of copper and nickel. Other potential sources of cobalt ores and concentrates include manganese-cobalt rich nodules along the ocean floor; however, current technological limitations prevent producers from accessing these sources. Cobalt Institute, "Ores Containing Cobalt" (accessed August 3, 2018). Bell, "Cobalt Metal – Properties, Production, and Applications," March 28, 2018.

[14] Trade data for copper-cobalt sulfide ores and other ores that cobalt is commonly found in may be captured in HS subheadings other than HS 2605.00.

[15] In fact, there is evidence that suggests this is becoming more widespread throughout the DRC. These firms then export the refined product (usually cobalt oxides and hydroxides (HS 2822.00)) to other markets, but primarily China.

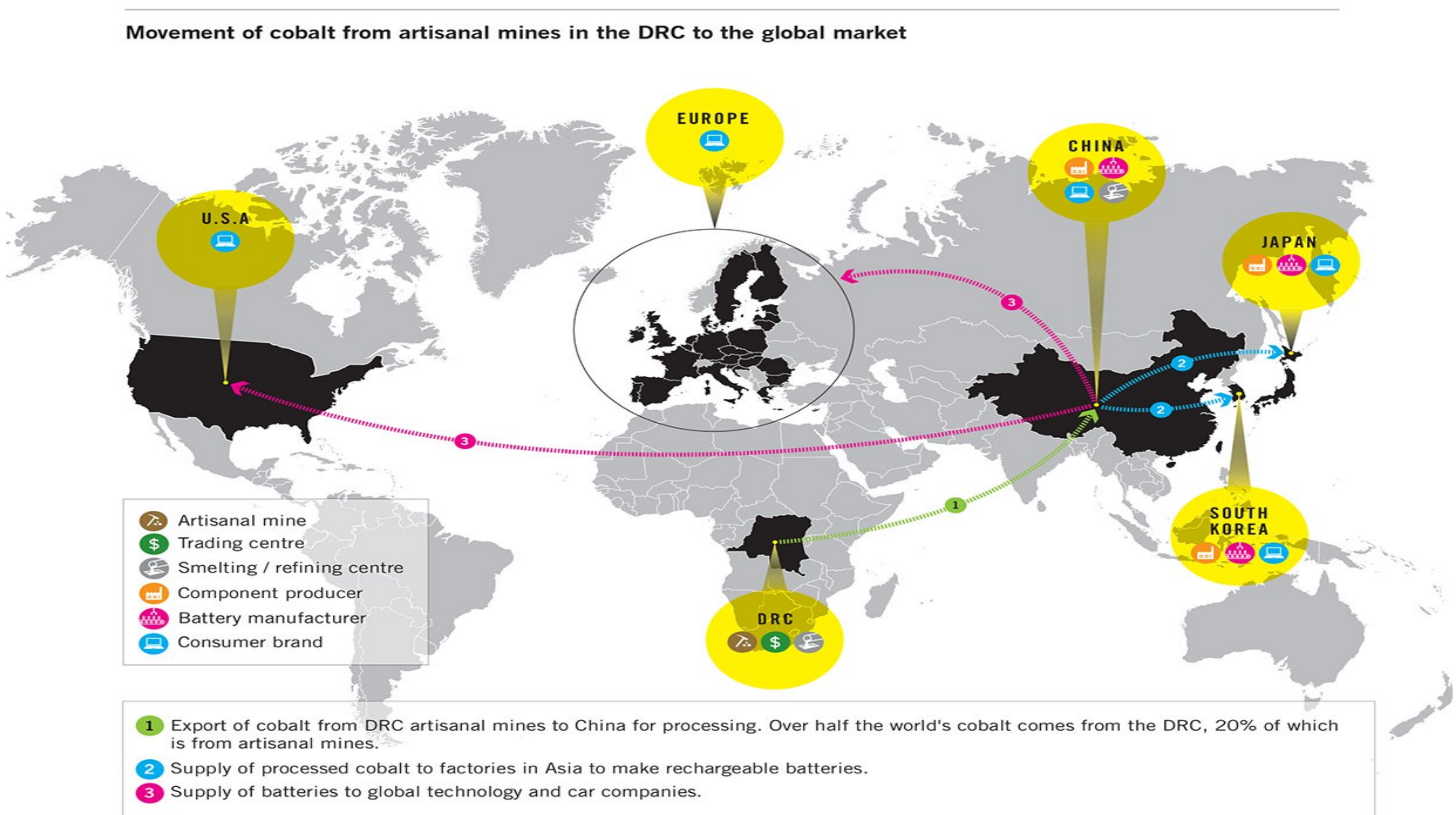
[16] Encyclopedia Britannica, "Cobalt Processing" (accessed August 6, 2018).

Figure 2 Cobalt processing for batteries and other electronic devices



Source: Felter, "The Cobalt Boom," June 15, 2019.

Figure 3 Overview of the global supply chain for cobalt used in batteries



Source: DeWinter-Schmitt, "What Do You Know About Batteries" (accessed May 18, 2020).

Major Sources of Unrefined Cobalt

As mentioned earlier, unrefined cobalt (cobalt ores and concentrates, HS 2605.00) is produced largely as a byproduct of copper and nickel mining. Unrefined cobalt is principally found in the African copper-belt region (primarily the DRC), Russia, Cuba, Australia, and the Philippines—all countries that have an abundance of copper and/or nickel deposits (figure 4).[17] Most of the world's largest cobalt mining firms (including Glencore, China Molybdenum (CMOC) International, Fleurette Group, and Gécamines) have active copper mining operations throughout the DRC.[18] Another firm—Vale—also produces unrefined cobalt, however, it is not active in the DRC and obtains cobalt from nickel mining operations in Canada. In addition to its facilities in the DRC, Glencore also has cobalt mining operations in Australia and Zambia, while smaller producers account for the remaining production in Cuba, and Philippines. Table 2 presents an overview of the estimated unrefined cobalt production (HS 2605.00) by major mining firms, and figure 4 presents the largest sources of unrefined cobalt, by country.

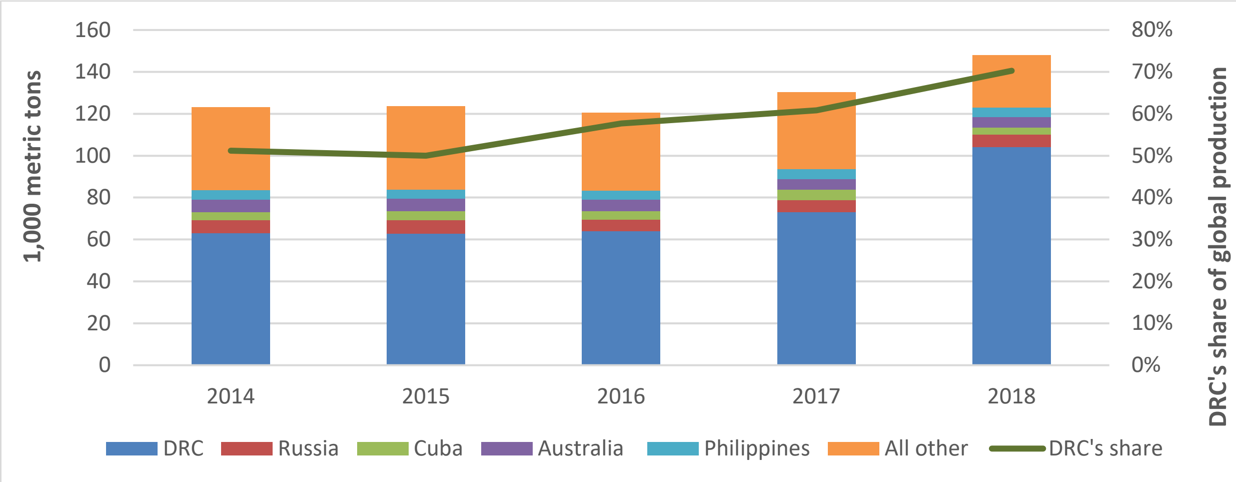
Table 2 Major cobalt mining (HS 2605.00) firms, headquarters, active operations (by country) and 2018 estimated production

Firm	Headquarters	Countries with active mining operations	2018 production (metric tons)
Glencore	Baar, Switzerland	Australia, DRC, Zambia	42,200
CMOC	Luoyang, China	DRC	18,747
Vale	Rio de Janeiro, Brazil	Canada, New Caledonia (French territory)	5,093
Gécamines	Lubumbashi, DRC	DRC	4,167
Eurasian Resources Group	Luxembourg	DRC	3,000

Sources: Glencore, n.d.; p. 61; CMOC, p. 18 n.d.; Vale, 2019 p. 60; Kay, 2018; and Eurasian Resources Group, 2019.
Note: CMOC International is a subsidiary of China Molybdenum Co., Ltd. headquartered in Phoenix, Arizona, United States. Production data for Gécamines are estimated using USGS data for 2015. Data for Eurasian Resources Group are total sales reported for 2017.

[17] Refined cobalt refers to cobalt extracted from copper-cobalt sulfide, cobalt-nickel sulfide, arsenide, or nickel-laterite ores via a pyrometallurgical or hydrometallurgical process, in the form of refined cobalt metal or refined cobalt chemicals. Bell, "Cobalt Metal: Properties, Production, and Applications," March 28, 2018.
[18] Kay, "5 Top Cobalt-mining Companies," July 18, 2018.

Figure 4 Global production of unrefined cobalt (HS 2605.00), metric tons, 2014-18



Source: Shedd, accessed March 16, 2020.

Market Profile: DRC

The DRC is the largest source of unrefined cobalt (HS 2605.00) and accounted for 70 percent of global production in 2018. Stakeholders throughout the global supply chain for LIBs and other products for which cobalt is a raw material have raised concerns about a global reliance on cobalt mined in the DRC due to the country's history of corruption, political volatility, and human rights violations (e.g., forced labor, including of children).[19] Stakeholders throughout the global supply chain for cobalt (including certain miners, refiners, and end users in the automotive and consumer electronics industries) are starting to use blockchain technology to trace cobalt from where it is mined to final end use applications. The use of blockchain technology could provide greater transparency in global supply chains by ensuring less cobalt is sourced from mines and firms that engage in human rights violations.[20]

There are several active miners throughout the DRC, including foreign and domestic firms and their respective subsidiaries, as well as a major state-owned firm (Gécamines) that participates as a joint-venture partner with major foreign mining companies. Table 3 presents a list of firms that mine cobalt ores and concentrates—primarily as a byproduct of copper mining—in the DRC.[21]

[19] Felter, "The Cobalt Boom," June 15, 2019; Gaughran, "Inside the DRC's Artisanal Mining Industry" (accessed May 18, 2020). A 2019 U.S. Department of State report on human rights for the DRC found that "significant" human rights abuses occurred throughout the country, including: unlawful or arbitrary killings, extrajudicial killings by the government; forced disappearances by the government; torture by government; arbitrary detention by the government; harsh and life-threatening prison conditions; political prisoners; forced labor of children; among others. U.S. Department of State, "2019 Country Reports on Human Rights Practices: Democratic Republic of the Congo" (accessed May 18, 2020).
[20] Lewis, "Ford and IBM among quartet in Congo cobalt blockchain project," January 16, 2019; DeCarlo and Matthews, "More Than a Pretty Color-The Renaissance of the Cobalt Industry," February 2019, 15.
[21] The data reflected in this table may not accurately reflect current market conditions has many mines have closed in recent months due to a precipitous drop in global cobalt prices (as is discussed later in this paper).

Table 3 Major cobalt mining firms in the DRC and equity ownership, 2015 (unless otherwise noted)

Firm	Headquarters	Equity ownership	Mining capacity (metric tons)
Mutanda Mining SPRL	Kinshasa, DRC	Glencore International AG (100%)[a]	23,000
Tenke Fungurume Mining SARL	Lubumbashi, DRC	CMOC (80%), Gécamines (20%)[b]	16,000
Katanga Mining Ltd.	Whitehorse, Canada	Glencore International AG (75%), Gécamines (25%)[c]	11,112 (2018 estimated)[d]
Boss Mining SPRL	Lubumbashi, DRC	Eurasian Resources Group (70%), Gécamines (30%)	10,000
La Société pour le Traitement du Terril de Lubumbashi (STL)	Lubumbashi, DRC	Enterprise Générale Malta Forrest SPRL (70%), Gécamines (30%)	5,500
Chemaf SPRL	Lubumbashi, DRC	Subsidiary of Shalina Resources Ltd.	5,000 (2017 estimated)[e]
Ruashi Mining SPRL	Lubumbashi, DRC	Metorex Group (75%) subsidiary of Jinchuan Group[f]	4,400 (2018 estimated)[g]
Congo Dong Fang International Mining SPRL	Lubumbashi, DRC	Zhejiang Huayou Cobalt (100%)	4,400
Compagnie Minière du Sud Katanga	DRC	Gécamines (100%)	4,000
La Générale des Carrières et des Mines (Gécamines)	Lubumbashi, DRC	Government of the DRC (100%)	2,500
Société Minière du Katanga SPRL (Somika)	Lubumbashi, DRC	N/A	2,400
Feza Mining SPRL	Lubumbashi, DRC	China North Industries Corporation (share unknown), Gécamines (share unknown)	1,000

Source: Unless elsewhere specified, information in this table is derived from Yager, 2015.
[a] In 2017, Glencore acquired the remaining 31 percent interest of Mutanda for $524 million. Glencore, 2019, 57.
[b] In January 2019, CMOC agreed to acquire BHR Newwood DRC Holdings for $1.14 billion, which included an additional 24 percent stake in the Tenke Fungurume copper and cobalt mining operations. *Mining Technology*, 2019.
[c] In 2017, Glencore increased its interest in the Kantaga copper and cobalt mining operations from 75.3 percent to 86.3 percent for $38 million. Glencore, 57, accessed September 18, 2019.
[d] Katanga Mining Ltd., 2019, 5.
[e] Chemaf, accessed September 27, 2019.
[f] Ultimate owner of this subsidiary is the Gansu People's Government State-owned Assets Supervision and Administration Commission (Gansu Province, China).
[g] Metorex, accessed September 27, 2019.

The government of the DRC has proposed and enacted various policies intended to promote domestic mining operations, support prices for artisanal miners, and retain a greater share of the revenue generated from the growing demand for the metal. In August 2017, the DRC suspended a value-added tax (VAT) on mining companies' imports of equipment and machinery in order to promote renewed investment in the country's mining industry (which includes cobalt and other metals).[22] However, a new mining code proposed in 2018 included a variety of provisions, including: a cap on firms' ability to repatriate excess capital earned above initial investment amounts; higher taxes and royalties on all active mining operations; and granting the government the authority to acquire up to 10 percent ownership in certain projects.[23] Furthermore, in January 2020, the government of the DRC announced that it would create a new state-owned firm to purchase cobalt directly from artisanal miners in an effort to support cobalt prices after a recent decline.[24] While the VAT suspension on mining equipment was expected to have a positive effect on investment in the mining sector, the new mining code, particularly the increase in royalties, is expected to lead to a decline in foreign investment in the DRC's mining sector and a rise in global prices.[25] Furthermore, the government's efforts to directly purchase cobalt from artisanal miners suggests that it is primarily interested in bolstering prices and retaining a greater share of the revenue generated by rising global demand for cobalt.

In early 2019, the government of the DRC notified major cobalt mining firms that it would introduce an export ban on cobalt and copper concentrates to promote domestic refining operations and retain a greater portion of the value chain. However, following the announcement, various mining firms and a major trade association in the country notified the government that it would be very difficult for firms to process these concentrates in the DRC due to the country's lack of sufficient energy supplies.[26] The refining process requires the direct use of electricity to extract cobalt from mined ores and concentrates, so cobalt refineries need access to reliable sources of energy.[27] The government responded to these concerns by delaying the export ban and announced that it would conduct a review every six months to determine whether it should reinstate the ban.[28]

Energy constraints, however, have not deterred certain foreign-owned firms from investing in value-added refining operations throughout the DRC. Various Chinese firms have constructed cobalt processing plants in the DRC that convert cobalt ores and concentrates into cobalt hydroxide, which is then exported to other markets, particularly China.[29] This has become increasingly evident in global trade data, as further discussed in the trade section of this paper, which shows a significant increase in the DRC's exports of refined cobalt products between 2016 and 2017.

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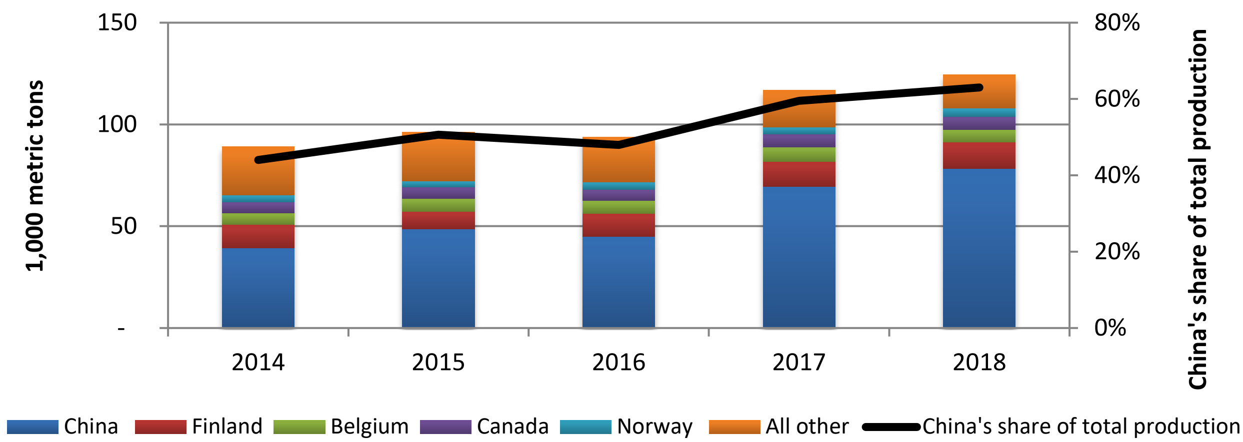
[22] Clowes, "Congo Suspends Value-Added Tax on Mining Imports," August 17, 2017.
[23] Glencore, "Responsibly Sourcing the Commodities for Everyday Life: Annual Report 2018," 28, 165, 176 (accessed September 18, 2019).
[24] Sanderson, "DR Congo to support cobalt prices by buying 'artisanal' supply," January 31, 2020.
[25] Sanderson, "Congo's mining code will raise costs for cobalt consumers — analysts," March 8, 2018.
[26] Hunter and Luk, "DRC Bans Cobalt, Copper Concentrate Exports, Cutting off Zambia Trade," March 20, 2019; Radford, Hunter, and Luk, "DRC U-turns on Cobalt, Copper Concentrate Export Ban," March 21, 2019.
[27] Bleiwas, Donald I, "Estimates of Electricity Requirements for the Recovery of Mineral Commodities, with Examples Applied to Sub-Saharan Africa," 2011, 1.
[28] Hunter and Luk, "DRC Bans Cobalt, Copper Concentrate Exports, Cutting off Zambia Trade," March 20, 2019; Radford, Hunter, and Luk, "DRC U-turns on Cobalt, Copper Concentrate Export Ban," March 21, 2019.
[29] Hunter and Luk, "DRC Bans Cobalt, Copper Concentrate Exports, Cutting off Zambia Trade," March 20, 2019.

Major Sources of Refined Cobalt

According to the Cobalt Institute, China was the world's largest producer of refined cobalt (including but not limited to HS 2822.00 and HS 8105.20) in 2018, accounting for 63 percent of global production.[30] Other major producers of refined cobalt materials in 2018 included Finland, Belgium, Canada, and Norway, which accounted for 10 percent, 5 percent, 5 percent, and 3 percent of global production, respectively. While there are no readily available data for global refined cobalt reserves, global production increased by approximately 35,000 metric tons (or 6.3 percent) during 2014-18, with China accounting for nearly all this increase (figure 5). The cobalt refiners listed below largely rely on imported ores and concentrates from sources in the DRC, Russia, Cuba, and Australia, however refineries in Canada largely source their raw materials as a byproduct of larger nickel mining operations located throughout the country.

Figure 5 Global refined cobalt production, by country, 2014-18 (quantity, percent)



Source: Cobalt Institute, 2019.

While figure 5 above includes production of all refined cobalt products, by country, two refined cobalt products—cobalt sulfate and cobalt oxides (HS 2822.00)—are the primary cobalt-containing inputs for LIB cathodes. According to one source, firms located in China accounted for 80 percent of global cobalt sulfate and cobalt oxides production, while most of the remaining 20 percent was produced at Freeport Cobalt's refinery in Kokkola, Finland.[31] During May 2019, Freeport Cobalt announced that it was selling

[30] Certain refined cobalt products such as cobalt sulfate are not captured in trade data presented throughout this paper because this product is not traded at the global harmonized 6-digit level. Cobalt Institute, "Table 2: Other Refined Cobalt Production/Availability (tonnes)," accessed August 3, 2018.
[31] Global trade data for cobalt sulfate are not discussed throughout this paper because these data are not captured at the global harmonized 6-digit level. Economist, "What if China corners the cobalt market," March 24, 2018. Freeport Cobalt is a joint venture between Freeport McMoran, Lundin Mining Corporation, and Gécamines. Freeport Cobalt, "Connecting the World with Cobalt" (accessed September 16, 2019).

its Kokkola, Finland refinery to Belgium's Umicore for $190 million. Umicore plans to have the Kokkola refinery supply cobalt chemicals to a new LIB cathode-materials facility in Nysa, Poland which will begin operations in 2020.[32]

Chinese cobalt refineries rely almost entirely on imported ores and concentrates from the DRC (figure 8). Major Chinese mining firms such as CMOC,[33] Jinchuan Group,[34] and Zhejiang Huayou Cobalt—through their respective subsidiaries—own and operate mining operations in both countries and supply raw materials to a variety of Chinese cobalt refiners. Major China-based refiners of cobalt used in LIBs and other applications include Zhejiang Huayou Cobalt Co. Ltd. (the world's largest refiner of cobalt),[35] Jiangsu Cobalt Nickel Metal Co. Ltd., [36] and GEM (Jiangsu) Cobalt Industry Co., Ltd. (formerly Shenzhen Green Eco-manufacture Hi-Tech Co. Ltd.).[37] Other major global producers of refined cobalt include Freeport Cobalt (Finland), Glencore (Australia, DRC, and Zambia), Umicore (Belgium and China), Chambishi/ENRC (operations in Zambia), Sumitomo (Japan and Madagascar), Sherritt/ICCI (Canada, Cuba, and Madagascar), and Ambatovy (Madagascar), among others (see table 4).[38]

[32] Scott, Alex, "Umicore Buys Big Cobalt Refinery in Finland," June 1, 2019.
[33] CMOC, "Tenke Fungurume" (accessed August 22, 2018).
[34] Jinchuan Group, "Mining Operations," accessed August 22, 2018.
[35] Pilling, "Pilot Scheme Seeks to Produce First Ethical Cobalt from Congo," March 25, 2018.
[36] In 2016, USGS reported Jinchuan and Huayou as China's largest producers of cobalt and estimated their annual production capacity at 10,000 and 3,000 metric tons, respectively. Xun, "2016 Minerals Yearbook: China," USGS, December 2018.
[37] GEM Co. is a major supplier of cobalt to Chinese LIB manufacturer CATL. Barrera, "Glencore Signs Cobalt Supply Deal with China's GEM," March 15, 2018.
[38] Bell, "The 10 Biggest Cobalt Producers 2014," October 9, 2017; Cobalt Institute, "2017 Production Statistics" (accessed August 22, 2018).

Table 4 Largest producers of refined cobalt, by company and country, 2014-18 (metric tons)

Country	Company	2014	2015	2016	2017	2018
Australia	Glencore	2,900	3,300	3,200	3,000	3,200
Belgium	Umicore	5,850	6,306	6,329	6,987	6,360
Brazil	Votorantim	1,350	1,300	400	46	8
Canada	New Providence	3,210	3,733	3,693	3,601	3,234
	Vale	2,051	1,858	1,851	2,906	2,918
China (total)	[1]	39,292	48,719	45,046	69,600	78,360
DRC	GECAMINES	500	400	400	400	400
	Glencore	2,800	2,900	-	-	-
Finland	Freeport Cobalt	11,452	8,582	11,187	12,221	12,874
France	Eramet	219	133	119	277	48
India	Rubamin	-	-	-	-	-
	[1]	100	150	100	100	100
Japan	Sumitomo	3,654	4,259	4,305	4,159	3,669
Madagascar	Ambatovy	2,915	3,464	3,273	3,053	2,852
Morocco	CTT	1,391	1,722	1,568	1,428	1,619
Norway	Glencore	3,600	3,100	3,500	3,500	4,200
Russia	Norilsk	2,302	2,040	3,092	2,077	1,800
South Africa (total)	[1]	1,332	1,300	1,101	1,062	1,089
Zambia	Glencore	-	-	-	-	-
	Chambishi Metals	4,317	2,997	4,725	2,520	1,613

Source: Cobalt Institute, accessed December 11, 2018.

[1] Firm-level data for China and South Africa are not readily available. Data for all other firms in India not readily available.

Global Cobalt Market Trends

Since unrefined cobalt (HTS 2605.00) is mined primarily as a byproduct of nickel and copper, prices have historically followed pricing trends for those other products (figure 6). In recent years however, refined cobalt (HS 8105.20) prices have been highly volatile due to new sources coming online and a subsequent rise in global supply. During the period of January 2016–May 2018, cobalt prices increased over 300 percent following speculation that there would be a significant rise in demand for LIBs from the EV industry, coupled with political instability in the DRC and general supply constraints. In order to meet this demand, major mining firms and cobalt smelting firms—particularly in China—expanded production capacity. When the anticipated growth in demand did not fully materialize, this build up in production resulted in a global oversupply of cobalt concentrates and intermediate products and a 67 percent decline in global prices between May 2018 and June 2019.[39] Other factors that have contributed to the decline in global cobalt prices include announced efforts to reduce cobalt content in EV battery

[39] China Molybdenum Co., Ltd., "2018 Annual Report," 15.

packs (particularly by producers such as Tesla) and a significant buildup in Chinese stockpiles over the past few years.[40]

Although global refined cobalt (HS 8105.20) prices fell sharply between May 2018 and June 2019, there was a slight increase in the second half of 2019. This is attributed to Glencore's announcement in August 2018 that it would close its Mutanda cobalt mining operation in the DRC as it is no longer economically viable with current prices. Since Mutanda is the world's largest cobalt mining operation, various industry experts believe that prices will continue to rise in the short term as the closure will likely lead to a market deficit in the coming months.[41]

Continued price volatility may further incentivize firms to reduce their exposure to cobalt by adopting new technologies such as LIBs with lower cobalt content and LIB recycling, as well as by finding viable substitutes for LIBs in EVs and other end use applications.[42] For instance, American Manganese Inc. and Umicore have announced plans to extract cobalt from recycled LIBs used in a variety of applications, including cell phones and other electronic devices. Additional research has focused on eliminating cobalt from the batteries by using different metals for the active material in the cathode such as nickel. Further, studies have been centered adopting alternative technologies such as sodium ion batteries and hydrogen fuel cells as substitutes for LIBs in EVs. However, these research efforts and technologies are still in early stages of development and are not yet commercially viable.[43]

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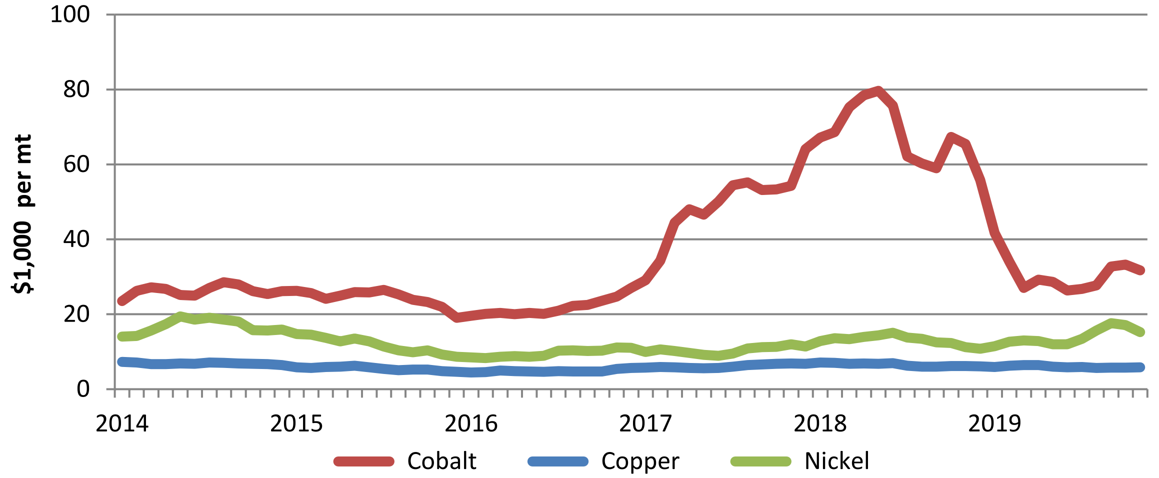
[40] Chinese LIB manufacturers have reportedly been purchasing more cobalt than they consume in order to reduce their exposure to price volatility. Larsen, Nicholas, "Why Have Cobalt Prices Crashed," July 31, 2019. Tesla plans to use new innovations such as low-cobalt and cobalt-free battery chemistries, in addition to new chemical additives and other technologies that will enable batteries to store more energy for longer periods of time. Shirouzou and Lienert, " Exclusive: Tesla's secret batteries aim to rework the math for electric cars and the grid," May 14, 2020.
[41] Sanderson, "Cobalt Rockets as Glencore Plans Closure of Major Mine," August 16, 2019.
[42] The concerns previously discussed, in addition to recent volatile prices, have led to a new drive in battery materials research to find potential alternatives to cobalt, including other metals such as iron, nickel, and manganese, among others. A major constraint to substitutes such as iron and manganese is their lower energy densities compared to cobalt. While nickel accounts for a larger share of the composition of LIB cathodes than cobalt, it has higher processing costs, is less corrosion-resistant, and is more flammable than cobalt. Hirtenstein, "How to Mine Cobalt Without Going to Congo," December 1, 2017; DeCarlo and Matthews, "More Than a Pretty Color-The Renaissance of the Cobalt Industry," February 2019, 15-16.
[43] DeCarlo and Matthews, "More Than a Pretty Color-The Renaissance of the Cobalt Industry," February 2019, 15-16.

Figure 6 London Metal Exchange (LME) prices for refined cobalt (HS 8105.20), copper, and nickel, January 2014–November 2019



Source: S&P Global Platts, 2019.
Note: S&P Global Platts offers a pricing reference for cobalt cathodes based on a survey of producers, merchants and consumers that follows a similar trend to the LME price for cobalt.

Market Profile: China

China—the world's largest producer of refined cobalt, LIBs, and their precursor materials—has played an increasingly important role in the GVC for LIBs used in EVs. In recent years, Chinese firms have acquired major assets in the global cobalt mining (HS 2605.00) and refining industry (e.g., HS 2822.00, HS 8105.20), which are related to policy goals set by the Chinese government to modernize the country's manufacturing industries (i.e. *Made in China 2025*) and to promote the use of renewable energy technologies. As previously discussed, China has developed an extensive cobalt refining industry, and certain Chinese firms have been acquiring mining assets around the world in order to ensure a reliable supply of cobalt ores and concentrates for the country's refining industry. For example, in November 2016, CMOC International acquired a 54 percent stake in the Democratic Republic of the Congo's Tenke copper mine, one of the largest in the world and a major source of cobalt byproduct (HS 2605.00), from U.S.-based Freeport McMoran Inc. In fact, Chinese firms are believed to control seven of the largest mines in the DRC, which directly feed refineries in China. Notably, some of these Chinese firms have also developed refining operations in close proximity to mining operations in the DRC.[44] By acquiring major upstream mining assets in the DRC, Chinese firms have developed a vertically integrated industry whereby they are able to exert a significant degree of control over the global supply chain for cobalt used in LIBs and other applications.[45]

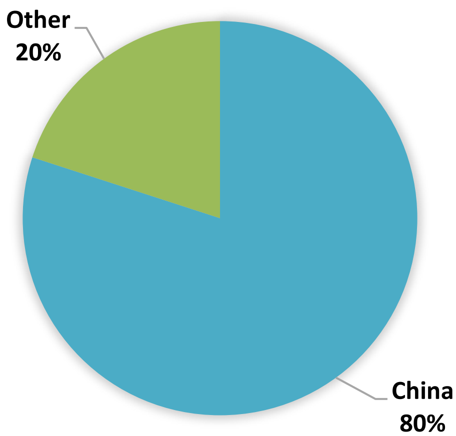
[44] Todd, "China Consolidates Vice-Grip on DRC Mining Sector with $194 Acquisition," October 9, 2019; Hunter and Luk, "DRC Bans Cobalt, Copper Concentrate Exports, Cutting off Zambia Trade," March 20, 2019.
[45] The vertically integrated nature of certain Chinese cobalt refining and mining firms with operations in the DRC and China may affect trade data/flows and the measures discussed later in the paper.

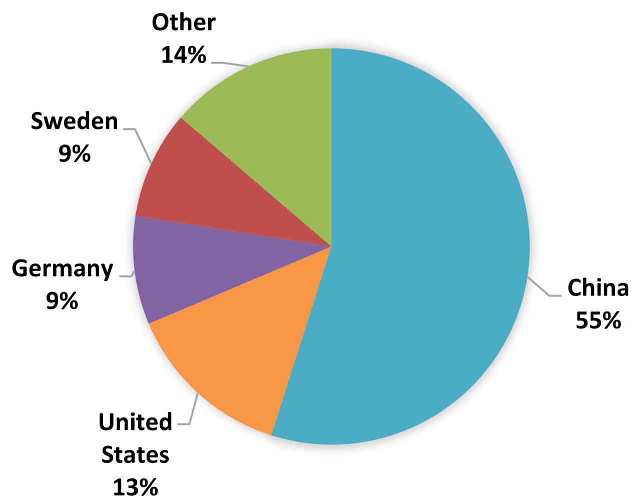
Due to the strategic importance of the EV industry to China's industrial modernization plan known as *Made in China 2025*, the country's demand for both unrefined (HTS 2605.00) and refined cobalt (HTS 8108.20) is expected to rise in the coming years.[46] Currently, China's rechargeable battery industry uses over 80 percent of the cobalt consumed in China.[47] China's *Made in China 2025* program calls for Chinese domestic firms to have 70 percent of the Chinese market for electric vehicles and plug-in hybrids (i.e., new energy vehicles) by 2020, and 80 percent by 2025, as well as for two Chinese firms to be among the world's top ten largest new-energy (primarily electric) vehicle manufacturers.[48]

China reportedly has pursued various policies intended to support the EV manufacturing sector, including subsidies, production quotas, and higher fuel economy standards.[49] To meet its ambitious targets, China has developed a vertically integrated supply chain comprised of both private and state-owned enterprises with domestic and/or foreign mining and refining facilities, as well as LIB and EV manufacturing facilities. According to Japan's Nano Research Institute, China accounted for over 66 percent of global LIB cathode (cobalt-intensive) manufacturing capacity in 2017.[50] Further, Benchmark Mineral Intelligence notes that the country's total share of global cobalt sulfate production and LIB manufacturing could increase to 80 percent and 55 percent, respectively, by 2020 (figure 7). Similarly, China already accounts for 47 percent of the global EV stock.[51]

[46] ReportLinker, "Global and China Cobalt Industry Report, 2018-2023," October 2018.
[47] Shedd, "Cobalt," February 2019.
[48] Economist Intelligence Unit, "The Road Ahead: China's New-Energy Vehicles," October 4, 2017; DeCarlo and Matthews, "More Than a Pretty Color-The Renaissance of the Cobalt Industry," February 2019, 8.
[49] Felter, "The Cobalt Boom," June 15, 2018.
[50] Yano Research Institute Ltd., "Global Market of Major Four LIB (Lithium Ion Battery) Components: Key Research Findings 2018," November 9, 2018.
[51] ZSW, "Global EV Stock" (accessed September 11, 2019).

Figure 7 Forecast for China's share of global cobalt sulfate production (left) and production capacity for LIBs (right), 2020





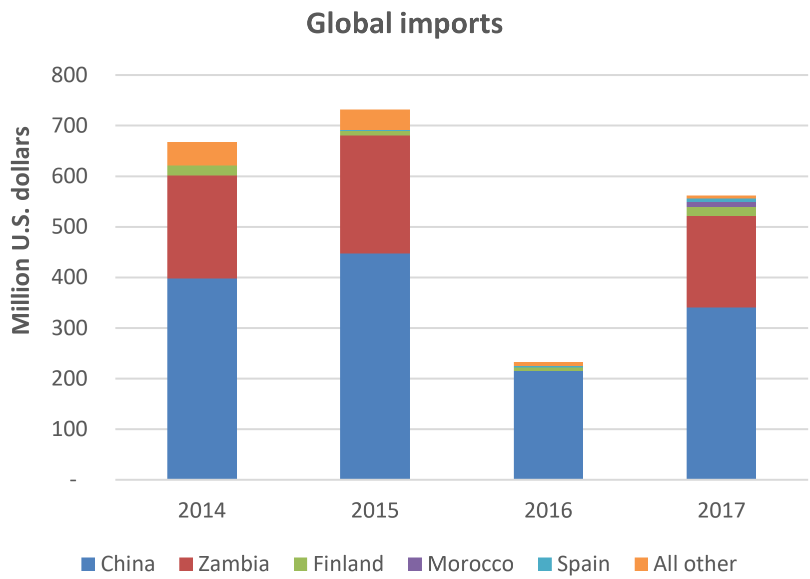
Source: Patterson and Gold, "There's a Global Race to Control Batteries—and China is Winning," February 11, 2018.
Note: Cobalt sulfate (HTSUS statistical reporting number 2833.29.1000) is the principal refined cobalt product used in the production of LIBs.

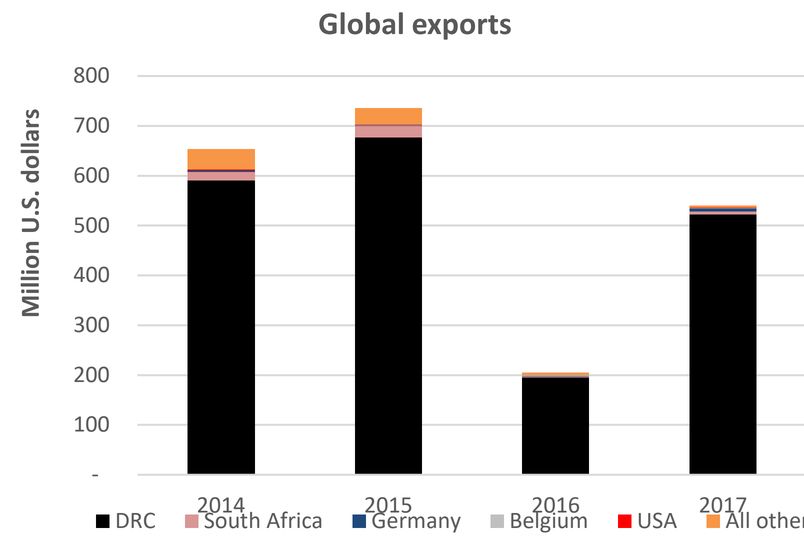
Trade

The GVC for cobalt is heavily concentrated in the DRC (where cobalt mining (HS 2605.00) occurs) and China (which is the predominant producer of refined cobalt products (e.g., HS 2822.00, HS 8105.20) used in LIBs).[52] Most cobalt mined (HS 2605.00) in the DRC is exported to processors in China (and to a lesser extent Zambia, and Finland and other countries) where it is refined into cobalt sulfate, cobalt oxides and hydroxides (HS 2822.00), and unwrought cobalt metal (HS 8105.20) used in the production of LIBs and other products (figure 8). Recently, Chinese producers have constructed cobalt-processing plants in the DRC that convert cobalt ores (HS 2605.00) into cobalt hydroxide, however cobalt miners continue to export significant amounts of mined ores and concentrates (HS 2605.00) to China.[53]

[52] The HS codes examined are not exclusive to cobalt used in EVs. According to IHS Markit's Global Trade Atlas, the most recent year with a world export total (HS 2605.00, 2822.00, and 8105.20) is 2017, at $3.8 billion.
[53] Hunter and Luk, "DRC Bans Cobalt, Copper Concentrate Exports, Cutting off Zambia Trade," March 20, 2019.

Figure 8 Unrefined Cobalt (HS 2605.00), 2014-17, by country and value



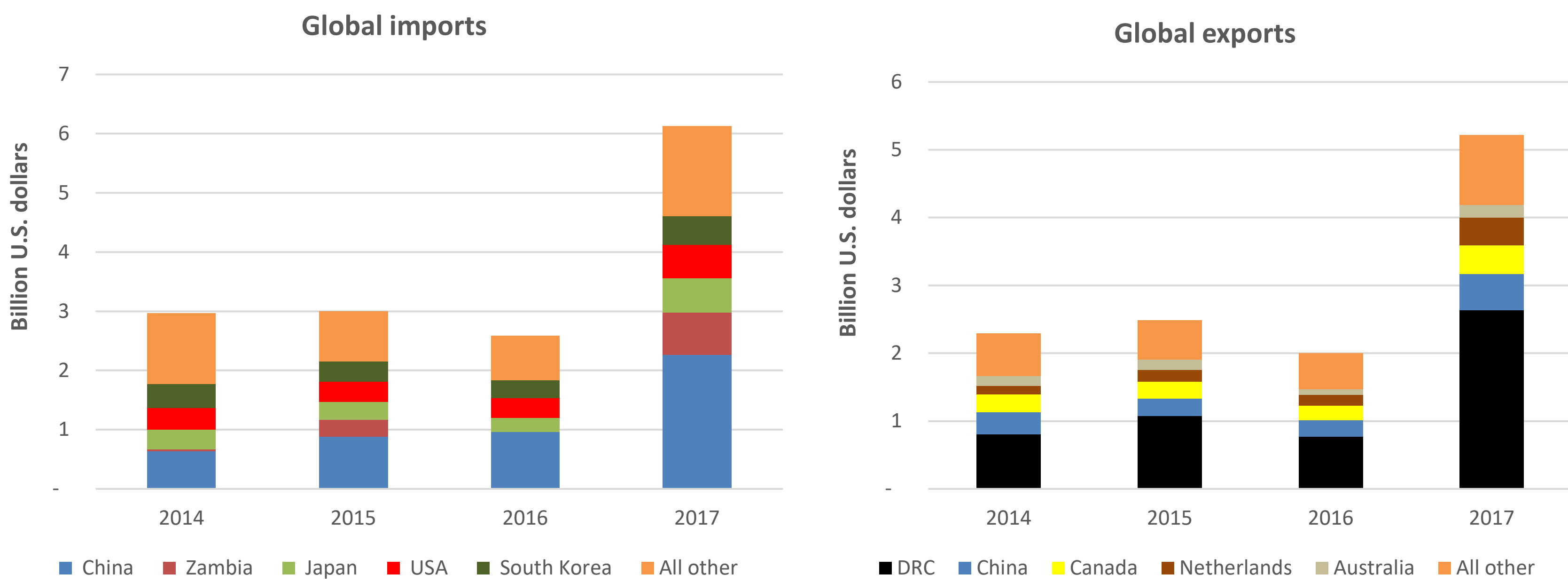


Source: IHS Markit, Global Trade Atlas database, HS subheading 2605.00 (accessed March 5, 2020).
Note: Discrepancies in import and export values are likely due to reporting issues in the Global Trade Atlas. Export figures use "mirror data" for DRC, which are derived using export statistics from partner countries' import data.

As the world's largest refiner and consumer of refined cobalt products (e.g., cobalt oxides and hydroxides, cobalt sulfate, and refined cobalt metal), China is a major importer and exporter of refined cobalt products—sourcing from foreign refineries in the DRC and other countries, and supplying LIB manufacturers and other industrial end-users around the world (figure 8).[54] While both China and the DRC play important roles in the GVC for cobalt used in LIBs, other sources such as those noted in figures 8 and 9 could assume important roles in the supply chain for LIBs if they are able to further develop their cobalt mining and refining capabilities.

[54] These products are classified under HS subheadings HS 2822.00 (cobalt oxides and hydroxides), HTS 2833.29.1000 (cobalt sulfates), and HS 8105.20 (unwrought cobalt). Because global trade data for cobalt sulfate are not harmonized at the 6-digit HS level, they are not discussed throughout this paper.

Figure 9 Refined cobalt (HS 2822.00 and HS 8105.20), 2014-17, by country and value



Source: IHS Markit, Global Trade Atlas database, HS subheadings 2822.00 and HS 8105.20 (accessed March 5, 2020).
Note: Official trade statistics under HS subheadings 2822.00 and 8105.20. Discrepancies in import and export values are likely due to reporting issues in the Global Trade Atlas. Export figures use "mirror data," for DRC, which are derived using export statistics from partner countries' import data.

Trade data indicate that much of the value added to cobalt occurs between the mining and refining stages. China, the largest importer of unrefined cobalt reported unit values per kilogram from the 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 from China show similar volatility, of $5.36 in 2016, $9.62 in 2017, and $16.26 in 2018.[55] Furthermore, China's total trade AUVs for refined products such as unwrought cobalt and cobalt oxides and hydroxides are nearly three to ten times as much as AUVs for cobalt ores and concentrates (see table 5).

[55] IHS Markit, Global Trade Atlas, accessed January 12, 2020.

Table 5 China total trade AUVs for unrefined and refined cobalt, U.S. dollars per kilogram, 2017

HS Subheading	Description	China total trade AUVs, U.S. dollars per kilogram (2017)
2605.00	Cobalt ores and concentrates	$3.41
2822.00	Cobalt oxides and hydroxides	$37.40
8105.20	Unwrought cobalt (metal)	$10.16

Source: IHS Markit, Global Trade Atlas, accessed March 16, 2020.

Global Value Chain Analysis

GVC measurements to evaluate the recent activity of certain countries trading intermediate goods before integration into a final good are available based on trade data.[56] Several trade-data based indicators are available that reveal the importance of a country's upstream participation—from mining to refining—as products cross borders through the EV LIB value chain. These indicators have shortcomings, however, mostly due to the broad HS categories that provide a wider range of related products than the intermediate good of interest.[57] The trade based GVC measures include the Coverage Ratio, Grubel-Lloyd index, and Revealed Comparative Advantage (RCA).[58]

The Coverage Ratio is a broad measure of a country's position in the value chain and compares the country's cobalt imports with its cobalt exports. Lower values indicate that a country is upstream (tends to produce the products at the beginning of the supply chain) in the value chain; conversely, higher values indicate that a country is downstream (at the end of the supply chain). Table 4 confirms that the DRC's coverage ratio in 2017[59] was much lower than that of the United States and China**.** This confirms that the DRC, as the main exporter of unrefined cobalt, is upstream in the value chain. China is downstream, as it accounted for over 60-percent of all global refined cobalt production in 2018 (figure 5). Chinese firms are expected to be the top suppliers of refined cobalt and LIBs for the next few years, even though capacity is expected to grow in other locations. The United States is provided for comparison purposes and its advantages are position is also downstream, reflecting its lack of cobalt mining and its industrial usage of refined cobalt.

The Grubel-Lloyd Index (GL) provides country-level information on intra-material trade. This measure relates absolute net exports of cobalt with total trade (sum of exports and imports) of cobalt. A higher index value reflects more trade (closer to 100 percent). At 100 percent, the country exports as much of the good as it imports, yielding a high percentage for countries that produce raw materials. Conversely,

[56] Other GVC indicators, such as TiVA are available at the industry, rather than intermediate product level. They also exclude relevant countries, such as DRC. OECD, "Trade in Value Added," https://www.oecd.org/sti/ind/measuring-trade-in-value-added.htm, 2019 (accessed December 9, 2019).
[57] World Customs Organziation (WCO). (n.d.). *What is the Harmonized System?* Retrieved December 11, 2019, from http://www.wcoomd.org/en/topics/nomenclature/overview/what-is-the-harmonized-system.aspx.
[58] Ahmad et al, "Indicators on global value chains: A guide for empirical work," July 6, 2017.
[59] The data to calculate DRC's RCA for 2018 are not available, so the RCA ratios for 2017 are provided.

if the value is zero, the country either only exports or imports the good. Lower percentages are likely outcomes for countries involved in refining and manufactures the LIB. The GL on cobalt trade (table 6) confirms the DRC's position as a large unrefined cobalt exporter. Although the United States and China largely reflect these countries' imports for final product manufacture, both countries are involved in cobalt trade throughout the GVC; they both have high intra-material trade.

The final GVC indicator using trade data is the Revealed Comparative Advantage (RCA) index, which provides information on the intensity with which a country exports a product.[60] The RCA is measured as a proportion of the country's exports of cobalt to its total goods exports, divided by the proportion of total global exports of cobalt to total global goods exports. DRC had the highest RCAs, reflecting its production and exportation of large volumes of raw and refined cobalt, relative to global export norms. As the largest exporter of cobalt, DRC has a significant comparative advantage. China and the United States have much lower outcomes. The United States is near unity, reflecting its relatively small proportion of cobalt exports to China. China, as the world's largest refiner and large consumer (LIB manufacturing), trades more modestly, compared with larger exporters such as DRC. However, China also exports more refined cobalt than is the global norm. The RCA measure for China does not capture the highly integrated nature of the country's LIB manufacturing industry. Most of the refined cobalt China produces is consumed internally and used in the manufacturing of LIBs and other products.

Table 6 Cobalt Measures, Selected Countries, 2017

Country	Coverage ratio (as a percent)	Grubel-Lloyd Index (as a percent)	RCA
China	492.42	33.80	3.4
DRC	0.00	0.00	3,340.9
United States	598.35	28.60	0.9

Source: Staff calculations, IHS Markit, Global Trade Atlas, accessed March 5, 2020; HS 2605.00, HS 2822.00, HS 8105.20. Underlying measures are provided in Appendix A.
Note: This is the most recent year where data are available for each of the selected countries.

The trade data and GVC measure results confirm the earlier descriptive analysis above and illustrate that the unrefined (upstream) product value chain is dominated by DRC, while the downstream value chain is mostly in China. DRC exports much more cobalt relative to other countries and at a greater share of its total export than other countries do. China is involved throughout the GVC, but it imports more than it exports.

Summary

Cobalt is critically important to the composition of LIBs, which fuel electric vehicles. Both qualitative analysis and GVC trade data measurement results show that the upstream value chain for cobalt is dominated by DRC and downstream is dominated by China. Currently, cobalt availability appears

[60] Values greater than unity (i.e. a score of 1) reveals a comparative commodity advantage, exporting more than its "fair" share. Conversely, values less than unity, the country has a comparative disadvantage, exporting less than its "fair" share in world trade.

adequate if there is no marked increase in EV demand worldwide. However, as consumers around the world adopt EVs in place of the vehicles based on traditional internal combustion engine technology, demand for energy storage systems such as LIBs and their precursor components—including cobalt—will continue to rise. As the global value chain for cobalt used in LIBs is currently concentrated in the two major players—the DRC and China—concerns over long-term supplies may result in major firms diversifying their supply chains to include alternative sources. Additionally, major Chinese firms have become increasingly vertically integrated as they and their respective subsidiaries acquire mining and refining assets in the DRC. These concerns may also lead to further research into potential substitutes and LIB recycling efforts, thereby ensuring greater resource security throughout the LIB supply chain.

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Appendix A
GVC Measures Analysis for Cobalt

Table A.1 Unprocessed Cobalt, 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
DRC	0.0	16.5	22.8	16.5	3.8	0.0	2.3
U.S.	43.2	1.6	0.1	0.3	0.0	0.0	0.0

Source: Staff calculations, IHS Markit, Global Trade Atlas database, HS subheading 2605.00 (accessed March 5, 2020).

Table A.2 Refined Cobalt, 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
China	428.4	100.0	87.0	89.2	0.0
DRC	0.0	83.5	77.2	83.5	19.1
U.S.	607.2	98.4	99.9	99.7	0.0

Source: Staff calculations, IHS Markit, Global Trade Atlas database, HS subheadings 2822.00 and 8105.20 (accessed March 5, 2020).