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Perspective

Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals

Elsa A. Olivetti,[1,*] Gerbrand Ceder,[2,3] Gabrielle G. Gaustad,[4] and Xinkai Fu[1]

Sustained growth in lithium-ion battery (LIB) demand within the transportation sector (and the electricity sector) motivates detailed investigations of whether future raw materials supply will reconcile with resulting material requirements for these batteries. We track the metal content associated with compounds used in LIBs. We find that most of the key constituents, including manganese, nickel, and natural graphite, have sufficient supply to meet the anticipated increase in demand for LIBs. There may be challenges in rapidly scaling the use of materials associated with lithium and cobalt in the short term. Due to long battery lifetimes and multiple end uses, recycling is unlikely to provide significant short-term supply. There are risks associated with the geopolitical concentrations of these elements, particularly for cobalt. The lessons revealed in this work can be relevant to other industries in which the rapid growth of a materials-dependent technology disrupts the global supply of those materials.

Context & Scale

The key conclusions of this perspective have shown that the supply of most materials contained within lithium-ion batteries will likely meet the demand for the near future. However, there are potential risks associated with the supply of cobalt. Furthermore, if there is rapid adoption of electric vehicles (incentivized by policy interventions including a carbon tax, higher fuel taxes, and more aggressive Corporate Average Fuel Economy targets), demand could outpace supply for some battery-grade materials (even for lithium in the very near term). The implications for research based on this perspective span many scales. First, continued research into cathode materials that alleviate some of these supply issues is of interest, particularly those that are cobalt free. Supply chain research and investigations in the policy domain may also help uncover ways to address materials availability in the future. Future investigations should provide a dynamic analysis with sufficient detail to map technological and operational changes to their impact on cost and to map performance to market value.

Introduction

Until recently, the market for lithium-ion batteries (LIBs) was driven by their use in portable electronics. A shift in demand to include larger form factor batteries, primarily for electric vehicles (EVs) (and stationary storage), catalyzed new supply chain dynamics for the materials used to make LIBs. There has been a great deal of focus in the scientific literature and popular press on this issue.[1–4] In 2016, *The Economist* dubbed lithium "the world's hottest" commodity because of perceived scarcity issues surrounding this material.[5,6] The *Washington Post* has traced the supply chains of both Li and Co in recent expositions that outline their impact on the local populations of South America and Africa, respectively.[7,8] Events within this decade surrounding materials supplied from the Democratic Republic of Congo (DRC) demonstrated that even minor materials markets can have major impacts on the technological strategies employed in many economic sectors.[9] Ultimately, this occurs because many advanced technologies are fundamentally "materials dependent." In other words, they are enabled directly by, or designed around, a particular set of material(s) and are therefore subject to the supply chain issues that accompany those materials. Given the demand growth for LIBs, driven by a continued drop in cost, and a desire by society to decarbonize the transportation fleet, continued attention should be given to understanding potential risks surrounding the resource availability associated with these products.

In this article we focus on the supply of elements found in LIBs, with strong emphasis on metals within current cathode materials. First, we explore the variation in the metal content of different cathode chemistries. Based on this estimated element intensity, we outline the supply chains for each of these elements to understand how supply might reconcile with future demand (quantitatively, we project demand up to 2025). We then scale per kWh intensity to demand for cobalt in LIB end-use products including automobiles, electronics, and grid storage. Finally, we make brief mention of mitigating factors such as the use of alternative materials and materials recovery at end of life. The overall question this article addresses is: what role do raw materials supply constraints play in the ability to meet future demand for LIBs?

Previous work has provided specific case studies on targeted battery chemistries, metrics for a particular metal's use, life-cycle assessment of various propulsion technologies, and analyses of issues surrounding end of life. In terms of resource metrics, Ghadbeigi et al.[10] have focused on supply concentration and crustal abundance. Other authors, meanwhile, have focused on metal intensity as a function of battery capacity and on the stocks and flows of some of the relevant materials.[11–13] Significant attention has been paid to the availability of lithium and less so on the other materials related to LIBs, although a recent study quantified resource use in the context of the European Union.[14] Estimates of battery demand vary significantly because of differences in assumed battery chemistry, the materials intensity per battery, the projection of EV use and penetration, and other potential applications, such as grid storage. Estimates of the supply of the required materials vary because of assumed concentrations, resource estimates, and the uncertain nature of future extraction projects.

What Is in a Lithium-Ion Battery?

Over the last decade, LIBs have been introduced in EVs. With more than two decades of improvements in energy and power density, safety, cost, and cycle life, LIBs have become the preferred battery system adopted by leading EV manufacturers such as General Motors, Honda, Nissan, Ford, BMW, and BYD. While some hybrid electric vehicles (HEVs) still use nickel metal hydride batteries, LIBs are more attractive for plug-in hybrid vehicles and battery electric vehicles (BEVs) due to their light weight, much higher energy density, longer cycle life, and ability to provide deep discharges. Therefore, we focus only on LIBs in our analysis.

A LIB consists of an anode, typically graphitic carbon, and a cathode, separated by a liquid organic electrolyte. Inactive components include a polymer separator, Cu and Al current collectors, as well as casing and packaging materials, but none of these is likely to be constrained by resource limitations, except potentially the electrolyte because of its Li content. Hence, we focus here on cathode materials, with some discussion on the graphitic anodes. Multiple cathode materials are currently in commercial use for LIBs. We examined layered oxides in the $LiMO_2$ family, where M is some combination of Co, Ni, Al, and Mn, as these elements provide compounds with the highest energy densities and, as a result, yield batteries that dominate the portable electronics and automotive fields. Non-layered cathodes, such as $LiFePO_4$ (LFP), mainly find use in China for electric bus and grid applications and are, thus, outside of the scope of this investigation. While it is used by some Chinese EV makers such as BYD, LFP is expected to be replaced in this application by layered cathodes to satisfy higher energy density requirements. $LiMn_2O_4$ spinel (LMO), used in early EVs, is likewise being phased out due to concerns about stability and energy density. LFP may continue to play a role in grid applications, though this outcome is far from clear.

Table 1 shows our estimate of the approximate amount of metal (in kg) required per kilowatt-hour for five prototypical cathode materials, although these numbers can

[1]Department of Materials Science & Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[2]Department of Materials Science & Engineering, University of California Berkeley, Berkeley, CA 94720, USA

[3]Materials Science Divisions, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[4]Golisano Institute of Sustainability, Rochester Institute of Technology, Rochester, NY 14623, USA

*Correspondence: elsao@mit.edu

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Table 1. Element Requirements (Li, Co, Ni, Mn, Al) for Three Battery Cathodes of Interest in Units of kg/kWh

	Li	Co	Ni	Mn	C
LCO	0.113	0.959	0	0	~1.2
NCA	0.112	0.143	0.759	0	
NMC-111	0.139	0.394	0.392	0.367	
NMC-622	0.126	0.214	0.641	0.200	
NMC-811	0.111	0.094	0.750	0.088	

LCO, lithium cobalt oxide; NCA, lithium nickel cobalt aluminum oxide; NMC, lithium nickel manganese cobalt oxide (numbers denote ratio of Ni, Co, and Mn on a mole fraction basis). C is also shown (this last data point from literature).[16]

vary somewhat depending on the charge cut-off and cell design used in each application. Graphitic carbon is also included, based on literature values.[15,16] We would like to emphasize that these metals are used in various precursor forms to produce the cathodes, such as hydroxides, sulfates, carbonates, and, in some cases, nitrates. By framing the use of these materials in terms of their metal content, we aim to provide a clear indication of the demand for the element on a metal basis. To be clear, this does not suggest that these materials are used in their metallic forms within the battery. Lithium cobalt oxide ($LiCoO_2$; LCO) is mainly used in the portable electronics market due to its superb energy content per unit volume, which has enabled thinner cell phones and laptops. Lithium nickel cobalt aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}$; NCA), developed in the early 1990s, has good energy density and high power capability, making it the technology of choice for the automobile manufacturer Tesla. Most other automakers and some electronics makers instead use some version of lithium nickel manganese cobalt oxide (NMC). While there are multiple commercially available compositions in the NMC class, we include three specific variants in our analysis: NMC-111, NMC-811, and NMC-622 (where the numbers denote the ratio of Ni, Co, and Mn on a mole fraction basis). As the Ni content increases in the NMC-class materials, the energy content goes up, but usually at the expense of stability. High-Ni-content materials also tend to incur extra processing costs. While NMC-111 is already commercially well established and NMC-622 has seen recent market introduction, NMC-811 appears on the automotive roadmaps due to its superb energy content. It still suffers, however, from significant capacity fade and higher safety risks. We are skeptical that it will see widespread adoption in the EV industry within the time frame of our assessment (2025). We note that Table 1 gives the elemental content in the final battery. Material waste in production would cause these totals to increase, although previous studies have indicated that production waste is likely to be minimal relative to the materials contained within the product.[17]

Materials Supply

Based on this assessment of the elements used in LIBs, we turn to the supply of each element and discuss potential supply issues. We will comment almost exclusively on the relative availability of the metal itself, but also add mention of the forms in which these materials are actually used. First, we consider several static metrics of materials availability for Li, Mn, Co, Ni, and C. Figure 1 shows several indicators of relative elemental availability. Data were obtained from the United States Geological Survey (USGS)[18] and British Geological Survey. As a brief aside, we note that materials costs are typically cited as between 70% and 80% of the total cell cost (although some estimates are closer to 50%[17]).[19] About half of that 80% is due to active cathode and anode materials (note: these cost fractions are based on processed materials,

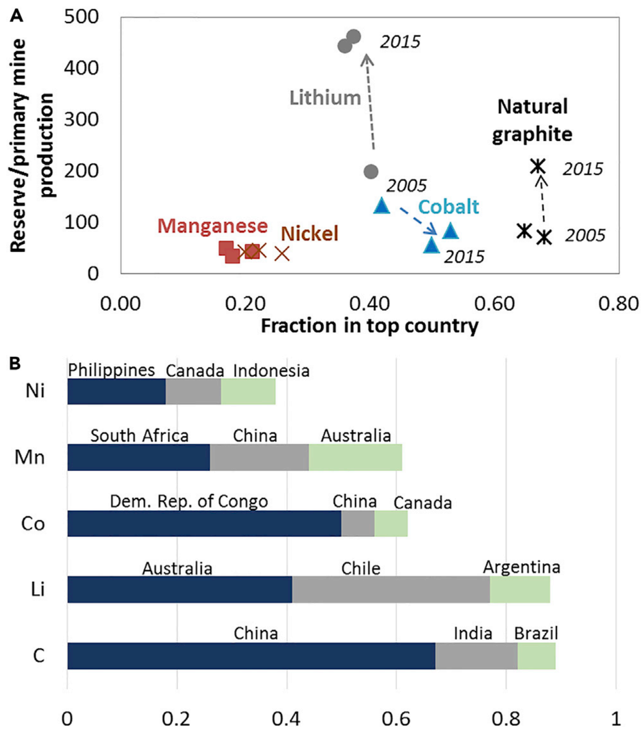

Figure 1. Static Metrics of Resource Use for Ni, Mn, Co, Li, and Natural Graphite

Static metrics of resource use for Ni, Mn, Co, Li, and natural graphite fraction in top country versus static depletion over time (arrow indicates increasing time) (A), and production fraction by country (B).

not on a metals basis). While material pricing may not have been particularly relevant when LIB costs were 1,000 USD per kWh, materials price becomes increasingly important as cell cost comes down toward 100 USD per kWh.

Figure 1A shows the reserves for each element (the part of a resource base that could be economically extracted or produced at the time reported), normalized by annual mine production, plotted versus the fraction of mining that is done in the top producing country. For each of the five materials three data points are shown based on data for 2005, 2010, and 2015, where the arrows shown for Co, Li, and natural graphite indicate increasing time (there is no trend in the directionality for Mn and Ni). The y axis is often termed the "static depletion index," and for all materials shown this number is higher than 30 years. For the larger, more developed, diversified markets (Ni and Mn), this number is lower (averaging around 45 years). However, for both metals this index is relatively constant over the 15-year time period, indicating that the economics of demand drive the supply toward continued economical extraction. Smaller numbers along the x axis of Figure 1A indicate that the supply of these materials is more diversified geographically. Generally, supply of Co has become more concentrated over time with 50% of current production in the top country. Natural graphite is even more concentrated, with more than 65% in the top country. We show this result in more detail in Figure 1B, which plots concentration in the top three countries for each material, based on 2015 production. This plot demonstrates that the supply of Co is concentrated in the DRC and natural graphite supply is concentrated in China. These concentrations have been cited as a concern, as one factor that makes materials critical is the possibility of supply disruptions caused by government policy or socio-political instability.[20,21] Disturbances in material supply can lead to short-term supply gaps, which have the potential to create significant price volatility and commodity price uncertainty.[22,23]

Based on this brief exploration, Figure 1 suggests potential concerns from a supply concentration perspective for Co, Li, and possibly natural graphite, but no detectable supply concerns for Ni or Mn, which is consistent with what previous work has shown.[13,24] In particular, for both of these latter materials their use in LIBs remains a small portion of their end-use demand, with steel manufacture dominating the use of both. Furthermore, Ni production in 2025 has been estimated at above 2,000 kt per year and both Ni and Mn are well distributed among the countries from which they are mined.[25]

Before exploring Li and Co in detail we comment briefly on the status of natural graphite, which is prevalent in the earth's crust and whose static depletion index has increased significantly in recent years. Natural graphite has a diverse set of end uses that includes refractory applications, steelmaking, brake linings, and batteries, which require flake and spherical graphite. This diversity in demand implies that battery use of natural graphite was only about 2% of total consumption in 2013 (flake graphite is used primarily in refractories and batteries, however), potentially increasing to 10% in the next year.[26] The main concern cited with regard to graphite is that current mined production is concentrated in China (>65%), so developments in the industry are currently focused there (the European Commission did list graphite among its 14 critical mineral raw materials in 2010).[27] However, crustal abundance for graphite is quite high; there is also potential for increased production in India, Brazil, and throughout Africa, as well as further exploration and development in the United States, such that the geographical supply concentration is likely only of short-term concern. Given the high crustal abundance and mining ease of natural graphite, extraction will become more geographically diverse as demand increases. Furthermore, synthetic graphite can be substituted for natural graphite, and manufacturing sources of synthetic graphite are quite well distributed (production of synthetic graphite was around 130 kt in the United States in 2013).[28] The raw materials for synthetic graphite may be feedstocks such as pet coke or coal tar pitch, which are then processed through several grinding, blending, heating, forming, and graphitization steps to make usable anode materials. Currently the LIB industry is mixing natural and synthetic graphite. Synthetic graphite is more expensive (by some estimates, almost double), however, so this tradeoff between cost and supply concentration will continue to influence the use of each of these graphites.

Next we focus in slightly more detail on supplies of Li and Co. The availability of Li has proved to be a controversial topic; results often present contradictory accounts of whether supply can meet demand in the near future. These contradictions result primarily from significant variation in the projected future supply, particularly around changes in deposit concentration. However, most studies imply that supply can outpace demand based on the significant reserves. Li also has a diversity of extraction technologies. First, Li can be recovered via evaporation from the brine of salt lakes, where recovery of potash also provides some offsetting revenue to materials producers.[2] Brine recovery from new or expanded locations has a relatively short ramp-up time of only about 12 months.[29] In this case the lithium brine is concentrated, impurities are removed, and the addition of soda results in the precipitation of lithium carbonate (Li_2CO_3), which is then filtered, washed, and dried. Another current extraction form is mined pegmatites, typically present in the mineral spodumene, which may also result in the extraction of Sn or Ta.[2] The mined concentrate is leached and precipitated as Li_2CO_3 or LiOH (this route is more expensive than extracting from brine). Sea water extraction is also referenced as a future reserve.[1] In each case, lithium precursors (typically carbonates or hydroxides) are combined with sulfate precursors (or others) of Mn, Co, or Ni in a series of steps to make the cathode materials of interest. (Further detail on these multi-step processes can be found in a variety of sources.[15,30]) Recent resource estimates for Li range from 33 to 64 million tonnes, and reserves range from 13 to 40 million tonnes.[2,3]

With regard to geographical focus, Chile and Argentina produce Li_2CO_3 from brine, while Australia produces lithium concentrate from spodumene. The production in China is split between these two routes (65% brine). This geographical distribution in type (and, therefore, extraction technology) and location indicates that Li supply is unlikely to suffer from constraints based on quantity. Furthermore, Li production remains relatively immature in terms of resource exploration, as demonstrated by the changes in static depletion index shown in Figure 1A. In other words, resources are still being discovered (for example, the USGS recently tripled their reserve and resource estimates over the course of 2 years), leading to increased resource estimates in recent years.[12] Figure 2A shows the global aggregated trade flows of lithium oxide, hydroxide, and carbonates based on data from UN Comtrade (for flows greater than 1 million US dollars [USD]). This map excludes concentrate flows of mineral-based trade in spodumene, because of lack of data (such a flow would be dominated by exports from Australia to China). The widths of flows are proportional to the trade value in USD, importers are marked in green, and exporters are marked in red. We see significant flows from the Americas to Asia, where the majority of battery manufacture occurs. Consumption of Li in China is 50% of the global share (largest in the world), while production is only 7%. China is therefore rather dependent on imports.[31,32]

Recent literature offers some consensus that the challenges of Li production are not whether there is enough material, but rather whether production can ramp up quickly enough.[29] Just examining whether supply meets demand does not provide insight into this rate problem.[12] The recent and rapid consumption of LIBs (73% growth from 2010 to 2014) is coupled with only a 28% growth in production, leading to a consumption-production imbalance.[34] Therefore, concerns continue to surface about the potential supply chain bottleneck between beneficiated Li_2CO_3 and battery-grade material. However, based on the supply diversity and the significant attention this topic has received, many firms are positioned to respond relatively rapidly to disruptions. Several studies rely on increased recycling to mitigate issues around Li supply, but given the lifetimes of LIBs used in EVs, recycling will not provide significant supply in the near future, as the stock in use will be small relative to the demand. Furthermore, as Li has proved challenging to recover (recycle) economically under current prices, any Li recovered in response to a short-term stock will come from resources currently in the ground.[29,35]

Co is produced mainly as the by-product or co-product of Ni and Cu. According to an estimate by the Cobalt Development Institute in 2015, 50% of Co production can be attributed to the Ni industry, 35% to the Cu industry, and 9% to platinum group metals and others, while only 6% is from primary Co production.[36] About half of global Co production comes from the leaching of nickel-bearing laterite ores and the smelting of nickel sulfide ores. Typically, laterite ores used for nickel mining contain 1.3%–2.5% Ni and 0.05%–0.15% Co, while sulfide ores contain 1.5%–3% Ni and 0.05%–0.10% Co.[37] In both cases, the value of Ni is ~10 times higher than that of Co, so Co is typically the by-product of Ni production. Co produced as a by-product of Ni is not geologically concentrated, and its supply risk is mainly a result of its by-product nature. In other words, if demand for Ni were to drop, one could expect a reduction in Co production from this supply chain.

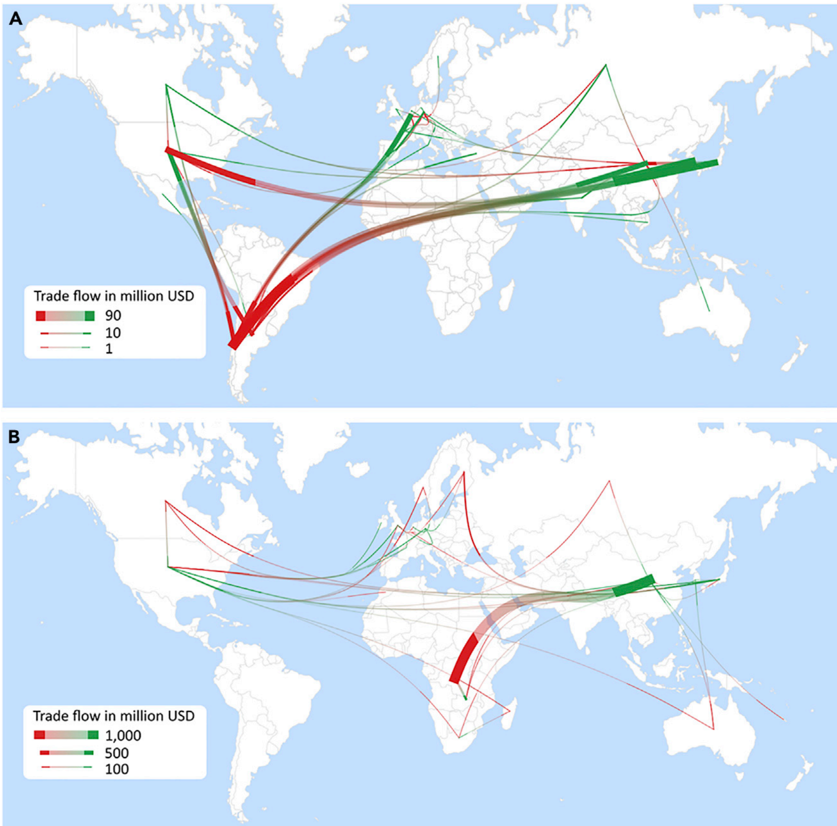

Figure 2. Global Aggregated Trade Flows

Widths of flows are proportional to trade value in US dollars (USD); importers are marked in green and exporters in red.

(A) Aggregated flows of lithium oxide and hydroxide as well as lithium carbonates (does not include concentrates, which would be dominated by Australia). Flows below 1 million USD in value are not included.

(B) Global aggregated trade flows of cobalt ores, concentrates, mattes, and other intermediate products of cobalt metallurgy, including waste and scrap for the year 2015. Flows below 10 million USD are not included.

Maps created in JFlowMap.[33]

On the other hand, however, the Co produced from Cu mining does not necessarily follow the trend of global Cu production (Co's other carrier metal). Almost all the Co production associated with Cu comes from mining copper-cobalt ores in the DRC.[38] Due to high Co concentration in these ores (typically 0.3% Co and 3% Cu), Co is produced mainly as co-product of Cu, and producers may be driven by the value of both metals simultaneously.[39] For example, the Mutanda mine in the DRC, one of world's largest Co mines, produced 250 kt of Cu and 25 kt of Co in 2016.[40] Considering a price of 5 USD per kg of Cu and 30 USD per kg of Co, ~40% of the mine's revenue comes from the value of Co. Extraction of Co from Cu mine tailings in the DRC are also possible, depending on the price ratio between the two metals. In addition, while the DRC accounts for more than 50% of world Co mining production, its Cu mining production only accounts for ~5% of world production.[41] Therefore, it is unlikely that the availability of Co is limited by world Cu production. Rather, Co availability will be greatly affected by the geopolitical stability of the DRC. The challenges with the supply of Co may be much more dependent upon the stability of the region than on the economics. This supply concentration can lead to more significant

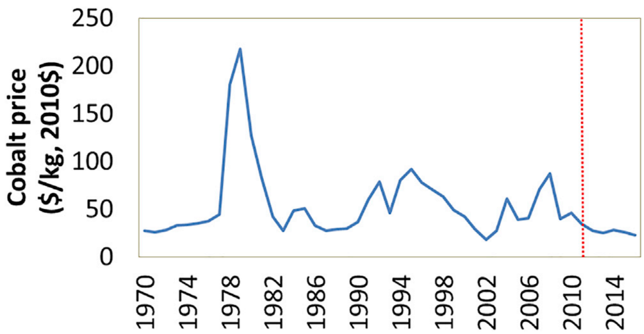

Figure 3. Cobalt Price from 1970 to 2015
Red dotted line indicates London Metal Exchange trading.[18]

volatility often manifested in significant price fluctuations. In the 1970s, institutional inefficiency led to price volatility and widespread supply disruptions of cobalt. Political unrest in the DRC (then Zaire) resulted in the temporary halting of Co exports. This restricted supply, combined with increasing Co demand and decreasing producer inventories, caused Co prices to skyrocket, as shown in Figure 3. Although the supply disruption was temporary and the year-end production of Co from the DRC exceeded the previous year's production, the Co market suffered.[23]

Not only is Co globally concentrated in mining, it is also geographically concentrated in refining, in China in particular. Figure 2B represents the global trade links of cobalt ores, concentrates, and other intermediate products, and includes only those flows above 10 million USD. This trade network is dominated by a small group of countries, including the primary link between the DRC and China (as well as Zambia, Finland, Japan, Canada, Norway, United States, and India). The largest trade flow is China's import from the DRC (1.2 billion USD), which accounts for almost 40% of total global trade value (3.1 billion USD). China was the world's leading producer of refined Co and the leading supplier of Co imports to the United States. Much of China's production was from ore and partially refined Co imported from the Congo; scrap and stocks of cobalt materials also contributed to China's supply. In 2015 and 2016, China was the world's leading consumer of Co, with nearly 80% of its consumption being used by the rechargeable battery industry.[42]

Despite various supply risks that might damage the stability of the Co supply chain, some recent changes in the industry might mitigate some of these risks. It is expected that with improvement in extraction technologies there will be a greater potential to extract Co as a primary metal in the future, which would make Co supply respond to changes in its demand more effectively. In addition, Co and Mo are the only two minor metals traded on London Metal Exchange (LME), which is the world largest exchange market for a variety of metals. Since LME started trading Co in mid-2010, the annual price volatility of Co has dropped from 0.426 between 1970 and 2010, to 0.126 after 2010 (price plotted in Figure 3, red dotted line indicates LME trading). Producers and consumers will both benefit from the transparency and effectiveness of this exchange market.

Based on this detailed discussion, we find that Co may be the main material risk in the short term for LIBs (with some scaling concerns around Li_2CO_3 as well). Therefore, in the next section we comment on how much Co will be needed as demand for LIBs grows over the short term (up to 2025) and compare this demand against a projected supply of Co.

Scaling Demand

To understand the broader demand for batteries (and therefore the elements used within them), we need to develop estimates of future demand. Several agencies have predicted widespread diffusion of electric-drive vehicles in the future, both in the United States and globally. The range of deployment scenarios by these agencies varies significantly across parameters (economic growth, oil price, proposed Corporate Average Fuel Economy [CAFE] standards, battery technology, etc.). To provide our estimated demand for Co we started from the estimated tonnages produced in 2016 (50 kt Co) and scaled this quantity with low (L) and high (H) assumptions to 2025 by making growth assumptions for each major LIB application. The end-use categories we consider are portable electronics, automotive, grid scale, drones/robots, and "other." The latter category includes emerging technologies such as uninterruptible power supply, electrification in aircraft, and various other current and future smaller applications. Note that our estimate for resource needs will largely be dominated by the EV and portable electronics market sizes and less by uncertainties in these other application categories. For the portable electronics market, which is dominated by LCO, the L and H scenarios are respectively 5% and 10% CAGR (Compound Annual Growth Rate), which are slightly lower than the historic growth of all of LIBs in the last 10 years (The International Data Corporation predicts around 4% growth in the number of devices up to 2021 for a subset of consumer electronics, but the higher percentage in our study reflects the trend toward larger devices and screens, which requires larger battery packs).[43] The automotive Li-ion consumption depends very much on both market growth rates and the relative adoption of full BEVs versus plug-in and HEVs. For the L scenario we assume that the distribution of sales between these three technologies (with an average battery pack size of 75 kWh) remains constant, and we extrapolate the market with a 36% CAGR.[44] For the H scenario we used 10 million BEV sales in 2025 based on the Bloomberg projection of 100 million cars by 2025 (with 10% EV). We assume each vehicle has an average battery pack of 75 kWh, which provides between 200 and 300 miles of driving range, bracketing the consensus driving range target for multiple recent EV models. Note that even our H growth estimate is below the requirement set by the World Energy Council (16% EV sales in 2020).[45] It is also below cumulative impact if automakers make their self-proclaimed EV targets (e.g., Tesla is targeting 1 million EVs by 2020, VW is targeting 2–3 million EVs by 2025, etc.) and below the trajectories that would have to be taken to achieve the goals recently set by several European countries to eliminate the sales of internal combustion engine vehicles by 2040.[46] Our assumed cathode chemistry for these vehicles is a market mix including 50% NMC-622, 35% NMC-111, and 15% NMC-811, to reflect the fact that NMC-622 is seeing initial commercialization and NMC-811 may see some minimal commercialization by 2025. For grid storage we use an estimate of 45 GWh market size in 2025 using NMC-111 (for both the L and H scenarios). For the "other" category we assume a 10% and 20% CAGR for the L and H scenarios, respectively (from a baseline of 23 GWh in 2016), and use NMC-111 as an "average" cathode. We assume that drones and robots will use an estimated 10 and 15 GWh for the L and H scenarios, respectively (using NMC-111). These estimates lead to an expected demand for cobalt according to our L and H scenarios of 136 and 330 kt, respectively.

Beyond 2025 there is room for substantial speculation. Currently, countries and car manufacturers are announcing aggressive targets for completely phasing out internal combustion engines within that time frame (e.g., Norway, France, India, the Netherlands, and the United Kingdom have stated that they want to end sales of

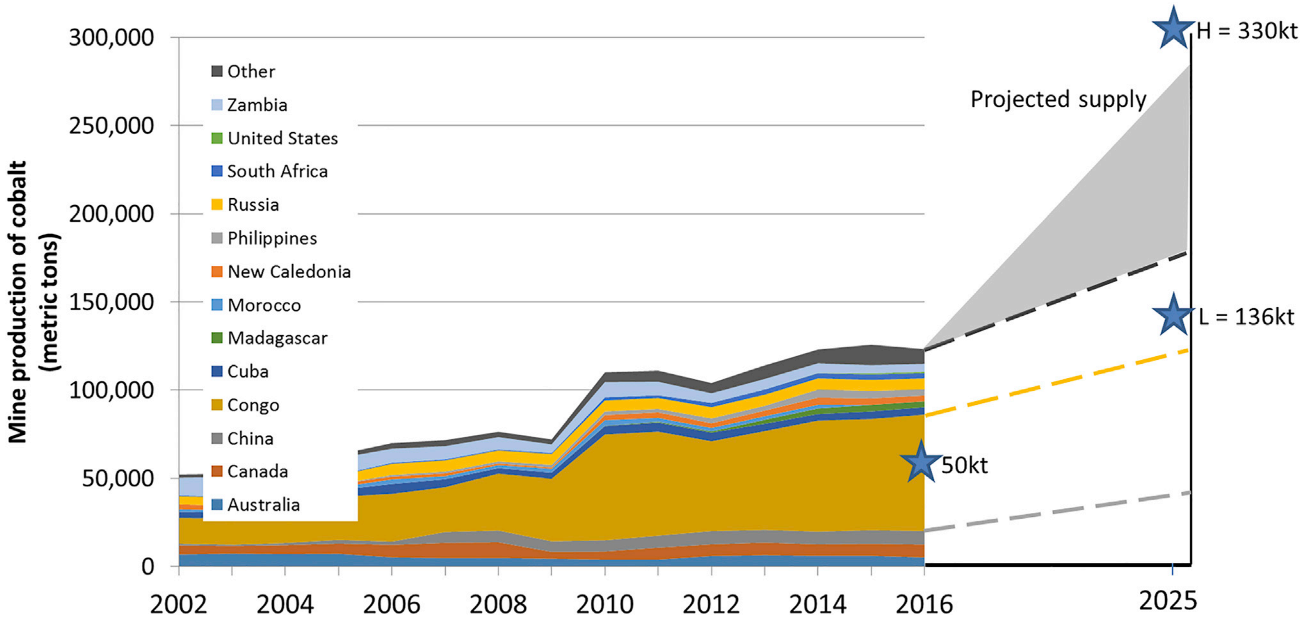

Figure 4. Cobalt Use in LIBs Including Historic Supply Broken Down by Country and Projected Supply Overlaid with Current and Projected Demand
Stars show the demand in tonnes in 2016 and the L and H scenarios in 2025. Dashed lines show supply projections based on published capacities and capacity expansions. Shaded supply shows linear growth in supply.

internal combustion [ICE] vehicles by 2040, and Volvo intend to phase out ICE models by 2020). Tesla has announced aggressive targets for its lower-cost Model 3. Meeting these goals requires a significant increase in the supply of battery-grade materials. However, the commodity and materials markets are gearing up for such demand. Industry intelligence cites that there are 16 LIB megafactories in the pipeline totaling 232 GWh. There has been no lack of major project announcements in 2017; dozens of major deals have been struck between original equipment manufacturers (OEMs) and materials companies.

Returning to our more quantitative projections, we provide a summary of how supply and demand of Co may align until 2025. Figure 4 shows this balance of supply and demand for Co metal. The vertical axis plots the mined production of Co by country from 2002 to the present as well as the projected supply until 2025. Our minimum in supply projection (black dashed line) is based on documented growth in mined and refined capacity in China and the DRC (shown by gray and gold dashed lines, respectively) assuming constant production in the other countries. This provides a lower projection of 180 kt in 2025.[25,36,37,41] A more aggressive supply projection (shown in gray) assumes growth in supply up to 290 kt in 2025. The stars indicate the demand for Co from the LIB industry in 2016 with projections for L and H in 2025. Our analysis finds that while Co supply will meet demand for the lower estimates of demand for LIBs, there is a potential for availability concern if there is rapid vehicle adoption. As a contrast, scaling Ni according to our scenarios leads to demand for Ni of 155 kt and 500 kt for L and H, respectively. Even the high demand is only 22% of Ni production in 2015. Perhaps more significantly, the supply risk is largely based on the geographical concentration in a politically challenging region as well as on the dominance of LIBs as an end-use market. Recycling could play a more critical role in mitigating a supply/demand mismatch if materials recovery from electronic waste can be increased in the short term, as Co has a viable recovery market.[47]

So far the discussions in this article have focused on the geographical distribution of the raw materials associated with LIBs. Also of interest is where the manufacturing of the actual cells will occur. Recent focus in the battery manufacturing industry has been in China, where significant manufacturing is projected to occur. Including production in Japan and Korea, these three countries constitute 85% of manufacturing capability for LIBs for all end-use applications. Generally the supply chain for LIBs is dominated by trade within Asia (South Korea, Japan, and China), with the largest trade flow of products from China to the United States.[32] While this may shift in the future, current trends indicate that China will still play a critical role in this supply chain. For example, while the gigafactory in Nevada has been projected to reach capacity of 35 GWh by the end of 2020, China's capacity could be almost double that by the same year.

We have said nothing so far in this analysis regarding the manufacture of LIB electrolytes, largely because electrolyte supply has not been subject to resource constraints to date. The most commonly used electrolyte is an Li salt such as $LiPF_6$, $LiBF_4$, or $LiClO_4$ in an organic solvent that combines linear and cyclic carbonates (e.g., ethylene carbonate and dimethyl carbonate). The market for LIB electrolytes was roughly 62 kt in 2015, with production dominated by Asian companies (China, 60%; Japan, 18%; Korea, 14%).[48] Industry reports indicate that there is currently likely overcapacity for electrolytes, with most Asian companies operating at less than half of capacity and with several American and European companies operating at less than 10% capacity.[49]

LIB Recycling

As mentioned above, another source of future materials for LIBs could be material or cell recovery from existing cells. However, based on the lifetime of these products, this will not be a significant source of material in the time horizon considered here. While LIBs have been generally found to be significantly less toxic compared with lead acid and nickel-cadmium batteries,[50] potential impacts from end of life remain. Such impacts have inspired a variety of legislation, including recycling targets such as the European Union Battery Directive[49] and landfill bans in states such as California and New York in the United States.[51] Understanding the right path for batteries at their end of life is complex given the many options available as well as the rapid technology trajectory of LIBs, the latter of which results in ever changing sizes, form factors, and cathode chemistries.[52] The hierarchy of options includes reuse in the original application, cascaded use in other applications, remanufacturing or refurbishment, recycling, and, ultimately, disposal.

The remaining life that EV batteries hold (often as high as 80% capacity) has inspired research looking at secondary or cascaded reuse of these batteries in other applications, such as stationary power and grid load leveling.[53–55] Reuse and cascaded use has the potential to distribute costs over multiple lifespans and reduce the overall environmental impacts of these products.[56] Despite the economic and environmental benefits of reuse, significant barriers remain. Most reuse avenues require significant testing protocols and battery management systems that are compatible with the deployment of an "aged" asset in a different application (e.g., EV batteries to grid). Significant safety issues[57] that have emerged make OEMs anxious about third-party use of their batteries; even if liability has been signed away, negative public opinion could still have disastrous effects if faced with an incident. Other reuse barriers include reliability, performance, and design requirement mismatch between original and secondary applications.[58–60]

Finally, much research has been done on recycling, covering a wide range of technologies including pre-processing such as disassembly, shredding, and segregation operations as well as recovery technologies such as pyrometallurgical, hydrometallurgical, solvent extraction, and electro-refining. Industry infrastructure has progressed as well, with some companies recycling LIBs on a commercial scale, such as Umicore and Retriev Technologies (Kinsbursky, formerly Toxco). In these instances, however, lithium is either not recovered or is recovered with impurities that make it undesirable for reuse in battery production. Studies have found resource savings[61] from recycling as well as the potential to greatly reduce the impact of EVs.[16,62,63] The focus of recycling efforts is on the cathode materials, as they make up a high percentage of the total battery mass and cost, and also contain the critical metals of interest here. Of course, secondary usage scenarios as described above would delay these materials reaching end-of-life recycling operations. Some forecasts estimate that the EV LIB recycling market could be worth as much as 2 billion USD by 2022; however, the economic incentive for recycling will depend heavily on the cathode chemistry of future vehicle batteries.[64] For example, recovering battery-grade manganese and lithium from $LiFePO_4$ and $LiMn_2O_4$ batteries via recycling is more expensive than mining these materials.[65]

Discussion of New Technologies

To understand whether new technical and scientific developments can displace Co from the Li-ion industry, it is important to understand the properties that make Co so attractive in Li-ion technology. Cobalt, specifically Co^{3+}, possesses a unique electron configuration with 6 *d*-electrons in a low spin state,[66] making it a very small ion, leading to cathodes with very high density. The superb energy density of $LiCoO_2$ is highly desirable for the portable electronics industry, where battery volume is the main constraint for increasing device run time. In addition, this electron configuration also enhances the ability of cathodes to form and remain in a layered structure, which is highly beneficial for Li motion and, as a result, for power density and effective capacity as well. For this reason, all commercial, high-energy density cathodes as of today contain a certain amount of cobalt. Non-cobalt-containing cathodes, such as manganese spinels and $LiFePO_4$, while attractive for some applications, have not been able to rival the energy density of other cathodes. The high stability and high power capability of $LiFePO_4$ do make it a contender for grid applications, in particular if its cost becomes even more attractive due to rising Ni and Co prices.

A recent scientific insight that layeredness, as imparted by Co, may not be essential for good cathodes as long as Li excess is added to the compounds may further hedge the need for Co in the industry. Indeed, several high-capacity cathodes without Co and with the so-called rocksalt structure have been demonstrated in the literature.[67] Compounds based on metals such as Mo and Cr,[67] Ni, Ti, and Mo,[68] Nb and Mn,[69,70] and V[71] have all shown very high energy content without any cobalt present. On the anode side, silicon may displace a certain amount of carbon.[72] Battery-grade silicon metal is produced from silica, which has adequate, and geographically diverse, reserves.

Several potential new directions for energy storage have the potential to significantly increase the amount of lithium needed. Li-air and Li-sulfur both may use as much as two times the amount of Li per kWh compared with Li-ion. This is due to the lower cell voltage of these chemistries, thereby demanding a higher capacity for each kWh. It is also due to the lower Coulombic efficiency of the Li metal anode, which requires the cell to contain excess lithium. However, we are skeptical that both of these technologies can achieve significant market penetration in the 2025 time frame. The anticipated market penetration of solid-state Li-ion is more difficult to estimate, as its progress is rapid and the technology is already intensely supported by industry for its safety benefits. Solid-state lithium would require higher Li content than Li-ion, because of both the likely use of a metallic Li anode and the high Li content of the solid-state electrolytes. While these are exciting new directions for the Li-ion battery field, the typical path of novel materials to commercialization, even when functioning in a research lab, is long and requires significant R&D, making it unlikely that such innovations will modify our projections for 2025 in any significant way.

This analysis has shown that while the supply of materials for LIBs will likely meet the demand for the near future, there are potential risks associated with the supply of Co. In particular, these risks are based on the geographical concentration of mining activities in the DRC as well as the refining focus in China. Furthermore, if there is rapid adoption of EVs (incentivized by policy interventions including a carbon tax, higher fuel taxes, and more aggressive CAFE targets), demand could outpace supply of these materials. For the large factories that are located in China this may not be of significant concern, but facilities in other locations (such as the United States) may face challenges in acquiring a stable supply of materials. The other dominant materials (lithium, natural graphite, manganese, and nickel) are not expected to have resource supply concerns in the short term, particularly as secondary supplies of lithium become available.

The analysis provided in this article is based on estimates of EV adoption and projected materials supply. Therefore, these are only estimates and accompanied by significant uncertainty. One significant limitation of this relatively static analysis is that understanding materials criticality requires comprehensive modeling of market actors. Identifying where challenges may arise requires a more complete and dynamic analysis than what has been provided here. Such an analysis should have sufficient detail to map technological and operational changes to their impact on cost as well as to map performance to market value.

AUTHOR CONTRIBUTIONS

Conceptualization, E.A.O., G.G.G., and G.C.; Writing – Original Draft, E.A.O.; Writing – Review & Editing, E.A.O., G.G.G., X.F., and G.C.; Formal Analysis, E.A.O., G.G.G., X.F., and G.C.

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