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More Than a Pretty Color: The Renaissance of the Cobalt Industry

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Abstract

Demand for cobalt—a major input in the production of lithium-ion batteries (LIBs) used in electric vehicles (EVs)—is growing due to recent technological advancements and government policies designed to promote the use of EVs. This has led major automakers, battery manufacturers, personal electronic device companies, and their suppliers to attempt to secure stable supplies and develop new sources of cobalt throughout the world. Moreover, the rising demand for cobalt has led to global supply constraints, higher prices, and renewed drive in battery materials research for potential substitutes for mined cobalt.

Keywords: Cobalt, lithium-ion batteries, supply, chemical, metal, superalloy, China, Democratic Republic of Congo, DRC

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Background

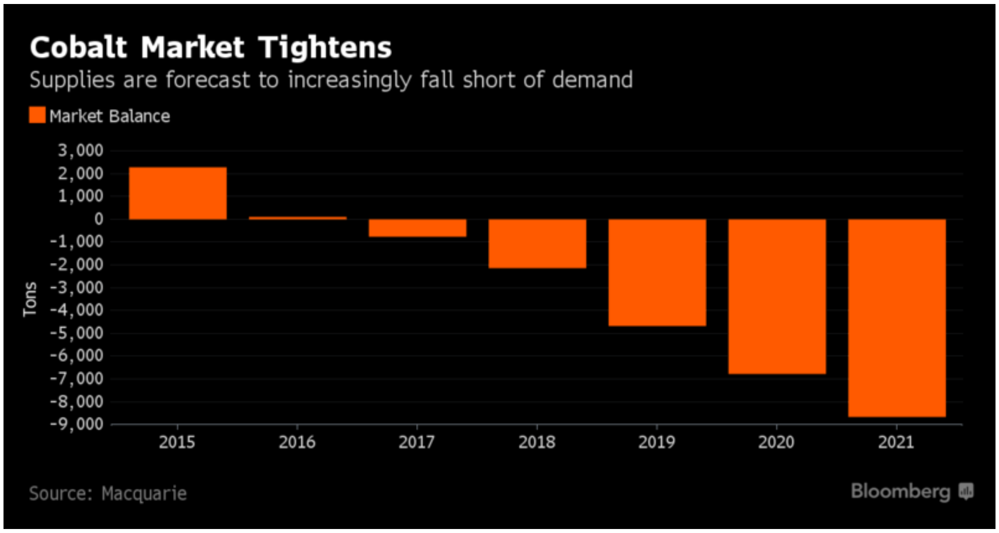
Cobalt is synonymous with images of the stable, clear-blue pigment, nominally referred to as "cobalt blue."[1] But cobalt (Co) is a metallic chemical element,[2] specifically number 27 on the Periodic Table of the Elements. Cobalt was first isolated in 1739 by George Brandt, a Swedish chemist,[3] but it was not until 1780 that cobalt was confirmed as an element by Torbern Bergman.[4] Cobalt has a long history of being mined, from which its name is a relic. Cobalt is derived from the German word *kobold*, which translates into "goblin" or "evil spirit," as it was obtained as a byproduct of silver mining in Germany. When the cobalt-containing ore was smelted to isolate the silver, toxic arsenic-trioxide (AsO_3) gas was released, which the miners attributed to the cobalt rather than the arsenic contained in the ore. Despite its inauspicious beginnings, cobalt has become an integral part of our technologically advanced world.

Beyond the color: Cobalt and its uses

Modern day demand for cobalt can be broadly categorized into two end uses: (1) metal and (2) chemical. Traditionally, the primary applications for cobalt have been attributable to its importance in metal industries, such as in the production of superalloys and steel products. However, increased demand for portable technologies, coupled with calls for greener alternatives to accepted practices in industry has led to a cobalt chemicals renaissance. According to various industry representatives, growth in the global electric-vehicle (EV) industry could result in a four-fold increase in cobalt demand by 2020 (from 2017 levels) and an eleven-fold increase by 2025.[5] Rising demand from the global EV industry is anticipated to lead to a cobalt supply shortfall in the near future (figure 1).

[1] Cobalt blue is an alumina-based pigment: cobalt (II) aluminate ($CoAl_2O_4$), Chemical Abstracts Services (CAS) number 1333-88-6.
[2] Material that cannot be broken down or changed into another substance using chemical means.
[3] Royal Society of Chemistry, "Periodic Table" (accessed September 4, 2018).
[4] Lindsay and Kerr, "Cobalt Close-up," May 23, 2011.
[5] Sanderson and Hume, "VW Fails to Secure Long-Term Cobalt Supply for Electric Vehicles," October 15, 2017.

Figure 1. Cobalt market balance 2015–21



Source: *Bloomberg*, "Owner of $1 Billion Cobalt Project Says Rally is Far From Over," June 5, 2017.

Demand for cobalt metal

Pure metallic cobalt, a hard, lustrous, silver-gray metal, is traditionally used in several industrial sectors including high-temperature superalloys (prevalent in jet turbines), stainless steels, medical prosthetics, hard-facing products, cemented carbides, and diamond tools, as well as other niche applications (figure 2). Batteries have become an increasingly important end use for cobalt which has increased significantly in recent years with the development of EVs (discussed later in this paper). Metallic cobalt is normally sold at 99.3-percent to 99.8-percent purity as ingot or cut cathode on the London Metal Exchange (LME).[6] One major end-use application for refined[7] cobalt metal, particularly in the United States, is in superalloys for jet engines, gas turbines, and other products that require high operating temperatures.[8] Although nickel-based alloys account for more than one-half of the superalloy market, cast and wrought cobalt alloys are also used due to their higher melting point, corrosion resistance, superior thermal fatigue resistance, and weldability as compared to nickel alloys.[9] Although metallic end-uses are

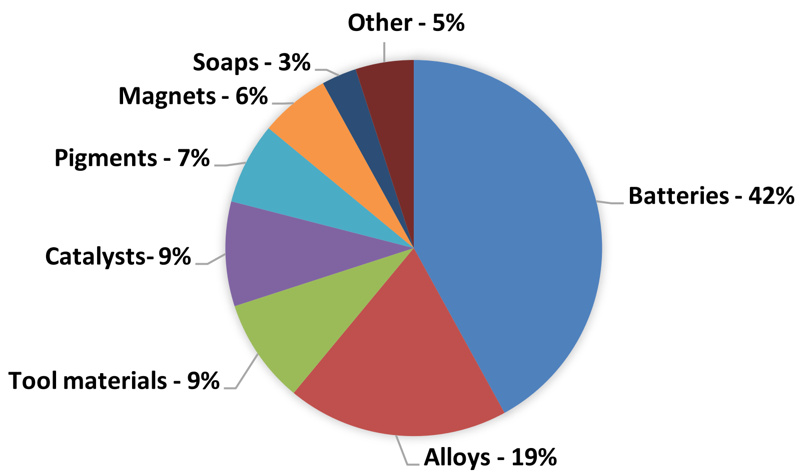
[6] S&P Global Platts, "Methodology and Specification Guide: Nonferrous," January 2019, 36.
[7] Refined cobalt refers to cobalt that is extracted from copper-cobalt sulfide, cobalt-nickel sulfide, arsenide (skutterudite), or nickel-laterite ores via a pyrometallurgical or hydrometallurgical process, in the form of refined cobalt metal or refined cobalt chemicals. Bell, "Cobalt Metal: Properties, Production, and Applications," March 28, 2018.
Cobalt is usually produced as either co-product or by-product of mining nickel and copper sulfide, sulfosalt, arsenide and oxide ores. See: Cobalt Institute, "About Cobalt," (accessed August 22, 2018).
[8] The first U.S. patent for a cobalt alloy was granted in 1907, improving the productivity of machining operations. With the advent of the gas turbine in the 1940s there was a need for superalloys that could withstand prolonged high operating temperatures. Kracke, "Superalloys, the Most Successful Alloy System of Modern Times- Past, Present and Future," October 10, 2010.
[9] Cobalt Institute, "Superalloys" (accessed July 11, 2018).

important, demand in this segment of the global cobalt industry is relatively stable but becoming smaller as a share of total consumption.[10]

Demand for cobalt chemicals

Cobalt chemicals are typically dry, granular, powdered salts, are used in the production of lithium-ion batteries (LIBs), catalysts, pigments, polymers, and tires. The most widely used cobalt chemicals are cobalt oxide (CoO), cobalt hydroxide ($Co(OH)_2$), cobalt sulfate ($CoSO_4$)[11] and cobalt acetate ($Co(CH_3COO)_2$),[12] along with various niche compounds for other applications.[13] Technological advancements have spurred growth in the market for cobalt chemicals. For example, demand for cobalt chemicals has increased, largely due to their use in LIBs. LIBs have become extremely popular, owing to their high energy, power density, and long lifetimes compared to other battery types, which makes them perfect for modern portable technologies.[14] As shown in figure 2, batteries (primarily LIBs) are the major driver in the global cobalt market. Box A provides additional information on the chemistry of LIBs and cobalt's role in this technology.

Figure 2. Global cobalt consumption, by end use industry, 2017



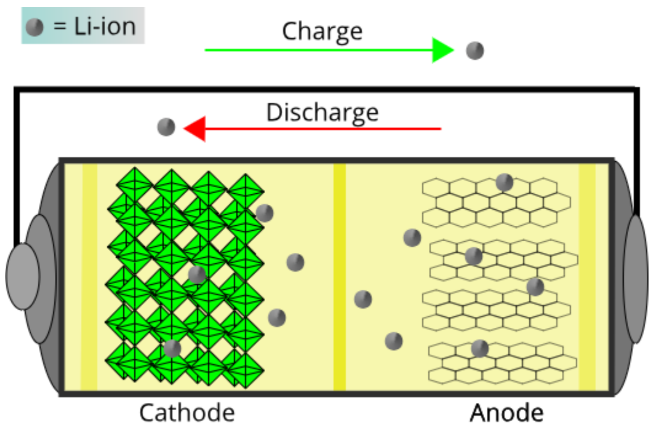
Source: Compiled from CDI, Roskill, MMTA, and other industry sources by Battery University, "BU-310: How Does Cobalt Work in Li-ion?" (accessed August 2, 2018).

[10] CRU, "Cobalt Shifts from Metal to Chemical Market," September 13, 2018.
[11] Cobalt sulfate is imported under HTS statistical reporting number 2833.29.1000, and cobalt oxide is imported under HTS subheading 2822.00.00.
[12] The past decade has seen a rise in the demand for cobalt chemicals due, in part to their increasing importance (specifically $CoSO_4$ and CoO) in modern technology, particularly the batteries sector. CRU, "Cobalt Shifts From Metal to Chemical Market," September 13, 2018.
[13] This includes drying agents for paint, glass decolorizers, ground coat frits for porcelain enamels, humidity indicators, magnetic recording media, pigments, and vitamin B_{12}.
[14] Berckmans et al., "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030," September 1, 2017.

Box A: Lithium-ion battery chemistry

Despite the name, LIBs consist of more than lithium. Cobalt is one of the key components of the most widely used battery chemistries. There are three key components to LIBs: the anode (negative electrode), the cathode (positive electrode), and the electrolyte (that promotes the movement of ions from the cathode to the anode).[a] The anode typically consists of a carbonaceous material (i.e., graphite), while the cathode is made of various formulations of oxidized metals which can include cobalt (figure A).[b]

Figure A. Representative diagram of a lithium-ion battery



Source: Based on information provided by the U.S. Department of Energy, "How Does a Lithium-ion Battery Work? https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work (accessed November 12, 2018).

Currently there are five main battery chemistries that comprise the majority of the LIB market: (1) lithium-cobalt-oxide (LCO), (2) nickel-cobalt manganese (NMC), (3) nickel cobalt aluminum (NCA), (4) lithium manganese oxide (LMO),[c] and (5) lithium iron phosphate (LFP) (table A).

Table A. Lithium-ion cathode configurations and corresponding specific energies

Li-ion cathode configurations[a]	**Representative cathode chemical formulas**	**Approximate percentage of cobalt in cathode**	**Specific energy**[b] **(Wh/kg)**	**Cycles**[c]	**Applications**
LFP	$LiFePO_4$	0	120	300	Large scale (grid storage), buses
LMO	$LiMn_2O_4$	0	140	820	Power tools, medical devices
NMC	$Li_{1.05}(Ni_{0.6}Mn_{0.2}Co_{0.2})_{0.95}O_2$	15	200	850	E-bikes, EV's
LCO	$LiCoO_2$	55	200	1000	Smart phones, laptops, cameras
NCA	$LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$	10	245	950	E-bikes, EV's disposable

[a] NMC and NCA are referred to as 'ternary cathodes,' there are three metals present not including lithium.

[b] Sometimes referred to as specific density.

[c] A battery cycle is one complete round of discharge and recharge.

Sources: The Visual Capitalist, Battery University, and Argonne National Laboratory.

Box A: Lithium-ion battery chemistry (continued)

The basic functioning of the LIB is attributable to the intercalation[d] of lithium ions in the anode and cathode (figure A). The intercalation and mobility of lithium ions is why LIBs have long lifetimes compared to other batteries.[e] LIB's capacity, however, decreases during its lifetime, arising from the fact that the lithium undergoes numerous side-reactions, which reduces the amount of lithium ions available for intercalation.

The cathode is fundamentally important to both the performance and cost-competitiveness of a lithium-ion cell, and the raw cathode materials used can represent on average nearly 40 percent of LIB overall raw-materials cost.[f] As shown in table A, LIBs that utilize cobalt in the cathode (LCO, NMC, and NCA) typically have higher energy densities and cycles than the alternatives, which is why LIBs are coveted for use in long "run-time" applications. Utilization of ternary cathodes has not reduced the desire for cobalt-based battery chemistries, but has lessened the amount of cobalt needed in the cathode (e.g. NMC and NCA). For reference, the amount of cobalt in final products that use LIBs are as follows: smart phones, 5-10 grams (equal to the weight of 2−4 pennies); laptops, 1 ounce (equal to a slice of bread); and an average electric car, 10−20 pounds (2−3 gallons of milk).[g] That boils down to nearly 1,000 times more cobalt, on average, in a car battery than that in a smart phone. Even with the relief that ternary cathodes provide, the basic fact remains that responsibly sourced refined cobalt has been difficult to obtain.

[a] There is also a separator usually a polymer based material, which is in place to limit the transport of electrons.
[b] The solid state structures of the cathodes vary which leads to their differing performance cycles. Clean TeQ, "Technology & Markets" (accessed September 20, 2018).
[c] Spinel structure.
[d] Refers to an insertion of molecules into a host lattice.
[e] Berckmans et al., "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030," September 1, 2017.
[f] Combined all raw materials represent around 60 percent of battery cost. Qnovo, "82. The Cost Components of a Lithium Ion Battery," January 11, 2016.
[g] Frankel, "The Cobalt Pipeline," September 30, 2016.

Demand for electric vehicles

Globally, many governments have and continue to respond to the effects of climate change by raising fuel-economy standards and promoting the use of EVs as an alternative to traditional fossil fuel-powered vehicles. During the Paris Climate Accords in 2016,[15] for example, many countries agreed to set goals to reduce and gradually eliminate the use of fossil fuel-powered vehicles, and to replace them with EVs. Under current targets, various European Union (EU) member states such as France will ban new sales of petrol and diesel cars by 2040,[16] while the

[15] Also referred to as the Paris Climate Agreement.
[16] Chrisafis and Vaughan., "France to Ban Sales of Petrol and Diesel Cars by 2040," February 6, 2018.

United Kingdom[17] and other EU member states have set similar targets.[18] India, which became the world's fourth-largest automobile market in 2017,[19] announced a similar goal to eliminate the sale of non-electric cars by 2030.[20] While there are multiple end uses for cobalt, the focus of this paper is cobalt used in EV-related applications (i.e., as LIBs) as this is a major emerging source of demand and has been the driving force behind a recent surge in global prices.

These actions have increased long-term demand for LIBs and their chemical inputs, including cobalt, and spurred partnerships amongst automakers, battery manufacturers, and cobalt suppliers. Earlier in 2018, Glencore, one of the world's largest metals trading firms, signed a four-year contract with Chinese LIB recycler GEM Co. Ltd. to supply the company with 52,800 metric tons of cobalt hydroxide to manufacture cathodic material used in the production of LIBs for EVs.[21] In 2017, Glencore signed a similar agreement with Chinese battery manufacturer Contemporary Amperex Technology Co. Ltd. (CATL)—CATL had previously struck a deal with Volkswagen Group to supply the automaker with LIBs for EVs.[22] In July 2018, CATL signed an agreement with BMW to supply the German automaker with $4.7 billion worth of EV battery cells. This agreement also entitles BMW to an equity investment of $430 million, making BMW the first foreign automaker to invest in a Chinese EV battery manufacturer.[23]

Recent government policies encouraging the production of LIBs used in EVs have led many Chinese firms to acquire and continue to acquire major assets in the global cobalt mining and refining industries. In November 2016, China Molybdenum Co. Ltd. (CMOC) acquired a 54-percent stake in the Democratic Republic of the Congo's (DRC's) Tenke Fungurume copper mine, one of the largest in the world and a major source of byproduct cobalt, from Freeport McMoran Inc. (Freeport).[24] Prior to this acquisition, CMOC was in negotiations to purchase Freeport's remaining cobalt assets, including the largest cobalt refinery outside of China (Kokkola, Finland) as well as an exploration project in the DRC, but the firms failed to reach a deal before CMOC's period of exclusivity expired on February 28, 2017.[25] Had CMOC acquired Freeport's Kokkola refinery, this would have given China-based firms near-total control of the world's global cobalt refining capacity. Other industry sources indicate that one Chinese producer may acquire Eurasian Resources Group's $1-billion Roan Tailings and Reclamation project in the DRC—a project that has received financing from Chinese firms and is producing

[17] Asthana, Anushka and Matthew Taylor, "Britain to Ban Sale of All Diesel and Petrol Cars and Vans from 2040," *The Guardian*, July 25, 2017.
[18] World Economic Forum, "Countries Are Announcing Plans to Phase Out Petrol and Diesel Cars. Is Yours on the List?" September 26, 2017.
[19] SteelGuru, "India Overtakes Germany to Become 4th Auto Market in the World," April 2, 2018.
[20] Sundria, "India's 2030 All-Electric Car Target Seen 'Ambitious' by IEA," May 11, 2017.
[21] *Reuters*, "Glencore Signs Massive Cobalt Sale Deal with China's GEM," March 14, 2018.
[22] Desai, "Glencore Makes Large Cobalt Deal, Securing EV Battery Supplies for VW,' July 6, 2017.
[23] Hancock, "BMW Gains Right to Buy into Chinese Battery Maker CATL," July 17, 2018.
[24] The Tenke Fungurume Mine in the DRC is the largest source of cobalt ores and concentrates to Freeport's cobalt refinery in Kokkola, Finland. *Reuters*, "China Moly to Help BHR to Acquire Stake in Congo's Tenke Copper Mine," January 22, 2017.
[25] *Reuters*, "Freeport, China Moly Agree to End Talk on Cobalt Assets," June 14, 2017.

15,000 metric tons of cobalt per year.[26] Acquisitions such as those previously discussed have raised concerns among end users of cobalt, particularly among South Korean and Japanese technology firms, who have become increasingly reliant on refined cobalt products from China.[27]

Regulators in China, the world's largest auto market, announced in late 2017 that they are developing a strategy to end production and sales of fossil fuel powered automobiles, however a deadline has not yet been set.[28] Moreover, the Chinese government has set a similar goal of having 12 percent of all vehicles produced in China to be electric by 2020 to address pollution and air-quality issues in major cities. While China is still developing its domestic EV manufacturing industry, it is already one of the world's largest producers—approximately 375,000 EVs were manufactured in China in 2016 (or 43 percent of global production). China is also the world's largest market for EVs—approximately 600,000 EVs were sold in China in 2017 compared to 200,000 in the United States.[29]

Made in China 2025

In May 2015, China announced the *Made in China 2025* initiative, which calls for Chinese domestic firms to acquire significant domestic and global market share within ten advanced-technology industries by the year 2025. Two industries within this plan that are likely to affect demand for cobalt chemicals and metals are new-energy vehicles (primarily EVs) and aerospace. Specifically, the initiative calls for Chinese domestic firms to have 70 percent of the Chinese market for EVs and plug-in hybrids by 2020,[30] and 80 percent by 2025, as well as for two Chinese firms to be among the top-ten largest new-energy vehicle manufacturers in the world. Demand for cobalt materials may also be impacted by similar initiatives under *Made in China 2025* for the aerospace industry, which is another major end user of cobalt. Goals for the aerospace industry include Chinese airline revenue of 100 billion yuan ($15.90 billion) by 2020 and 200 billion yuan ($31.8 billion) by 2025, and aerospace manufacturers to capture 10 percent of the domestic market and 80 percent of civil space-industry equipment manufactured by domestic sources by 2025.[31]

Electric-vehicle competition for cobalt with other industries

As demand for cobalt from the automotive industry increases, other advanced technology manufacturers that use LIBs—such as smartphone and laptop manufacturers—are attempting to secure their own long-term supplies of the material. Samsung C&T, a subsidiary of the Samsung Group, announced that it was pursuing negotiations with Somika SPRL, a miner and processor of cobalt in the DRC, to secure cobalt supplies for LIBs used in smartphones and other electronic

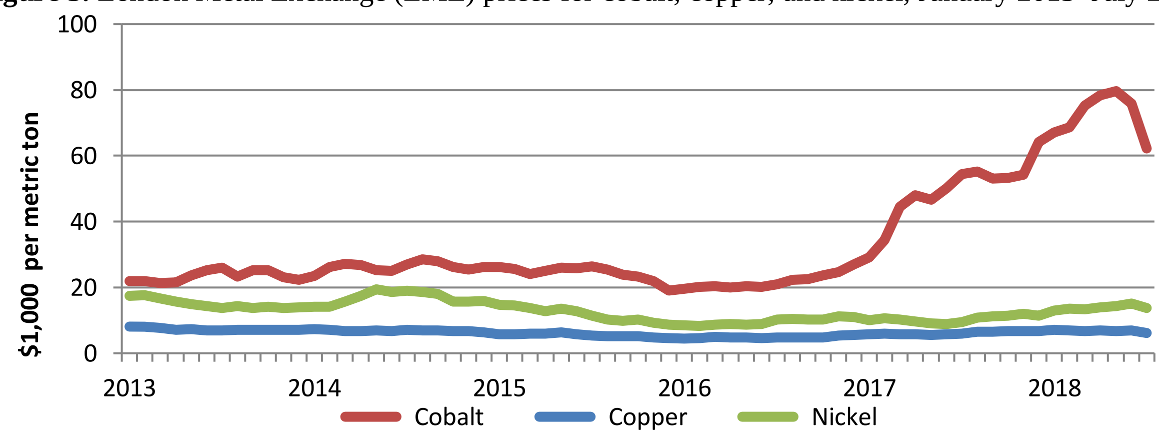
[26] Vella, "Inside China's Move to Monopolize Cobalt," June 4, 2018.
[27] *Economist*, "What If China Corners the Cobalt Market?" March 24, 2018.
[28] *Bloomberg*, "China Fossil Fuel Deadline Shifts Focus to Electric Car Race," September 10, 2017.
[29] Vella, "Inside China's Move to Monopolize Cobalt," June 4, 2018; Hertzke, Muller, and Schenk, "China's Electric-Vehicle Market Plugs In," July 2017.
[30] *Economist Intelligence Unit*, "The Road Ahead: China's New-Energy Vehicles," October 4, 2017.
[31] *Reuters*, "Factbox: Made in China 2025: Beijing's Big Ambitions from Robots to Chips," April 20, 2018.

applications.[32] Similarly, Apple Inc. announced its intention to start purchasing cobalt directly from mining firms rather than through third-party suppliers and metal traders to secure enough material for its own manufacturing needs.[33] Like Samsung and Apple, other manufacturers of laptops, cellular phones, and other electronic devices that use LIBs may try to secure their own cobalt supplies if prices rise or continue to remain at record levels.

Prices

Cobalt pricing has traditionally followed demand trends for copper and nickel due to the fact that cobalt is mined as a byproduct of these metals. However prices have diverged as demand for cobalt used in LIBs has increased.[34] In 2010, the LME launched a futures contract for cobalt in response to a global supply shortfall, price volatility, and in order to provide greater transparency and security to producers, consumers, and traders. Following this announcement, major producers of refined cobalt such as Vale, Votorantum, Sumitomo, and various Chinese producers registered with the LME.[35] From 2013−16, global cobalt prices, as measured by Platts, ranged between $20,000 and $30,000 per metric ton. During the period of January 2016–May 2018, prices increased over 300 percent following an increase in demand in the market for EV LIBs, coupled with political instability in the DRC and general supply constraints. Although global cobalt prices declined 22 percent since peaking in May 2018, they remain relatively high compared to historic trends (figure 3), a trend likely to continue unless new cobalt sources or viable substitutes for cobalt in LIB applications are developed.

Figure 3. London Metal Exchange (LME) prices for cobalt, copper, and nickel, January 2013–July 2018



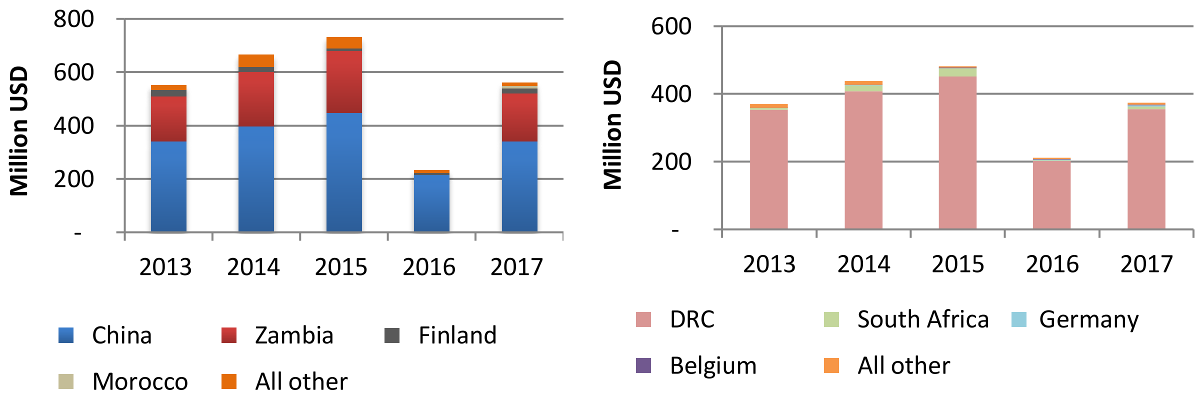
Note: S&P Global Platts offers a pricing reference for cobalt cathodes based on a survey of producers, merchants and consumers that follows a similar trend to the LME price for cobalt.
Source: S&P Global Platts, *Metals Week Price Notification Monthly Report*, January 2013–July 2018.

[32] Clowes and Kim, "Samsung in Talks for Multi-Year Cobalt Deal from Congo," March 13, 2018.
[33] Farchy and Gurman, "Apple in Talks to Buy Cobalt Directly from Miners," February 21, 2018.
[34] Demand for copper and nickel are driven largely by the building and construction industry (electric wiring and plumbing pipes) and stainless steel, respectively. Battery University, "BU-310: How Does Cobalt Work in Li-ion?" (accessed August 2, 2018).
[35] *Recycling Today*, "LME Launches Cobalt and Molybdenum Contracts," February 19. 2010.

International trade

In 2017, China accounted for 61 percent of global imports of cobalt ores and concentrates, in terms of value (figure 4). Although China is the world's second-largest source of cobalt ores and concentrates, China relies on imports to meet domestic consumption needs, particularly for LIB manufacturing. The DRC, the world's largest producer of cobalt ores and concentrates, accounted for 99 percent of China's imports in 2017.[36] Nearly all of Zambia's imports of cobalt ores and concentrates are also from the DRC, and likely supply Chambishi Metal's copper and cobalt refinery in Ndola, where the cobalt is refined before being shipped to customers via ports in South Africa.[37]

Figure 4. Global cobalt ores and concentrates imports (left) and exports (right), by country and value, 2013−17

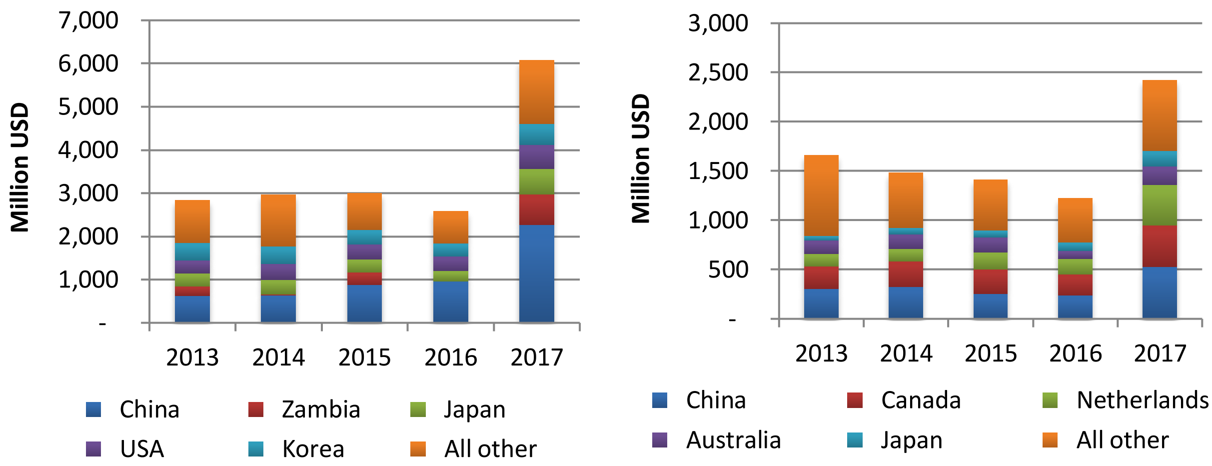


Note: Official trade statistics under HS subheading 2605.00. To minimize discrepancies with import values, export values are based on "mirror data," derived from partner countries' corresponding reported import statistics. Global export shares in 2017 were: China (60.7 percent), Zambia (32.2 percent), Finland (3.1 percent), and Morocco (1.9 percent). Global import shares in 2017 were: the DRC (95.2 percent), South Africa (1.8 percent), Germany (1.3 percent), and Belgium (0.4 percent).
Source: IHS Markit, Global Trade Atlas database (accessed September 19, 2018).

During 2013−17, China was the world's largest importer and exporter of certain refined cobalt products in terms of value; imports increased 259 percent during 2013−17 while exports remained relatively stable during 2013−16 before increasing over 120 percent from 2016−17. Other major importers include Zambia, Japan, and the United States. Zambia's imports are likely refined cobalt products from the DRC which may undergo further processing in Zambia before they are exported to other markets (figure 5). Most of the refined cobalt imported into the United States is for applications other than batteries (e.g., superalloys, cemented carbides, etc.).[38]

[36] A review of official Chinese import statistics from GTIS indicates that the DRC accounted for 99.1 percent of China's total imports of cobalt ores and concentrates in terms of value in 2017. IHS Markit, Global Trade Atlas database (accessed September 19 2018).
[37] ZCCM Investments Holdings Plc, "Chambishi Metals Plc" (accessed July 17, 2018).
[38] Approximately 45 percent of cobalt consumed in the United States in 2017 was used in superalloys for aircraft turbines, while 7 percent was used in cemented carbides. Shedd, "Cobalt," *Mineral Commodity Summaries 2017*," January 2018, 50.

Figure 5. Global refined cobalt imports (left) and exports (right), by country and value, 2013–17



Note: Official trade statistics under HS subheadings 2822.00 and 8105.20. Discrepancies between import and export values are likely due to differences in reporting by national customs authorities.
Source: IHS Markit, Global Trade Atlas database (accessed September 19, 2018).

Production

Mining of cobalt ores and concentrates

The majority of the world's cobalt is obtained as a byproduct[39] of mining endeavors for more abundant metals.[40] Typically cobalt is recovered at copper- and/or nickel-rich mines.[41] For example, in the Central African Copperbelt (DRC and Zambia) copper is mined from stratiform, sediment-hosted copper-cobalt deposits that contain relatively high concentrations of cobalt. CMOC International[42] and Jinchuan Group,[43] which are among the largest China-based cobalt mining firms in the world, own and operate mines in the DRC and Zambia. According to the U.S. Geological Survey (USGS), the DRC was the leading producer of cobalt ores and concentrates in 2017, accounting for approximately 58.2 percent of global production. Other major sources of cobalt ores and concentrates include Russia (5.1 percent), Australia (4.5 percent), and Canada (3.9 percent) (table 1). Cobalt is primarily mined through conventional underground and open-pit methods, and typically in operation for decades. Specific recovery practices are dependent on the mineral composition of the ore, and the minerals are subject to a wide variety of metallurgical techniques. Generally, current techniques for cobalt-ore isolation include leaching or leaching combined with roasting or smelting. Purification and refinement to

[39] Also referred to as a byproduct in some literature. The only operational mines that currently mine cobalt as the primary product are located in the Bou Azzer district in south central Morocco and artisanal mining in the DRC. FSC wire, "Supreme Metals Corp. Enters Agreement with Moroccan Mining Company Explore District Scale Cobalt in Bou-Azzer," February 21, 2017; Canaccord Genuity, "Cobalt: Out of the Shadows and Into the Spotlight," May 25, 2017.
[40] Crustal abundance of: Cobalt = 25 parts per million (ppm).
[41] Cobalt also naturally occurs in other ores including those containing silver.
[42] CMOC, "Tenke Fungurume" (accessed August 22, 2018).
[43] Jinchuan Group, "Mining Operations" (accessed August 22, 2018).

separate out the individual metals are accomplished through hydrometallurgical and/or electrometallurgical methods.[44]

Table 1. Global production of cobalt ores and concentrates, by country and quantity, 2013−17 (metric tons)

Country	2013	2014	2015	2016	2017
Democratic Republic of the Congo	54,000	63,000	63,000	64,000	64,000
Russia	6,300	6,300	6,200	5,500	5,600
Australia	6,400	5,980	6,000	5,500	5,000
Canada	6,920	6,570	6,900	4,250	4,300
Cuba	4,200	3,700	4,300	4,200	4,200
All other	15,200	14,280	19,300	15,300	5,900
Total	110,000	123,000	126,000	111,000	110,000

Note: Estimated for 2017.
Source: Shedd, "Cobalt," *Mineral Commodity Summaries*, various years.

New ore and concentrate resources under development

Concerns over a potential shortfall in global cobalt supplies[45] and a rapid increase in prices over the past three years[46] have led many mining firms to explore and develop additional cobalt resources, particularly outside of the DRC. Fortune Metals Ltd. (Fortune), a Canadian mining company, is currently developing the NICO Cobalt-Gold-Bismuth-Copper Project in Canada's Northwest Territories. Once operational, cobalt from this mine will be transported to a proposed cobalt processing plant in the Canadian province of Saskatchewan, where it will be refined into cobalt chemicals used in the production of LIBs for EVs and other applications.[47] As of April 2018, test mining, environmental assessments, and feasibility studies have been completed, and the company is now in the process of securing financing for construction of the mine and refining plant.[48] FinnCobalt, a Finish mining company, acquired the mining rights to the Hautalampi Cobalt-Nickel-Copper mine near Outokumpu, Finland, and will begin mine tests later in 2018. The company is in the process of securing financing for the project. FinnCobalt has partnered with Outotec Oyj, a manufacturer of mineral processing technology, to refine cobalt and nickel concentrates from the mine into battery-grade chemicals.[49] Due to the recent rise in

[44] Specific separation methods include chemical precipitation, electrowinning, hydrogen reduction, ion exchange, and solvent extraction. Bell, "Cobalt Metal: Properties, Production, and Application," March 28, 2018.
[45] Currently, the largest cobalt stockpile is China's State Reserve Bureau (SRB); the second-largest stockpile is owned by Cobalt 27 Capital Corporation (Cobalt 27), headquartered in Toronto, Canada. Burton, "This Commodity Investor Is Hoarding the World's Cobalt Supply," March 13, 2018.
[46] Concerns over cobalt pricing and sourcing culminated over a recent theft of 112 metric tons of cobalt from the Vollers warehouse in Rotterdam, the Netherlands. Several companies store their cobalt in the warehouse, but most (76 metric tons) of the stolen cobalt belonged to Cobalt 27. Sanderson, "Cobalt 27 Says $5m Worth of Cobalt Stolen From Rotterdam Warehouse," August 30, 2018.
[47] Fortune Minerals Ltd., "NICO Cobalt-Gold-Bismuth-Copper Project" (accessed August 22, 2018).
[48] A final completion date for the mine and processing plant has not been set. Fortune Minerals Ltd., "Fact Sheet," April 2018.
[49] FinnCobalt, "Hautalampi Cobalt-Nickel-Copper Mine Project" (accessed August 22, 2018).

global cobalt interest and associated prices, these projects, and similar projects in Australia[50] are now economically feasible.

Refined cobalt production[51]

According to the Cobalt Institute, China is the world's largest producer of refined cobalt, and accounted for over 60 percent of global production in 2017 (figures 6 and 7). As noted above, Chinese firms import cobalt ores and concentrates mainly from sources in the DRC. These mines are major suppliers to firms such as Jinchuan Nonferrous Metals Corp. (Jinchuan), Huayou Cobalt Co. Ltd. (Huayou),[52] and GEM Co. Ltd. (formerly Shenzhen Green Eco-manufacture Hi-Tech Co. Ltd.),[53] all of which are major suppliers to LIB manufacturers and other end users of cobalt in China. Nornickel (formerly Norilsk Nickel) and Freeport Cobalt are the largest producers of refined cobalt in Finland, and are supplied by mines in Russia and the DRC, respectively.[54] Other major global refiners include Omicore (Belgium), Vale (Canada), and Chambishi Metals (Zambia).[55] Various members of the Cobalt Institute, which includes some of the previously identified firms, have undertaken efforts to promote sustainable practices in their cobalt mining and refining operations, which are further discussed in box B. Published reports in 2018 state that, 80 percent of cobalt sulfate ($CoSO_4$) and oxides (CoO)—the primary cobalt-containing inputs for LIB cathodes—are refined in China, with the remaining 20 percent produced at a refinery in Finland (Freeport's Kokkola refinery) that is supplied with cobalt ores and concentrates from a mine in the DRC (CMOC's Tenke copper-cobalt mine).[56]

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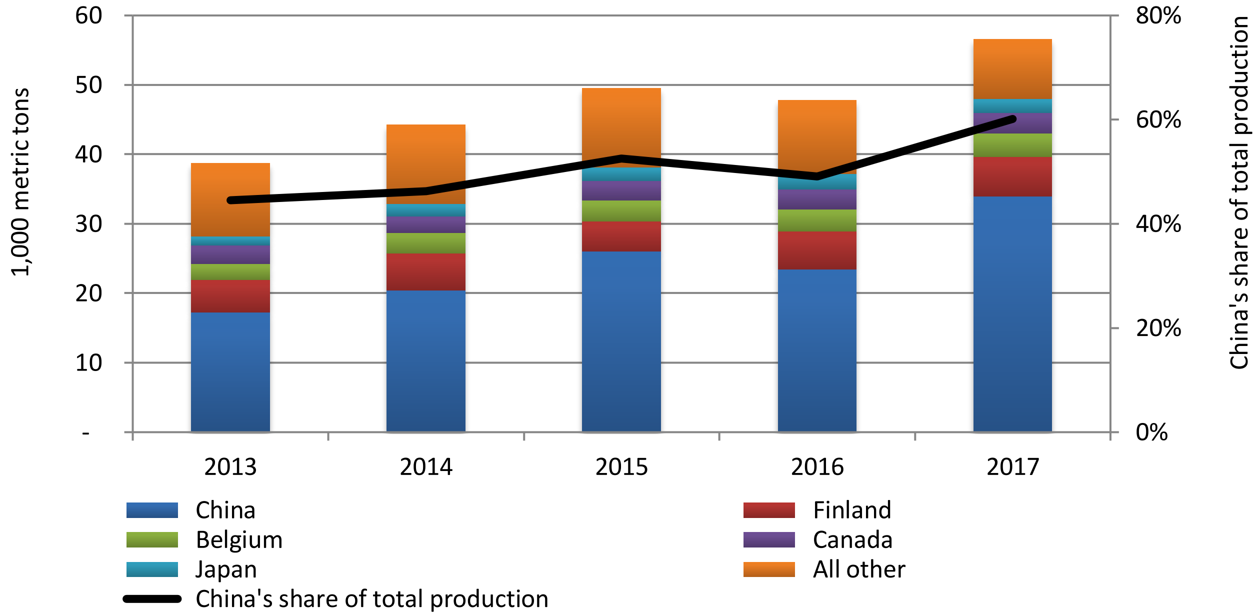
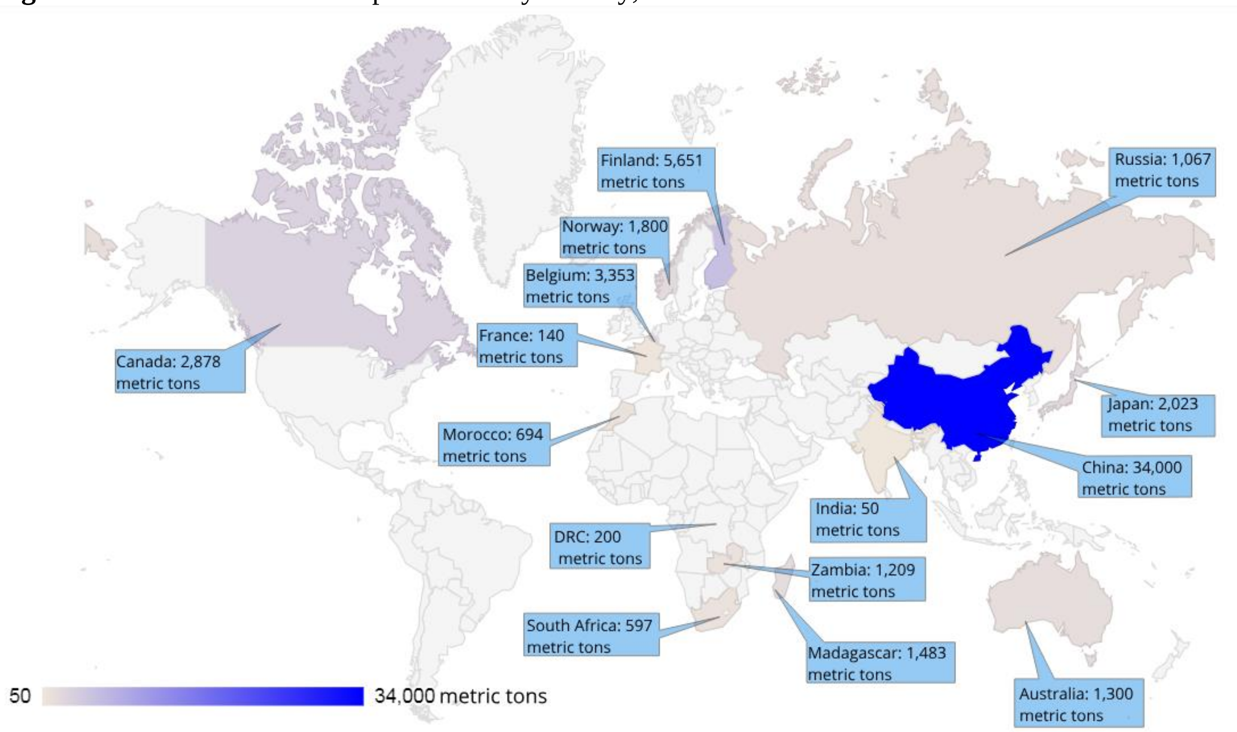
50 Nicholas, "Cobalt Stocks on the ASX: The Ultimate Guide," January 20, 2018.
51 Appendix A provides an overview of major global cobalt refining firms, by country.
52 In 2014, the USGS reported Jinchuan and Huayou as China's largest producers of cobalt and estimated their annual production capacity at 10,000 and 3,000 metric tons, respectively. Xun, "The Minerals Industry in China," May 2017, 8.22.
53 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.
54 *Economist*, "What If China Corners the Cobalt Market?" March 24, 2018.
55 Cobalt Institute, "2017 Production Statistics" (accessed August 22, 2018).
56 China Molybdenum, one of the world's largest producers of molybdenum, copper, cobalt, and other metals, has a controlling stake in this mine. *Economist*, "What If China Corners the Cobalt Market," March 24, 2018.

Figure 6. Global refined cobalt production, quantities and shares by country, 2013−17



Source: Cobalt Institute, "Cobalt Production Statistics, 2017" (accessed August 22, 2018).

Figure 7. Global refined cobalt production by country, 2017



Note: Data for major refined cobalt producers by country and company is provided in Appendix A, table A-1.
Source: Cobalt Institute, "Cobalt Production Statistics, 2017" (accessed August 22, 2018).

Box B: Sustainable cobalt initiatives

Concerns over human rights abuses and environmental degradation have led many cobalt producers, including miners and refiners, as well as end users in the automotive and consumer electronic industries, to develop an international framework for responsible and ethical sourcing. The Cobalt Institute, in coordination with its member firms, has established mandatory and voluntary initiatives to ensure that cobalt produced in the DRC and other countries is sourced without the use of child labor, and that member firms provide substantial economic and social benefits to those countries in which they operate.[a] Efforts are underway by several multinational cobalt refiners and end users in the automotive and consumer electronics industries to develop a "Better Cobalt" pilot project that will trace cobalt produced from artisanal mines in the DRC to its final end uses.[b]

[a] Cobalt Institute, "Responsible Mining of Cobalt" (accessed September 7, 2018).
[b] Pilling, "Pilot Scheme Seeks to Produce First 'Ethical Cobalt' From Congo," March 25, 2018.

Emerging technologies and alternatives to cobalt

Recycling

The expected increase in demand for cobalt has led to renewed efforts in recycling practices to recover this sought after metal. The Metalkol RTR (The Roan Tailing Reclamation Project) near Kolwezi in the DRC began construction in June 2015 and was expected to become operational in late 2018.[57] The goal of the project is to reprocess old tailings[58] dumped from mining in the 1950's through Metalkol's new hydrometallurgical facility. Umicore, a producer of cathodes for electric cars', has indicated that it may extract cobalt from old cell phones,[59] a relatively untapped resource for recycled cobalt.[60] In Vancouver, American Manganese Inc., of Vancouver, Canada, is developing technology that recycles faulty batteries to recover the raw materials, which would help ease the immediate stress for battery makers when they source cobalt.[61]

Battery materials research

Given their superior performance characteristics and the existing supply infrastructure, cobalt-based technologies for LIBs are likely to remain the top choice for battery applications for the immediate future. However, current cathode chemistries in LIBs are likely unsustainable, and cobalt production will be unable to meet demand. [62] As a result, there has and will be research into alternative batteries and technologies that may reduce or eliminate the need for cobalt in battery chemistries. The desire to reduce costs and increase battery safety and energy density have driven the development of promising new battery technologies such as the utilization of

[57] Eurasian Resources Group. "Metalkol RTR (the Roan Tailings Reclamation Project)," n.d. (accessed September 24, 2018).
[58] Tailings refer to materials that are left over after separating out the metal-bearing materials from the ore.
[59] Which utilize 10 percent of global cobalt production.
[60] Sanderson, "Cobalt in Old Smartphones Could Be Used to Power EVs, Umicore Chief Says," February 12, 2018.
[61] Hirtenstein, "How to Mine Cobalt Without Going to Congo," December 1, 2017.
[62] Canaccord Genuity. "Cobalt: Out of the Shadows and Into the Spotlight," May 25, 2017, 19.

sulfur or silicon in the electrode as oppose to cobalt.[63] But designing-out cobalt in these well-established LIB technologies is not going to occur overnight.

Concerns related to previous LIB raw-material shortages has led to development of battery technologies that eliminate lithium in favor of another alkali metal,[64] sodium (Na).[65] Utilizing sodium eliminates the need for cobalt in the cathodic material—it only needs nickel. Though promising, this technology is still relatively young, has not been adopted by industry, and would necessitate new contracts and supply chains[66]

A key aspect of clean energy beyond EVs is grid storage. Newer technologies such as the Powerwall (Tesla) use LIB technology for home use. These technologies benefit from consumer name recognition and could represent another growing source of demand for cobalt. But alternative technologies suited for larger-scale energy storage already exist, such as vanadium-flow batteries. Vanadium-flow batteries have been used around the world for decades due to their ability to fully cycle and stay at zero-percent charge, making them ideal for storage applications where the battery needs to start each day empty such as when paired with solar power.[67] However, even with progress, vanadium-flow batteries are large and not portable like LIBs, and represent an unknown quantity to the everyday consumer.

For several years the potential promise of hydrogen fuel cells has been a main focus and competitor to the LIB especially for EV applications. Hydrogen fuel cells generate electricity from hydrogen and emit only heat and water in the process.[68] Adoption and research into hydrogen fuel cells has been lower in the United States over the past decade, as LIB utilization increased.[69] Even with less investment on the U.S. side, progress has still been made on hydrogen fuel-cell research and development: (1) costs associated with hydrogen production have declined (2) hydrogen storage has improved (3) fuel cells have become more efficient, durable, and less costly. However, this technology has not been embraced globally, which means that LIBs are still the choice alternative energy source for personal vehicles. For example, Toyota has, and continues to, pursue hydrogen fuel cells for electric car applications but has

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[63] Both sulfur and silicon have higher theoretical capacities compared to materials used in current cathodes. Berckmans et al., "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030," September 1, 2017.

[64] Metals found in group 1 (first column) of the periodic table.

[65] Faradion, "About Us," n.d., (accessed September 18, 2018).

[66] Another longer-term goal in battery technologies is to shift more toward solid-state electrolytes, helping eliminate leaks that can occur when using liquid electrolytes.

[67] The size of the battery is still a concern (the aqueous electrolyte also makes the battery extremely heavy) and comparatively poor energy to volume ratio which why vanadium-flow batteries are not universally used for grid energy storage. Sandia National Laboratory. "DOE Global Energy Storage Database." (accessed September 24, 2018).

[68] Mench, "High Hopes for Hydrogen," November 09, 2015.

[69] Mench, "High Hopes for Hydrogen," November 09, 2015.

recently acknowledged that LIB-based EVs are “better” due to the ability of the consumer to plug the car in to charge rather than having to look for hydrogen fueling stations.[70]

Overall, great strides have been made in new technologies, but widespread adoption is still far off. As a consequence, LIBs with cobalt containing cathodes will remain the top choice in the EV sector for the foreseeable future.

Outlook

Since the first half of the twentieth century, cobalt has played a major role in metallurgy, but the need for cobalt in LIBs has led to a resurgence for cobalt chemicals. There are legitimate fears that there is not enough refined cobalt supply to meet increased demand, which is reflected in the meteoric rise of cobalt pricing over the past two years. Industry has dealt with these supply concerns by securing long-term contracts with cobalt suppliers, financing cobalt recycling efforts, investing in alternative technologies that could meet or exceed the performance of cobalt-containing LIBs, and developing new sources of cobalt. However, these efforts will not solve the short-term problems of consumer preferences for the tried-and-true cobalt-containing LIBs, and supply constraints and high prices are anticipated to persist for the near future.

[70] Lambert, “Toyota Admits ‘Elon Musk Is Right’ about Fuel Cell, but Moves Forward with Hydrogen Anyway.” October 26, 2017.

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Appendix A

Table A-1. Largest producers of refined cobalt, by country and company, 2013−17 (metric tons)

	Company	2013	2014	2015	2016	2017
Australia	BHPB/QNPL	1,065	([a])	([a])	([a])	([a])
Australia	Glencore	([a])	1,400	1,600	1,500	1,300
Belgium	Umicore	2,300	2,958	3,018	3,164	3,353
Brazil	Votorantim	796	700	700	400	([a])
Canada	New Providence	1,558	1,463	1,709	1,951	1,743
Canada	Vale	1,144	937	1,090	927	1,235
China	([b])	17,249	20,460	26,030	23,483	34,000
Democratic Republic of the Congo	GECAMINES	350	250	200	200	200
Democratic Republic of the Congo	Glencore	([a])	1,000	1,800	([a])	([a])
Finland	Freeport Cobalt	4,690	5,284	4,322	5,472	5,651
France	Eramet	172	146	88	76	140
India	Rubamin	25	([a])	([a])	([a])	([a])
India	([b])	125	100	100	50	50
Japan	Sumitomo	1,291	1,753	1,994	2,209	2,023
Madagascar	Ambatovy	1,165	1,405	1,520	1,587	1,483
Morocco	CTT	780	606	882	833	694
Norway	Glencore	1,600	1,700	1,500	1,800	1,800
Russia	Norilsk	1,224	1,173	1,053	1,617	1,067
South Africa	([b])	625	705	610	615	597
Zambia	Glencore	([a])	([a])	([a])	([a])	([a])
Zambia	Chambishi Metals	2,583	2,227	1,326	1,937	1,209

[a] Not reported.

[b] Company-specific production is not readily available.

Source: Cobalt Institute. “Cobalt Production Statistics, 2017” (accessed August 22, 2018).