Global trends affecting the supply security of cobalt

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The earliest known use of cobalt was to make blue glass in Mesopotamia before 2000 B.C.E. Since then, innovations across many diverse industrial sectors transformed cobalt into an essential commodity for contemporary society. The physical and chemical properties of the element cobalt and its alloys and compounds make them indispensable for a variety of applications, including aircraft engines, hybrid electric vehicles, machine tools, missile guidance systems, petroleum refining and smartphones. As a major industrialized nation, the United States is a leading consumer of cobalt and cobalt-containing products. However, with few exceptions, U.S. cobalt-containing ore deposits are of low cobalt grade. Historically, U.S. cobalt mine and refinery output have not met domestic cobalt demand. As a result, U.S. cobalt chemical and alloy producers need to procure most of their cobalt from the international market, which can become susceptible to supply risk.

The 1978 Cobalt Crisis illustrates supply risk. At that time, the Democratic Republic of the Congo (DRC) (then known as Zaire) was the world's leading producer of mined and refined cobalt. An insurgent invasion of the country's copper-cobalt mining region during a period of high cobalt demand and low producer inventories caused a temporary supply shortage in the international market. The monthly average cobalt spot price increased from $18/kg ($8/lb) before the crisis to $99/kg ($45/lb) seven months later. The high price and concern about potential disruptions in supply prompted manufacturers to reduce or substitute for cobalt where possible, and encouraged increased recovery of cobalt from scrap. The DRC has regained its position as the leading producer of mined cobalt globally and continues to be characterized by high governance risks (U.S. Central Intelligence Agency, 2015; World Bank, undated). This article will present current and historical world cobalt production trends, which can help inform discussion about the variety of international supply chain risks consequential to its trade.

Material overview

Most cobalt mine output is a byproduct of copper and (or) nickel mining. Therefore, most cobalt supply is contingent upon the strength of the copper and nickel markets (Cobalt Development Institute, 2016). In 2015, an estimated 43 percent of world cobalt production was from copper mining and 44 percent was from nickel mining. Cobalt, which is present in these ores in much lower concentrations than those of the principal metals, usually follows copper or nickel through most of the mining and processing until it is separated from them at the final refining stage. In 2015, there was only one active, modern, mechanized mining operation from which cobalt was the principal commodity being produced — the Bou-Azzer Mine in Morocco — but its contribution to world cobalt mine production was estimated to be only 2 percent. The remaining 11 percent of the world's cobalt mine production was estimated as principal production from artisanal mining and the recovery of cobalt from previously stockpiled, partially-refined materials.

Tenke Fungurume Mine, Democratic Republic of the Congo, October 2014. Tenke Fungurume is an example of a large mechanized copper-cobalt mine. Photo courtesy of Omayra Bermúdez-Lugo, U.S. Geological Survey.

Cobalt's ferromagnetism, hardness, corrosion- and wear-resistance when alloyed with other metals, low thermal and electrical conductivity, high melting point, and multiple valences are among its unique set of properties that make it essential for the manufacture of numerous diverse goods. For example,

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cobalt is a ferromagnetic metal with a high Curie temperature, which means that magnetic alloys containing cobalt retain their magnetism at high temperatures. These magnets are used in numerous advanced technology applications, including inertial guidance systems in aerospace and defense applications. Cobalt is also used in nickel-base and cobalt-base superalloys, which are capable of withstanding high temperature, high stress and highly oxidizing conditions, such as those in jet engines. Similar to other transition metals, cobalt and its compounds make good catalysts, one of which helps make cleaner fuels by removing sulfur compounds during petroleum refining.

Lithium-cobalt oxides, alone or in combination with other metal oxides, have electrochemical properties well-suited for cathodes in rechargeable batteries. These lithium-ion batteries are used in portable electronics, electric and hybrid electric vehicles and energy-storage systems. On a worldwide basis, rechargeable batteries are the leading use of cobalt (Cobalt Development Institute, 2016) and the demand for such batteries is increasing at a rapid rate. As a result of this, and growth in other applications, a 68 percent increase in world consumption of cobalt is forecast between 2015 and 2025 (Spencer, 2016a). Ongoing manufacturing innovation is expected to reduce cobalt demand per unit of application, but this alone may not prevent potential world supply disruptions or shortages.

Although substitution for cobalt is sometimes possible in certain applications with nickel or other elements, it can result in increased cost and (or) decreased performance. In the case of superalloys used for aircraft turbine engine parts, lengthy and expensive certification requirements slow down potential substitution. In some applications, significant cobalt reduction or replacement already took place following the 1978 Cobalt Crisis. However, in certain instances, cobalt was later re-added or gradually increased over time to improve product performance.

Worldwide trends and global supply chain vulnerabilities

It is useful to evaluate historical trends to better understand evolving risks associated with the global cobalt supply chains. Vulnerability to supply-chain disruptions can result from many factors, such as dependence on the profitability of the primary metals in the case of byproduct production, concentration of production in a limited number of countries, production dominated by a single country or region, the risk of natural disasters in producing countries or regions, the transport of materials between multiple countries for various processing stages, and dependence on countries with high sociopolitical instability. To a certain degree, global cobalt trade is subject to all of these risk factors.

Annual mine production discussed in this article and shown in Figs. 1 and 2 are derived from U.S. Bureau of Mines and U.S. Geological Survey (USGS) Minerals yearbooks (Shedd, K.B., 1996; 1997–2016). In some instances, data have been revised to reflect the current state of knowledge. Mine production represents recoverable cobalt produced in ores, concentrates or partially refined materials from cobalt, copper, nickel, platinum-group metals (PGM) or zinc operations. From 1990 through 1996, production data for the DRC do not include considerable quantities of cobalt recovered from previously produced partially refined materials, although data for more recent years do include production from such materials.

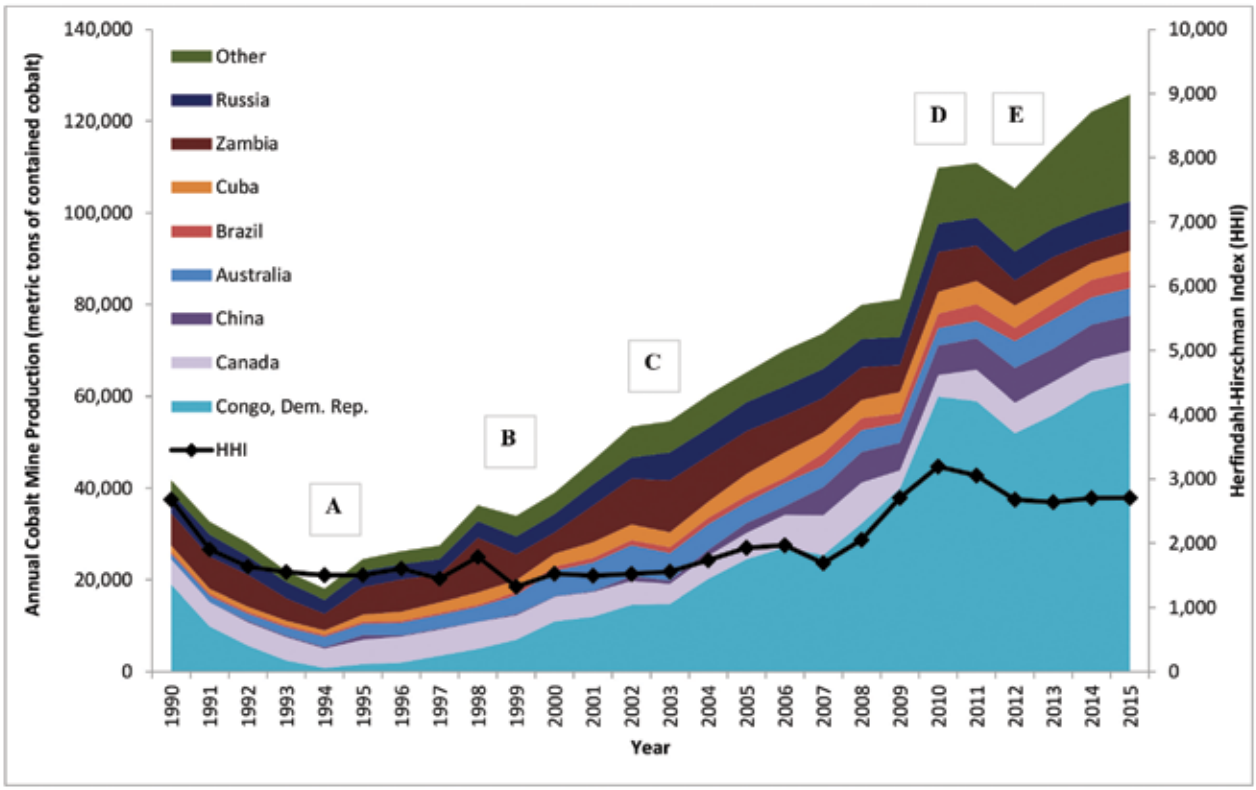
Cobalt is mined in a number of countries, most of which produce a small portion of world production (Fig. 1). In 1990, cobalt was mined in at least 14 countries, five of which accounted for 90 percent of world production. The DRC was the leading producer with a 46-percent share of world mine production, followed by Zambia (17 percent), Canada (13 percent) and Russia (11 percent). In September 1990, a structural collapse at a major copper-cobalt mine in the DRC reduced that country's production of cobalt ore. This was followed by several years of political and social unrest, declining economic conditions, a lack of foreign investment and declining cobalt mine production.

By 2000, at least 15 countries mined cobalt and mine production in the DRC was approaching levels prior to the mine collapse. Six countries produced 86 percent of world cobalt mine production. The DRC was the leading producer with a 28-percent share of world production, followed by Australia and Canada (14 percent each), Zambia (12 percent), Russia (10 percent) and Cuba (7 percent). Cobalt of Cuban origin has not been available as a supply source, directly or indirectly, to the United States since the early 1960s, when an embargo on all trade between the United States and Cuba was implemented (U.S. Department of State, undated).

From 2000 to 2015, cobalt mine production in the DRC continued to trend upward. By 2015, cobalt was mined in at least 20 countries. One-half of world mine production

Figure 1

World cobalt mine production by country from 1990–2015. Data represent the recoverable amount of cobalt produced in ores, concentrates or partially refined materials from cobalt, copper, nickel, platinum-group metals or zinc operations. The events indicated on the graph correspond as follows: A, Decreased production following a 1990 mine collapse in the DRC and several years of political and social unrest, declining economic conditions and a lack of foreign investment; B, Release of the first smartphones to achieve mass adoption in 1999; C, Passage of a new mining code in the DRC in 2002 and formal end of civil war in the DRC in 2003; D, Production ramp-up at several large, mechanized copper-cobalt operations in the DRC and increased artisanal mining; E, Inventory reduction in China and decrease in artisanal mining in the DRC. Estimates for Russian production in 1990 to 1991 were originally published as part of the estimated production in the USSR. Countries listed under other include Albania, Botswana, Finland, Indonesia, Kazakhstan, Madagascar, Morocco, New Caledonia, Norway, Papua New Guinea, Philippines, South Africa, United States, Vietnam and Zimbabwe.



was from the DRC. China, Cuba and Russia combined produced another 14 percent of mine production. No other country accounted for more than 6 percent of world production. During this period of increasing production in the DRC, production changes in most other countries were minimal in comparison. As a result, the geographic distribution of world cobalt mine production became increasingly concentrated.

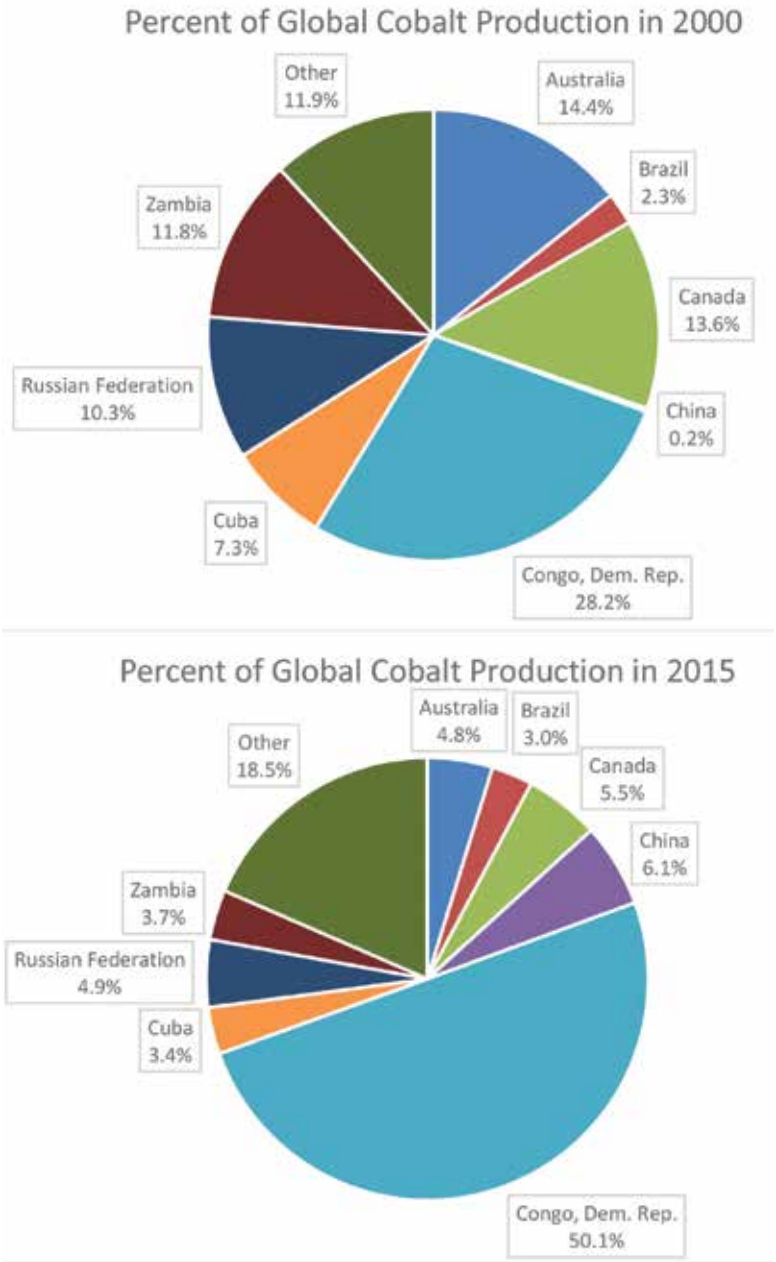
The aforementioned trends represent a foundational change in cobalt concentration over time. One way to capture this analytically is through an annually computed Herfindahl-Hirschman Index (HHI), a measure approved by the U.S. Department of Justice and the Federal Trade Commission for characterizing market concentration (U.S. Department of Justice, 2015). Instead of measuring individual firms, the HHIs computed for this study, as shown in Fig. 1, evaluate the concentration of mined cobalt production by country.

HHIs theoretically range between zero and 10,000 points, which indicate low-and high-market concentrations, respectively. Increased risk theoretically corresponds to high HHI measures, and scores exceeding 2,500 show high concentration (U.S. Department of Justice, 2015). Since 2009, HHI scores for mined cobalt have exceeded 2,500, with the 2015 score equal to approximately 2,700. It is foreseeable in future years that the HHI will continue to show high concentration until the market share controlled by the DRC is offset by increased production in another country, or until production in the DRC decreases considerably.

The total size of the global mined cobalt market has changed as well. World cobalt mine production increased from an estimated 39 kt (43,000 st) in 2000 to 126 kt (139,000 st) in 2015. This tripling of production represents

Figure 2

Distribution of world cobalt mine production in 2000 and 2015. In 2000, countries listed under other include Botswana, Indonesia, Morocco, New Caledonia, Norway, South Africa and Zimbabwe. In 2015, countries listed under other include Botswana, Finland, Indonesia, Madagascar, Morocco, New Caledonia, Papua New Guinea, Philippines, South Africa, United States, Vietnam and Zimbabwe.



a compound annual growth rate (CAGR) of 8.1 percent. In contrast, during the same time period, world copper and nickel mine production increased at CAGRs of 2.5 percent and 3.9 percent, respectively. Because cobalt is, in large part, a byproduct of copper and nickel mining, it is noteworthy that the low growth rates for those metals did not limit the growth of cobalt mine production. The higher growth rate for cobalt, compared to those of the principal metals in the ores from which it is usually recovered, was the result of multiple factors. Since 2000, there has been an increase in nickel production from lateritic ores, from which cobalt is recovered. This production took place in Australia, Brazil, Cuba, Indonesia, Madagascar, New Caledonia, Papua New Guinea and the Philippines. For copper, the increases in cobalt production were greater than those for nickel and took place in the DRC as a result of modern, mechanized copper-cobalt mining operations, the recovery of cobalt from previously stockpiled partially refined materials (e.g. slags), and artisanal mining of cobalt ore. The DRC is one of only a few copper-producing countries with copper ores that contain cobalt, which is why trends in world cobalt mine production don't track those of world copper mine production. Although stockpiles of partially-refined materials were produced during past copper mining, reprocessing those materials to recover the cobalt is not associated with current copper production. In addition, cobalt produced by artisanal mining is independent of copper mining. Instead, the quantity of artisanal cobalt production is typically correlated with cobalt prices (Spencer, 2016b).

DRC cobalt mine production. Cobalt production in the DRC from 2000 to 2015 increased by more than 470 percent during the 16-year period at a CAGR of more than 12 percent. Various factors, including passage of a new mining code in 2002 and the formal end of civil war in the DRC in 2003, led to increased foreign investment in the country's formal mechanized mining sector. A rapid increase in cobalt consumption, as new battery applications were introduced, resulted in increased investment by China, where much of the battery production takes place. A substantial portion of the DRC's increased mine production was from the start-up or ramp-up of three large modern mechanized copper-cobalt operations — the Mukondo Mountain Mine, the Mutanda Mine and refinery and the Tenke Fungurume Mine and refinery. By 2010, these three operations accounted for more than 40 percent of the DRC's estimated cobalt mine production, and by 2013 they accounted for more than 60 percent. During 2011 through 2014, each of the three operations outproduced any single country in the world. Mechanized mining now dominates DRC's cobalt mine production.

A significant percentage of the DRC's cobalt production continues to be a result of the work of tens of thousands of artisanal

miners employing crude, labor-intensive mining methods. Actual amounts of artisanal mining are difficult to determine. The share of cobalt production in the DRC attributed to artisanal mining was estimated to be as high as 60 to 90 percent by one analyst in 2009 (Tsurukawa and others, 2011). More recently, artisanal mining has been estimated to represent only 17 to 20 percent of DRC's total cobalt mine production (Amnesty International, 2016; Spencer, 2016b). Most of this artisanal mining is unregulated, unsafe, can cause environmental damage and, in some cases, involves child labor and other human rights abuses (Tsurukawa and others, 2011; Amnesty International, 2016). These conditions are beginning to have potential downstream economic impact, as nongovernmental organizations and consumers begin to demand goods produced from ethical supply chains.

The World Bank's assessment of the DRC's public sector in 2015 determined that the country continues to rate very low based on transparency, accountability and corruption (World Bank, undated). The U.S. Central Intelligence Agency (2015) reported that the DRC economy was slowly recovering after decades of decline, systemic corruption, and countrywide instability and conflict. The uncertain legal framework, corruption and lack of transparency in government policy continue to be problems for the mining sector and economy as a whole. These governance factors present a variety of long-term problems for the mining sector. They make it difficult to negotiate contracts and to provide adequate infrastructure such as power and transportation. Periods of social or political unrest can disrupt operations. The quality of governance becomes a particularly important consideration when world production is highly concentrated, leaving few alternatives to replace supply if disruption occurs. Despite the DRC's low governance indicators, both artisanal and mechanized mine production have increased to meet world demand.

Rest of world cobalt mine production. Most cobalt producing countries showed significant increases in cobalt mine production during the 2000-2015 time period. Combined production from all countries, except the DRC, trended upward at a much slower rate than the DRC's exponential growth. As a result, many individual countries experienced a decrease in their share of world production (Fig. 2). For example, Russia's cobalt mine production increased by 55 percent, but its share of world production decreased from 10 percent in 2000 to 5 percent in 2015. Cuba's production expanded by 51 percent by 2015 (with higher production in most interim years), but its share of world production decreased from 7 percent in 2000 to 3 percent in 2015. Australia's and Canada's shares also decreased, despite increases in production.

In contrast, by 2012, China was estimated to be the world's second leading producer of mined cobalt and its share of world cobalt mine production increased from less than one-half percent in 2000 to 6 percent in 2015. China's cobalt refining capacity expanded from 1.9 kt (2,100 st), or 3 percent of world capacity, in 2000 to approximately 55 kt (61,000 st), or 40 percent of world capacity in 2015. China's refineries import most of their cobalt feed materials, in the form of ore, concentrate or partially refined materials from the DRC. This increase in China's refining capacity was in direct response to the increase in cobalt use by the battery industry, much of which is in China (Xu, 2016).

U.S. cobalt mine production and consumption. Substantive domestic cobalt mine production resumed in 2014 after a hiatus of more than four decades. From the late 1990s to 2013, only negligible amounts of cobalt were recovered as a byproduct of partially refined materials from U.S. mining operations. In 2015, estimated cobalt production from a nickel-copper mine in Michigan and a PGM operation in Montana was less than 800 t (880 st) (Shedd, 2017). The cobalt-containing nickel concentrate from Michigan and the partially refined cobalt-containing nickel sulfate from Montana were exported for refining. The cobalt mined in the United States represented less than 1 percent of the estimated world cobalt mine production that year, while the U.S. consumed an estimated 10 percent of world refined cobalt supply (Cobalt Development Institute & World Bureau of Metal Statistics, 2017).

The United States is a leading consumer of refined cobalt, cobalt scrap and cobalt-containing materials and products. Based on data published by the USGS, U.S. net import reliance as a percentage of apparent consumption averaged 78 percent between 2000 and 2015, meaning that more than three-quarters of U.S. supply has been from imports and stock releases of refined cobalt. The remainder — less than one quarter of U.S. supply — has been from domestic or imported scrap. Therefore, the United States is ultimately dependent on cobalt mined in other countries

and inherently at risk of supply disruptions. As U.S. imports of refined cobalt from China have increased, the United States has become increasingly dependent on the DRC to mine cobalt and China to refine it.

Discussion

Because most cobalt is produced as a byproduct of other more abundant metals, opportunities to significantly increase cobalt production are limited by demand for those other metals. Cobalt recovery from stockpiled, partially refined materials produced from past mining operations and artisanal mining of cobalt in the DRC are exceptions to this byproduct relationship, because cobalt is sought after as the principal commodity and production can increase or decrease to match market demand. However, most artisanal mining is unregulated and can be associated with negative social and environmental impacts (Tsurukawa and others, 2011; Amnesty International, 2016). As downstream processors and industrial consumers become more concerned with responsible sourcing of their raw materials, dependence on unregulated, artisanally mined cobalt becomes less desirable.

Nonetheless, during the past two decades, the DRC has regained its position as the world's leading producer of mined cobalt. The DRC has a history of political instability and armed conflicts and continues to be a high-risk business environment (U.S. Central Intelligence Agency, 2015; World Bank, undated). These conditions could directly affect international cobalt supply, because adequate governance is necessary to attract investors, uphold law and order, and to maintain infrastructure. Additionally, the fact that mined cobalt supply is highly concentrated in one country poses high risk compared to a circumstance where the global mine production is distributed more evenly over a large number of countries. Currently, no alternative country is positioned to increase production to meet global demand if production from the DRC were to be constrained or disrupted.

It is important to note that the emphasis of this article was cobalt mine production, but cobalt supply chains extend well beyond the production of ores and concentrates. It is common for cobalt-containing ores to be mined and sometimes partially refined in one country, and then to be shipped to a second country for final refining. As cobalt mine production in the DRC increased during the past two decades, China has imported increasing amounts of cobalt ores, concentrates, and partially refined materials from the DRC and has become the world leader in refined cobalt production. As a result, China has invested in the DRC's mining sector to help ensure that it receives adequate supplies of raw materials. Foreign investment can restrict cobalt supply available on the international market, especially if the production is committed through offtake or other purchase agreements. This means that competition for existing sources of cobalt will increase until technological innovations provide improved recovery at the mining and processing stages, substitute materials, reduced consumption, and (or) increased recycling. ■

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