CEMAC Clean Energy Manufacturing Analysis Center

SUPPLY CHAIN OF RAW MATERIALS USED IN THE MANUFACTURING OF LIGHT-DUTY VEHICLE LITHIUM-ION BATTERIES

Tsisilile Igogo, Debra Sandor, Ahmad Mayyas, and Jill Engel-Cox

Clean Energy Manufacturing Analysis Center
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CEMAC is operated by the Joint Institute for Strategic Energy Analysis for the U.S. Department of Energy's Clean Energy Manufacturing Initiative.

Technical Report
NREL/TP-6A20-73374
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Preface

This report aims to integrate raw materials into the Clean Energy Manufacturing Analysis Center (CEMAC) Benchmark framework. Benchmarking raw materials provides a broader view of the supply chain of clean energy technologies, from the mines to the manufacturer. This report provides insight into resource location and ownership, global production, demand, and trade, highlighting potential supply chain risks and opportunities. The report focuses on the lithium and cobalt supply chains. It serves as a foundation for incorporating the raw materials link for other clean energy technologies into future CEMAC Benchmark reports.

Acknowledgments

We would like to thank Allison Anderson Book and Ben Mandler from American Geosciences Institute for their support in developing this topic and providing information that enabled this report. We also thank Kim Shedd and Brian Jaskula, U.S. Geological Survey cobalt and lithium experts, for sharing their insight on data. Finally, would like to thank all of the National Renewable Energy Laboratory and American Geosciences Institute employees who contributed to the success of this report.

List of Acronyms

DRC	Democratic Republic of Congo
HS	Harmonized System
LCE	lithium carbonate equivalent
LDV	light-duty electric vehicle
Li	lithium
Li-ion	lithium-ion
LIB	lithium-ion battery
mt	metric tons
MWh	megawatt-hour
NCA	nickel cobalt aluminum
NMC	nickel manganese cobalt
NREL	National Renewable Energy Laboratory
ROW	rest of world
USGS	United States Geological Survey
WCO	World Customs Organization
IEA	International Energy Agency
UN	United Nations
CEMAC	Clean Energy Manufacturing Analysis Center

Executive Summary

When assessing the value and potential risks to manufacturing supply chains for clean technologies, data for upstream raw materials has been confounded with data for larger materials markets and is therefore difficult to differentiate. The report lays the foundation for integrating raw materials into technology supply chain analysis by looking at cobalt and lithium—two key raw materials used to manufacture cathode sheets and electrolytes—the subcomponents of light-duty vehicle (LDV) lithium-ion (Li-ion) battery cells from 2014 through 2016.

Both cobalt and lithium are highly concentrated in a few countries. For example, from 2014 through 2016, an average of 53% of global mined cobalt production came from the Democratic Republic of Congo (DRC), while an average of 47% of global cobalt refining took place in China (USGS 2018; Cobalt Institute 2018). Additionally, more than 80% of global lithium production comes from Australia, Chile, and Argentina, while more than 60% of manganese is mined in South Africa, China, and Australia (USGS 2018). Due to high geographic concentration in production, the markets for most of these materials are generally less transparent than those for conventional materials like aluminum and copper. These materials are also used in other industries, but as electric vehicle deployments increase, battery production is becoming an increasingly important source of demand. Understanding these materials' markets is therefore critical to understanding the impacts of continued LDV development on mineral production, and vice versa.

This analysis suggests that the cobalt supply chain is relatively less secure than the lithium supply chain. Between 2014 and 2016, in addition to demand shocks generated by economic slowdown, cobalt production was also affected by price volatility in other metal markets. Cobalt is mainly produced as a byproduct or coproduct of copper and nickel, both of which have volatile markets. Cobalt supply responded strongly to the sharp drop in base metal prices during this period.

We also find that most leading producers of cathode active materials are highly involved throughout the raw material value chain in some capacity. As for the lithium market, although Australia owns about 47% of global lithium reserves and accounts for an average of 41% of global lithium production, China accounts for 47% of lithium carbonate refinery capacity, mostly because it processes the vast majority of Australian lithium. China also leads in demand of cobalt and lithium for LDV Li-ion battery (LIB) materials. Its estimated use from 2014 through 2016 was between 15,000 metric tons (mt) and 24,000 mt of cobalt, and between 15,000 Mt and 40,000 Mt of lithium carbonate equivalent. Other top markets for cobalt and lithium for LDV LIB materials include Japan, South Korea, and Belgium.

As for trade, the Democratic Republic of Congo is the leading exporter of cobalt materials, with about $4.5 billion worth of cobalt materials exported from 2014 through 2016. China is the leading importer of cobalt materials, with about $3.5 billion worth of cobalt materials imported in the same period. Of the lithium materials analyzed in this report (lithium carbonate and hydroxide), Chile leads on exports, with about $151 million worth of lithium exported from 2014 through 2016, whereas Japan leads on imports, reporting about $478 million worth of imported lithium materials. Lithium trade flow records for Australia are not tracked separately by the Harmonized System (HS) code. Australia exports most of its unprocessed lithium (spodumene) ore to China. The analysis described in this report is limited to lithium materials tracked by the HS code and used in LDVs.

Table of Contents

List of Figures

List of Tables

1 Introduction

The first of the four links in the Clean Energy Manufacturing Analysis Center (CEMAC) manufacturing supply chain analysis is raw materials (CEMAC 2017). This link is intended to track the supply chain from mine production and processing to manufacturing of components used in production of clean energy technologies. While information about the final products is often available, the upstream data are often intertwined with data for much larger markets and are difficult to track. Disaggregating trade and market data to estimate technology-specific demand and supply is challenging. The challenge is even greater with clean energy technologies, such as light-duty vehicle (LDV) lithium-ion (Li-ion) batteries, that account for a very small, although growing, fraction of the market.

Critical raw materials used in manufacturing Li-ion batteries (LIBs) include lithium, graphite, cobalt, and manganese. As electric vehicle deployments increase, LIB cell production for vehicles is becoming an increasingly important source of demand.

This report represents the first effort to explore the raw materials link of the supply chain of clean energy technologies. We analyze cobalt and lithium—two key raw materials used to manufacture cathode sheets and electrolytes—the subcomponents of LDV Li-ion batteries from 2014 through 2016.

1.1 Location of Key Raw Materials

These materials are finite resources, and their production is highly concentrated in a few countries. Due to high geographic concentration in production, the markets for most of these materials are generally less open and less defined than those for conventional materials such as aluminum and copper.

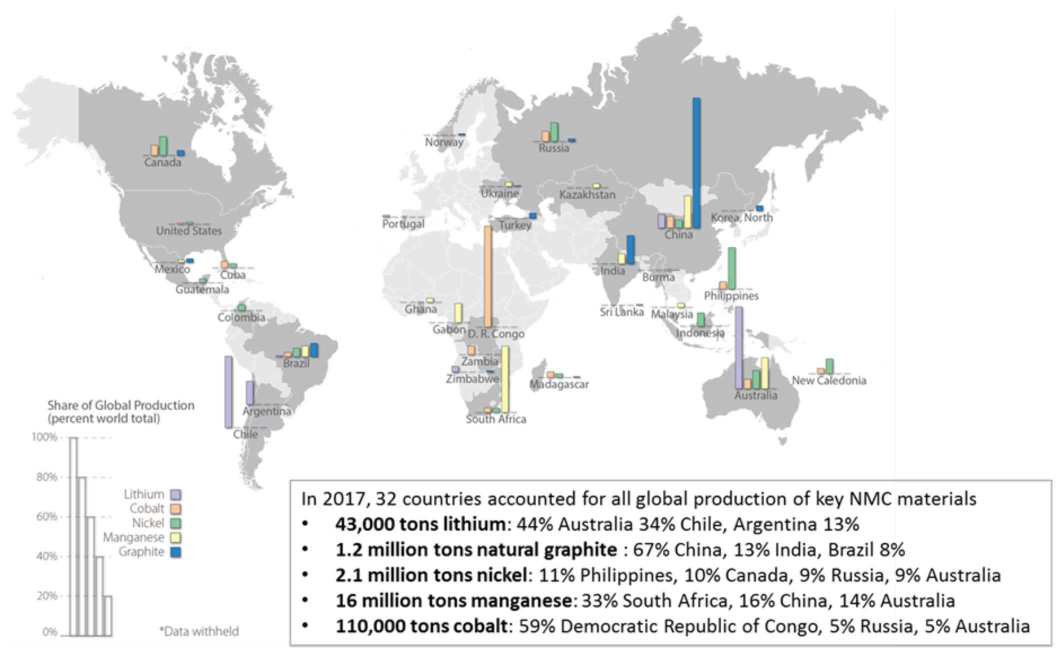

Figure 1. Key nickel, manganese, cobalt materials locations

Source: Mayyas et al. 2019

As shown in Figure 1, cobalt production is highly concentrated in the Democratic Republic of Congo (DRC), while lithium production is concentrated in Australia, Chile, and Argentina. Graphite is highly concentrated in China, while manganese is highly concentrated in South Africa. Nickel is relatively less concentrated in several countries. These are commodity materials that are also used by other industries. Understanding these materials' markets is therefore critical to understanding the impacts of continued LDV development on mineral production, and vice versa.

1.2 LDV Materials Use

From 2014 through 2016, the LDV LIB market had been a growing source of demand for these materials (see Table 1).[1] For example, in 2016, LDVs used about 31,260 megawatt-hours (MWh) of LIB capacity compared to an estimated 9,600 MWh in 2014. During the same period, lithium and cobalt use by LDVs grew to about 11.8% and 5% of total mine production, respectively, in 2016 compared to 4.4% and 1.4%, respectively, in 2014. This report explores the markets of cobalt and lithium—materials used to manufacture cathode sheets for LIBs.

Table 1. LDV Materials Use Estimates (2014–2016)

Years	Total LDV	Units	Material Consumption				
			Cobalt	Lithium[1]	Nickel	Manganese	Graphite
2014		metric tons	1,691	1,381	4,558	1,595	10,649
	(9,600 MWh)	% of mine production	1.40%	4.40%	0.20%	0.00%	
2015		metric tons	3,593	2,935	9,685	3,390	22,630
	(20,400 MWh)	% of mine production	2.90%	9.30%	0.40%	0.00%	
2016		metric tons	5,505	4,497	14,841	5,195	34,677
	(31,260 MWh)	% of mine production	5.00%	11.80%	0.70%	0.00%	

Notes: Total LDV LIB use (MWh capacity) estimates for 2014–2016 are based on CEMAC "Benchmarks of Global Clean Energy Manufacturing" 2017 report.[1] Lithium consumption estimates represent material used in cathode and electrolyte manufacturing. At least 60% of graphite used in LDV batteries is synthetic.

Source: NREL estimates

[1] In this report LIBs refer to battery packs, while LIB cells refer to the cells that go into the battery packs.

2 Cobalt Market

2.1 Cobalt Supply for All Applications

The main cobalt supply chain encompasses mining, ore processing to produce concentrates, and refining (through metal and chemical refineries).[2] Battery-grade chemicals (battery precursors) from chemical refineries are then used by cathode active material manufacturers (see Figure 2). Cobalt is generally mined as a byproduct of either copper or nickel. From 2014 through 2016, 67% of cobalt mined was a byproduct of copper, and 32% was a byproduct of nickel, whereas only 1% was produced from primary cobalt mines. Most cobalt deposits are in the Central African Copperbelt, which includes countries such as the DRC, the Central African Republic, and Zambia. In 2016, the U.S. Geological Survey (USGS) estimated global cobalt reserves at about 7 million metric tons, of which 47% is found in the DRC. The major cobalt-producing countries and their respective reserves are shown in Figure 3. Global cobalt production decreased 7%, from 119,004 metric tons in 2014 to 110,515 metric tons in 2016 (USGS 2018).

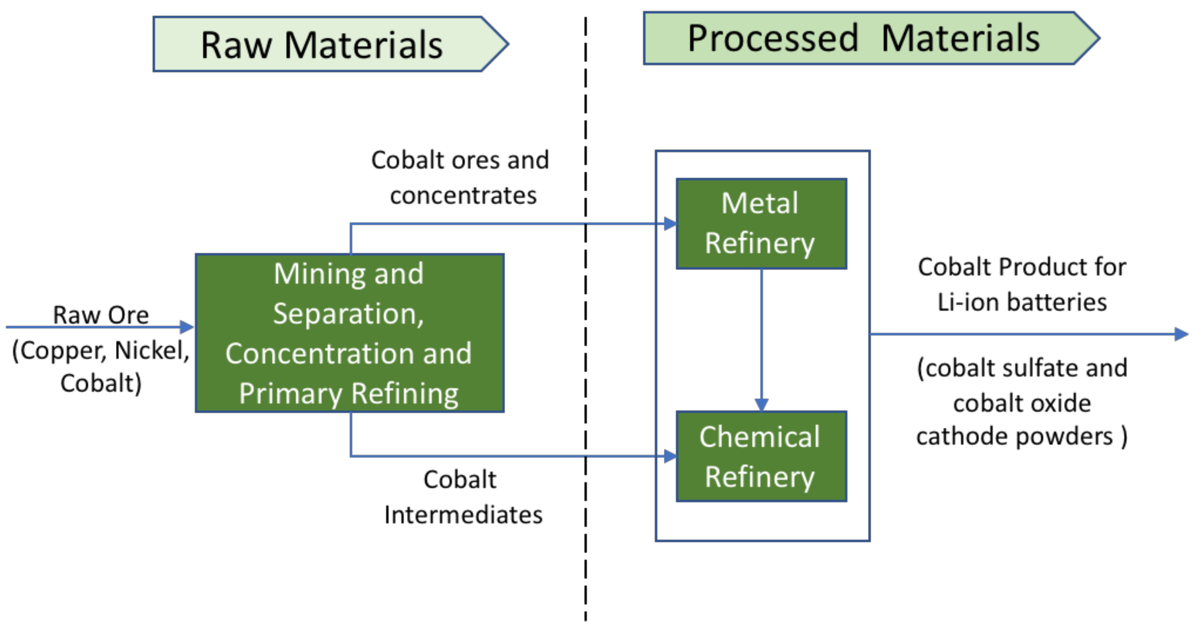

Figure 2. Cobalt supply chain in LIB manufacturing

Notes: Mining production includes output from both large-scale and small-scale (artisanal) mining.

The decline in cobalt production was due in part to declining prices of copper and nickel. These declines were attributed to metal oversupply and economic slowdowns in emerging countries such as China (Shumsky 2015, Valley Recycling 2015, Miller 2016, Burns 2016, IMF 2016, and

[2] With nickel-cobalt or copper-cobalt ore and concentrates, the main goal is to extract nickel or copper; thus, these concentrates are likely to end up at metal refineries rather than chemical refineries. Metal scraps are likely to be processed to produce metal first, whereas recycled batteries are likely to be directly converted into cobalt chemicals.

World Bank Database 2018). While most countries saw a decrease in cobalt production over this period, the DRC was not affected. This might be explained in part by the DRC's rich cobalt reserves compared to other countries, enabling the DRC to produce profitably even when prices are lower, as well as the presence of artisanal miners who are likely to accept lower cobalt prices.

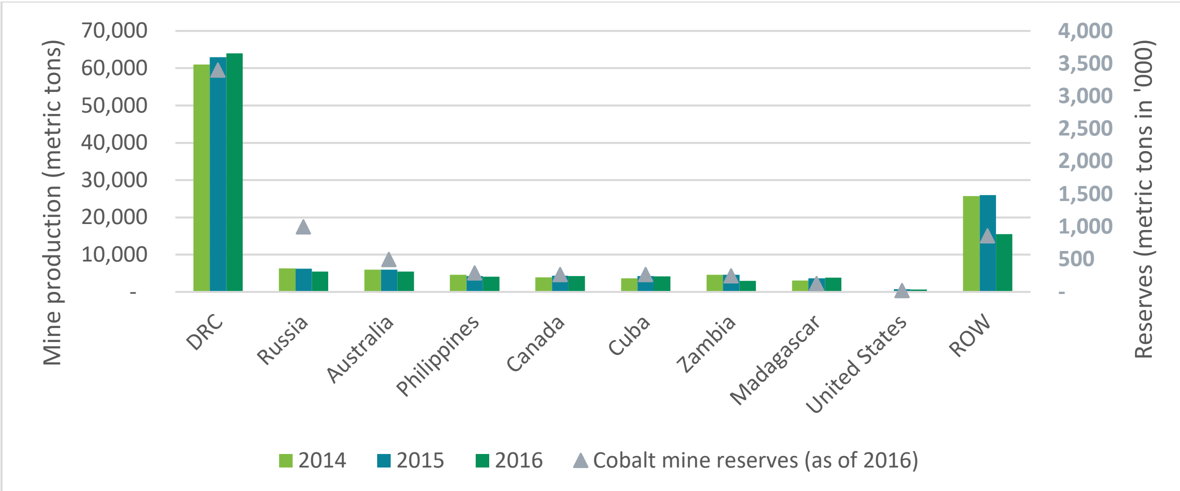

Figure 3. Cobalt reserves and mine production

Source: USGS 2018 and NREL estimates

From 2014 through 2016, about 53% of global mined cobalt production came from the DRC (see Figure 3). The majority of the country's producing mines are owned by Chinese companies (Darton Commodities 2018). Some of the Chinese companies operating in the DRC include China Molybdenum Co., Ltd., Zheijiang Huayou Cobalt, Jinchuan Group, Shalina Resource, Wanbao Mining, and Nanjin Hanrui Cobalt. Likewise, during the same period, China accounted for about 47% of global refined cobalt production (see Figure 4). China's interest in cobalt mining and refining stems from its dominance in LIB manufacturing for LDVs and its related priority to secure the supply chain (see Figure 6). During the same period, global excess manufacturing capacity was about 37,037 metric tons, implying that most refineries were producing under capacity.

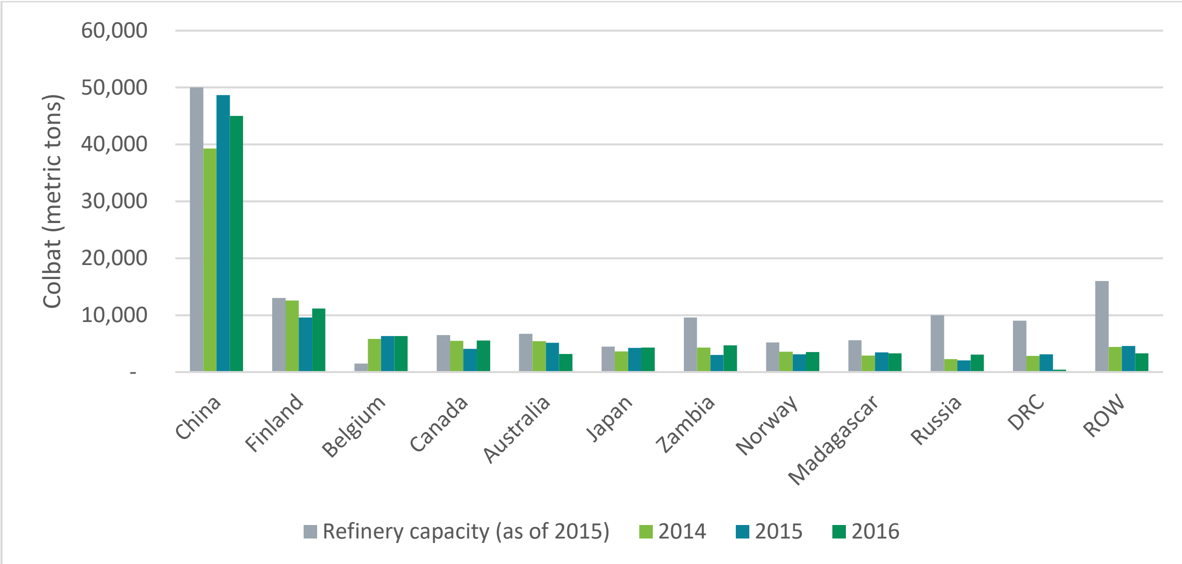

Figure 4. Refinery capacity and production

Notes: The data suggest that Belgium's refinery output is greater than capacity. However, some of its refined cobalt is refined in China, while some is recovered by Umicore from recycling. Belgian refinery capacity shown in the graph does not include recycling capacity and excludes Umicore's Chinese capacity.

Source: USGS 2018, Cobalt Institute 2018, and NREL estimates

2.2 Cobalt Demand

2.2.1 Demand for All Applications

Cobalt is predominantly used in chemical applications (especially batteries), and metallurgical applications (especially superalloys). In 2016, about 40% of total global cobalt production was used in LIB cells; 5% of global production was used for LDV batteries (see Figure 5).

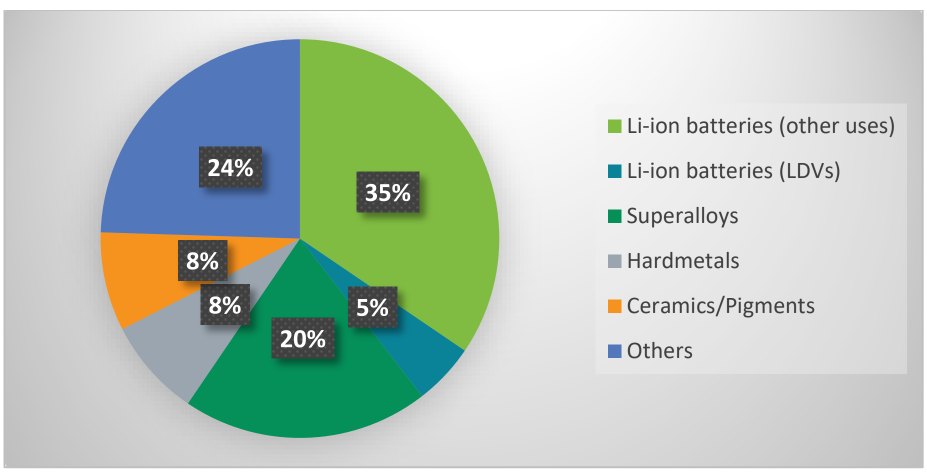

Figure 5. Global consumption of cobalt in 2016 (110,100 metric tons).

Source: NREL estimates

2.2.2 Cobalt Demand for Manufacturing of LDV Li-ion Batteries

The demand for Li-ion batteries for electric vehicles increased by 191% in the 2014–2016 period, from 11,000 MWh to 32,000 MWh (Pillot 2017, BNEF 2017, and NREL analysis 2018).

Concurrently, the proportion of global cobalt consumption accounted for by electric vehicles increased from 1.4% to 5% of total mine production. As of 2016, China remained the leading consumer of cobalt used to manufacture cathode active materials for LDV Li-ion batteries (see Figure 6).

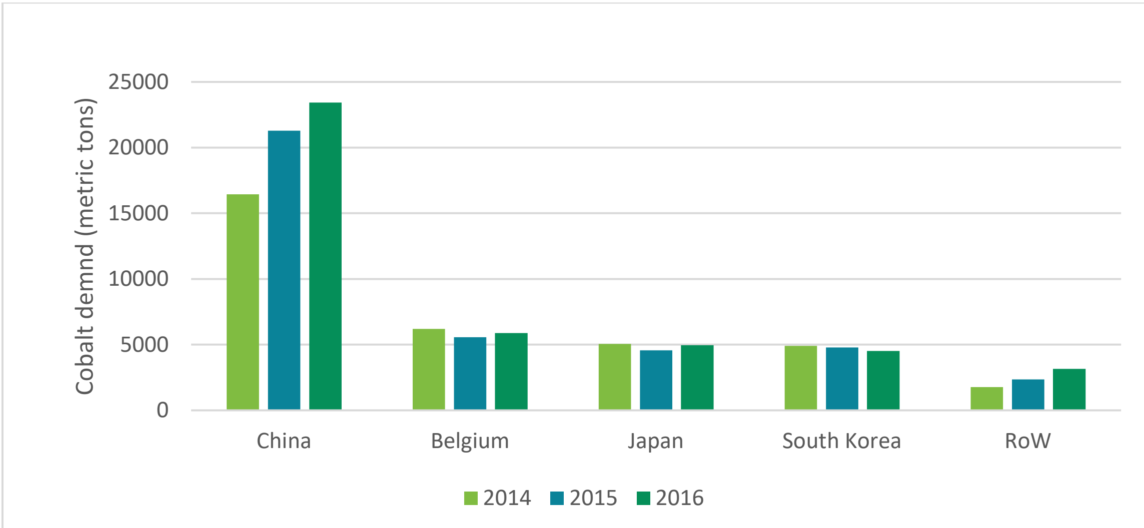

Figure 6. Cobalt demand for LDV LIB materials

Source: NREL estimates

Other major consumers of refined cobalt include Japan, South Korea, and Belgium. As shown in Figure 6, Japan, South Korea, and Belgium slightly reduced consumption of cobalt for LDVs from 2014 through 2016, while China's consumption increased significantly. The trend of increasing cobalt use in China might partly be explained by the growing domestic and global demand for LDVs. For example, LDV sales in China increased from about 73,000 vehicles in 2014 to about 336,000 in 2016, equivalent to an average annual increase of 115% (IEA 2017).

2.3 Cobalt Trade Flows

Cobalt trade across the globe can be traced in three main groups represented by the Harmonized System (HS) codes created by the World Customs Organization (WCO). The export and import of these cobalt materials are presented in Figure 7.

The DRC is the leading exporter of cobalt materials, while China is the leading importer. From 2014 through 2016, the DRC exported approximately $4.5 billion in cobalt materials, primarily to China and Zambia. In the same period, China imported approximately $3.5 billion in cobalt materials, almost entirely from the DRC. Most countries experienced a decrease in exports and imports of cobalt in this period. For example, the DRC experienced a decline of about 31% in exports in 2016, with exports decreasing from approximately $1.8 billion in 2015 to approximately $1.3 billion in 2016. The decrease is consistent with the emerging market economic slowdown and the associated decline in metal prices during this period.

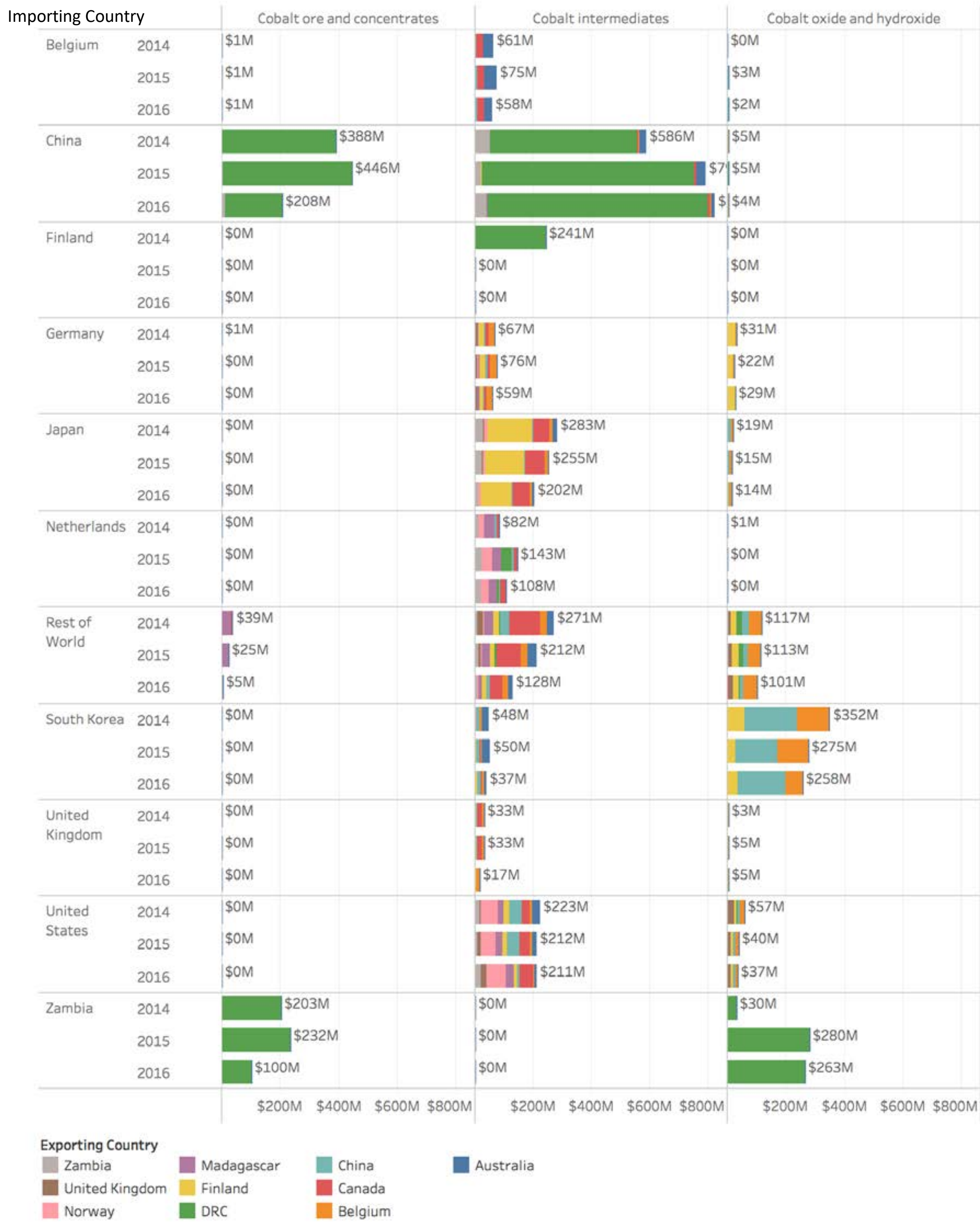

Figure 7. **Import and export of cobalt materials, 2014–2016**

Notes: Importing countries are listed on the left; sources (i.e., key exporting countries) are color coded. Cobalt ores and concentrates represent HS-260500; cobalt intermediates represent HS–810520, which is cobalt mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, and powders; cobalt oxides and hydroxides represent HS–282200.

Source: Data from UN COMTRADE, Trademap, and NREL estimates

3 Lithium Market

3.1 Lithium Supply for All Applications

Lithium is generally extracted from brine or hard rock (spodumene). Brine lithium recovery involves drilling and pumping liquids from underground salar brine to evaporation ponds. Hard rock lithium recovery consists of extracting lithium from the ore. As of 2016, most spodumene reserves were concentrated in Australia, whereas most lithium brine reserves were concentrated in Chile, Argentina, and China (USGS 2015–2018). The lithium supply chain is simpler than that of cobalt. Generally, the supply chain includes mining (from brine or spodumene) as well as beneficiation and refining into lithium carbonate (which can then be used to produce lithium hydroxide and other compounds). Refined lithium carbonate is then purified into battery precursors used by cathode active material and electrolyte manufacturers. While both lithium carbonate and lithium hydroxide are used in LIB cell manufacturing, the former has been used predominantly because of the higher cost of producing lithium hydroxide. However, most popular Li-ion battery materials for LDVs, such as nickel cobalt aluminum (NCA) and nickel manganese cobalt (NMC), require lithium hydroxide, so as the LIB LDV market share grows, more lithium hydroxide will be needed. In most cases, lithium carbonate is used as a precursor to lithium hydroxide, which requires an extra processing step reflected in its relatively higher price. The major lithium mine producers and their respective reserves are shown in Figure 8.

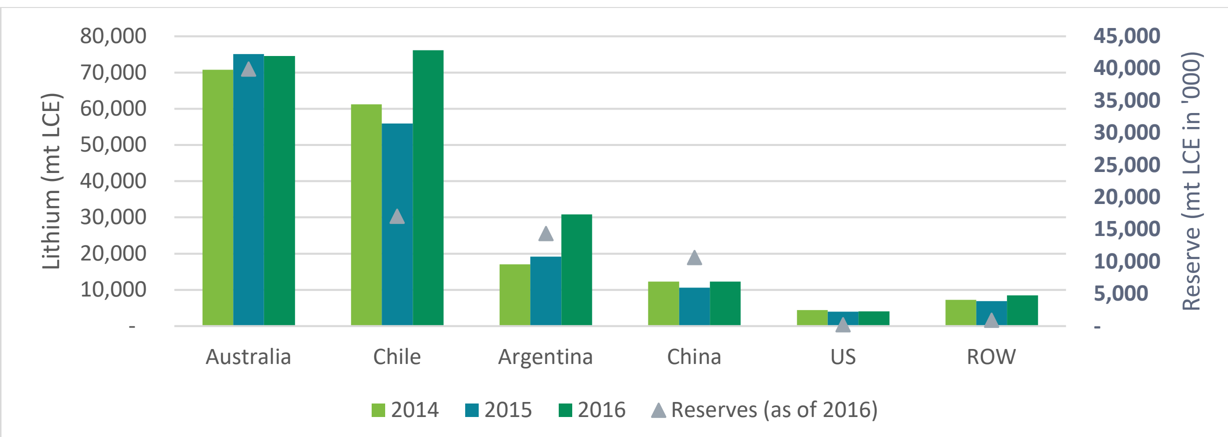

Figure 8. Lithium reserves and mine production

Source: USGS and Cobalt Institute 2018

In 2016, total global lithium reserves were estimated at 16 million metric tons, equivalent to 83 million tons of lithium carbonate equivalent (LCE).[3] Unlike cobalt, lithium production notably increased from 2014 through 2016. While other commodity prices—such as nickel and copper—were crashing during this period, lithium prices (carbonate and hydroxide) surged. For example, the price of lithium carbonate increased 80% from approximately $5/kg in 2014 to $9/kg in 2016.[4]

[3] Lithium carbonate equivalent is the industry standard for measuring lithium volumes.
[4] Lithium price is based on South America lithium carbonate free on board (FOB) swap.

The higher lithium price was partly caused by increasing demand driven by an increase in LDV manufacturing that used Li-ion batteries. Figure 8 shows countries with brine reserves such as Chile and Argentina were able to adapt to increased demand and produce more lithium, whereas Australia (which produces spodumene) was not. The result suggests hard rock mines are less able to respond to rapid market changes. This behavior is consistent with the fact that hard rock lithium extraction is relatively more expensive than easier-to-extract brine (Desjardins 2015, Energy & Capital 2018, IHS Markit 2018, McKinsey & Company 2018, and PR Newswire 2018).

Figure 9 shows the leading producers of lithium carbonate from 2014 through 2016. Chile and Argentina processed most of their mined lithium (from brine). While Australia led in raw lithium production, it did not process its lithium ore, instead exporting most of it to China, where it underwent beneficiation and refining into lithium carbonate. This explains why China, despite mining an average of less than 15,000 metric tons of LCE per year from 2014 through 2016 (see Figure 8), produced an annual average of 70,000 to 80,000 metric tons of lithium carbonate during this period.

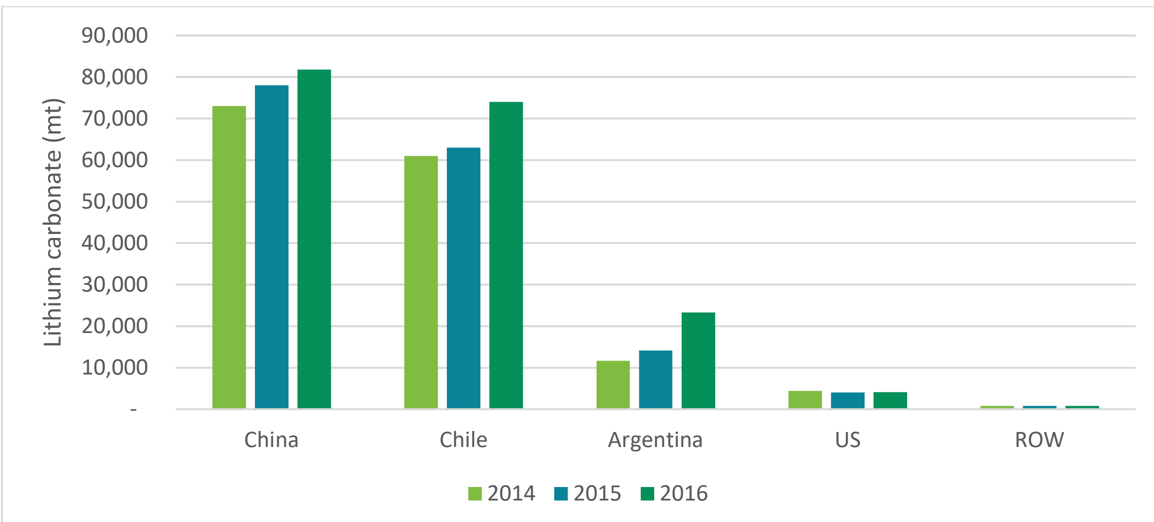

Figure 9. Lithium carbonate production

Source: USGS 2018 and NREL estimates

3.2 Lithium Demand

3.2.1 Demand for All Applications

Aside from its use in batteries, lithium has a wide variety of other uses, most notably in ceramics and glass. By 2016, about 34% of the total global lithium production was used in LIB cells; 12% of global production was used for LDV batteries. In LDV batteries, lithium is used to make cathodes and electrolytes—the subcomponents of the Li-ion cell. Lithium end uses are shown in Figure 10.

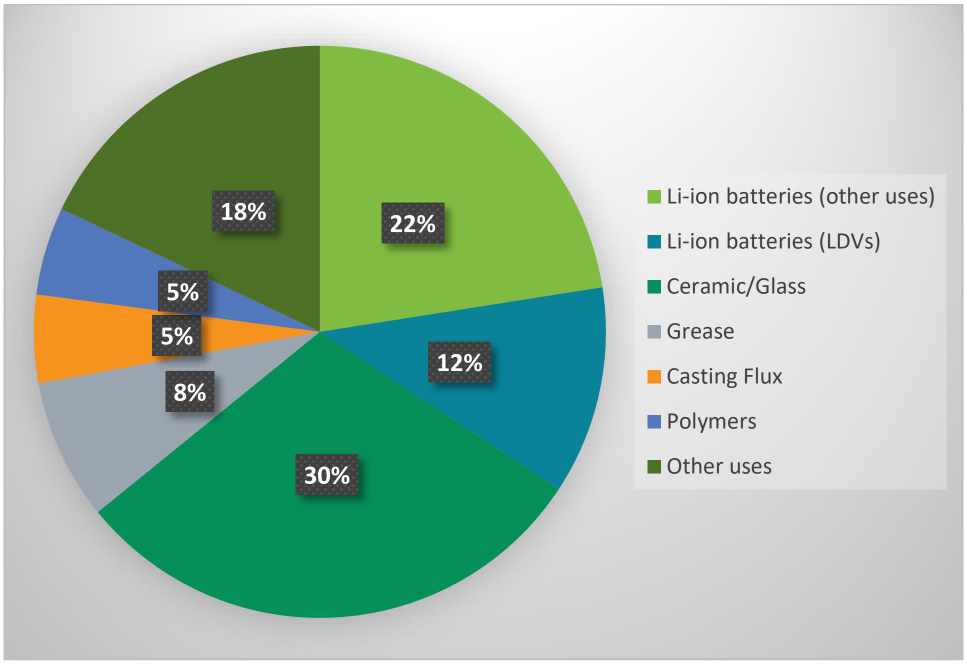

Figure 10. Global consumption of lithium in 2016 (199,479 metric tons LCE)

Source: NREL estimates

3.2.2 Lithium Demand for Manufacturing of LDV Li-ion Batteries

Global lithium consumption for LDVs grew 46% from 2014 through 2015 and another 28% from 2015 through 2016. Lithium demand for all applications is presented in Appendix 1. The leading consumers of lithium for LDVs are shown in Figure 11. China is by far the largest consumer of lithium for LDVs, and its share of global consumption grew substantially from 2014 through 2016, due in part to increasing global demand for LDVs.

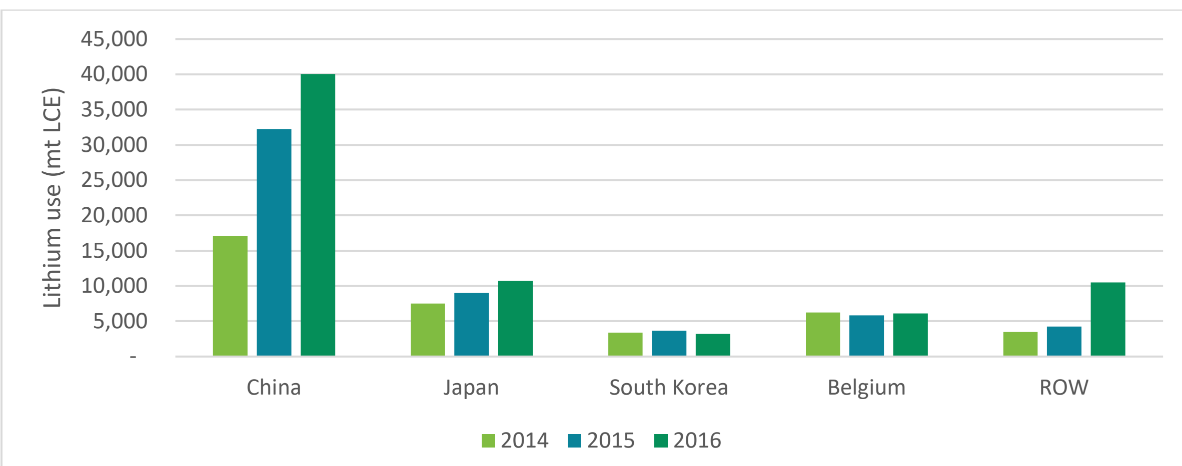

Figure 11. Lithium use for LDV LIB materials

Source: NREL estimates

3.3 Lithium Trade Flows

Lithium is processed into a variety of compounds, but lithium carbonate and lithium hydroxide are the compounds of interest for LDVs. The imports and exports of these lithium materials are presented in Figure 12. As expected, Australia has no record of lithium exports despite being the leading producer of lithium. This is because Australia exports most of its unprocessed lithium (spodumene) ore to China, and the lithium ore trade flow, due to its small quantities relative to other exports, is not tracked separately by the HS code in the UN COMTRADE database. In this analysis we only focus on tracked lithium materials used in LDVs. Chile is a leading exporter of tracked lithium materials, mostly in the form of lithium carbonate. From 2014 through 2016, Chile exported approximately $1.1 billion in lithium materials, most of which were exported to South Korea, Japan, and China.

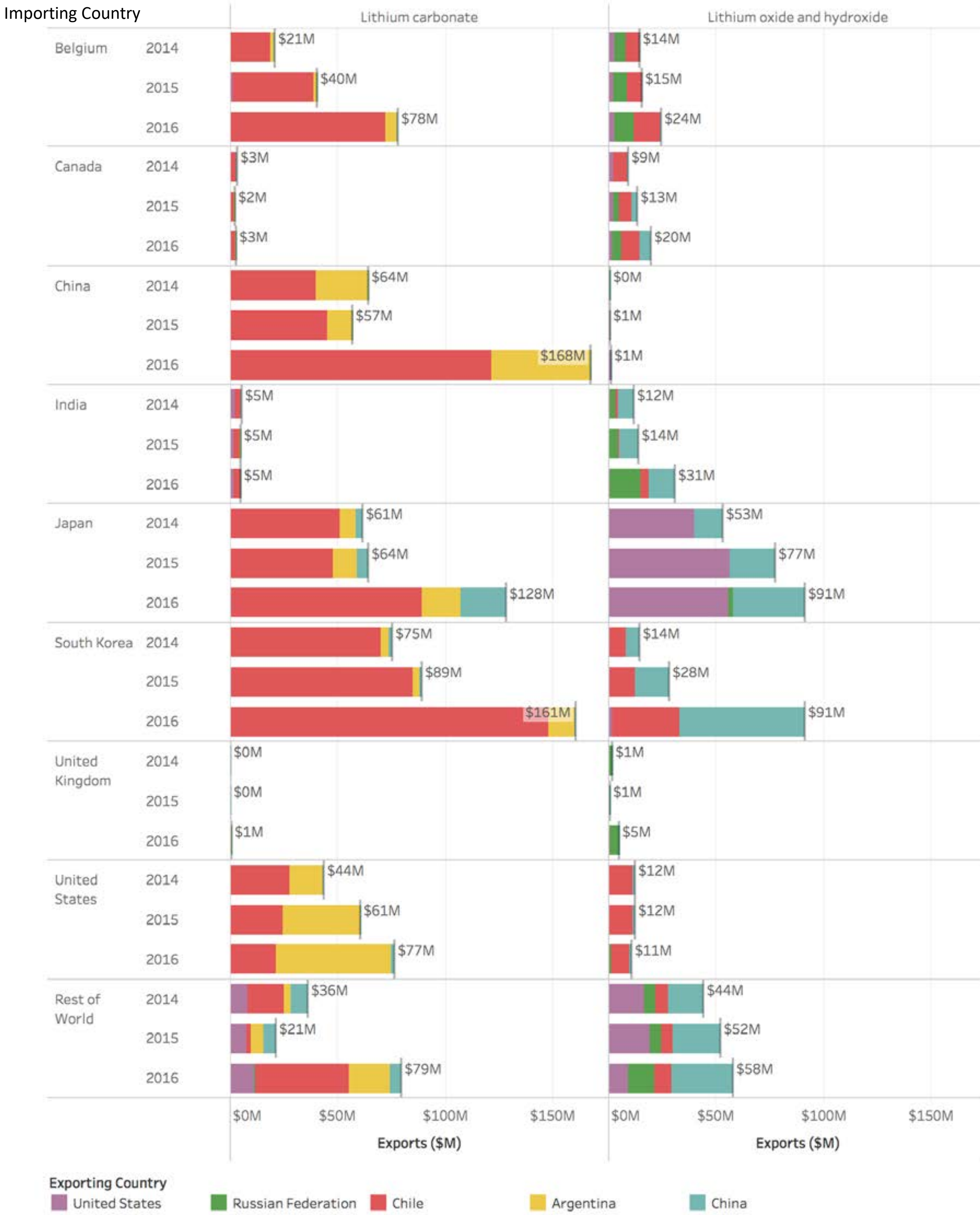

Figure 12. Import and export of lithium materials

Lithium carbonate (HS – 283691) and lithium oxide and hydroxide (HS – 282520) importing countries are listed on the left; sources (i.e., key exporting countries) are color coded.

Source: Data from UN COMTRADE, Trademap, and NREL estimates.

4 Conclusion

This analysis is a first effort to integrate raw materials into the CEMAC analysis framework. This report serves as a foundation for incorporating the raw materials link for other clean energy technologies into CEMAC Benchmark reports (CEMAC 2017) and into future supply chain analysis. Benchmarking raw materials provides a broader view of countries gaining value from the manufacture of clean energy technologies, along with additional insight into who owns the resource, potential supply chain risks, and opportunities. Finding data at the required level of detail to conduct robust analysis, however, remains a challenge.

This analysis suggests that the cobalt supply chain is relatively less secure than the lithium supply chain. Lithium suffered only the effects of an economic slowdown during the period of analysis, whereas cobalt production was also affected by price volatility in other metal markets. This production impact occurred because cobalt is mainly produced as a byproduct or coproduct of copper and nickel, both of which have volatile markets. As our analysis shows, cobalt supply responded strongly to the crashing of base metal prices during the 2014–2016 period.

The analysis also demonstrates countries' efforts to assure future materials availability. Most leading producers of cathode active materials are highly involved in some capacity throughout the raw material value chain. For example, while the DRC leads in production of cobalt, most companies that own mines in the DRC are from China. As for the lithium market, while Australia owns about 47% of global lithium reserves and accounts for an average of 41% of global lithium production, China accounts for 47% of lithium carbonate refinery capacity, mostly because it processes the vast majority of Australian ore. In addition, the leading producer of lithium ore in Australia is Talison Lithium Limited, whose parent company, Tianqi Lithium Corp, is from China.

Disaggregating trade and market data to estimate the contribution to a specific technology is challenging, regardless of the industry. The challenge is even greater with clean energy technologies, such as LDV Li-ion batteries that account for a very small, although growing, fraction of the market. Additional data collection and analysis of raw materials and their role in the supply chain may enable supply risk reduction for clean energy technologies as they expand in the energy markets.

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