Cobalt is an essential metal for a wide variety of applications, particularly those involved in highly technical sectors. Primary demand of cobalt is based on end uses specifically in lithium ion batteries (LIB) and other, non-battery superalloys, as well as in hard materials, cutting tools, magnets, and catalysts (Shedd). LIB, concentrated in consumer electronics and electric vehicles (EVs), are currently the largest end use of cobalt (accounting for 50% of the global cobalt demand). While consumer electronics and superalloy demand for cobalt are projected to remain constant in the coming years, the market for EVs is expected to increase exponentially after 2020, as costs for EVs equalize with those for traditional ICE vehicles (Darton, Valero). Along with cost, country-specific policy decisions are limiting the production and sell of traditional vehicles in favor of a more sustainable alternative, such as EVs. These regulations, ecologically, politically, and economically driven, will likely affect the geographic distribution of cobalt demand in the coming years (Pelegov). This could be further exacerbated by potential mineral stockpilings in certain countries for both political and economic reasons (Schmidt, Eggert).

While projections of extreme EV growth represent sustainable ideals, there is still a significant amount of risk associated with large increases in EV demand and implementation. Various risk factors have been well documented in a number of recent publications. Pelegov and Pontes indicate production scalability, cost, policy variation across governments, and EV battery recycling impacts (both environmental and economic) as the four most pressing risks to global, wide-scale EV adoption (Pelegov). Additional studies have focused more specifically on supply chain concerns, particularly raw material availability and accessibility, as high-risk factors for global EV adoption in the coming years (Valero, Pelegov, Shedd).

As detailed in various publications, cobalt is affected, at least to a small extent, by the entire range of supply chain disruption factors, covering supply chain concentration, demand increases, supply decreases, and political instabilities (Helbig). Within these broad categories, by-product production dependence, geographically concentrated production, processing transportation, sociopolitical instability and unrest, resource extent, and cost are often analyzed as risk factors for cobalt (Shedd, Helbig, Valero). Primary supply of cobalt, often considered the main risk, is heavily geographically concentrated, both for mining/production and processing of the mined materials. Current estimates put approximately 60% of all mined cobalt production in the Democratic Republic of Congo (DRC); this value is expected to reach upwards of 65% before 2030 (Hamilton – BMO). Cobalt processing is also heavily concentrated; 2017 numbers indicate that China is responsible for 58% of refined cobalt, 91% of which originates in the DRC (Darton).

While many countries are projected to increase their cobalt production in the coming years, this market is expected to remain concentrated, as cobalt mining in the DRC is expected to outpace growth in other countries. Although many countries will increase their overall production, their worldly market share will decrease due to exponential-scale increases in the DRC (Shedd, Schmidt). Apart from problems directly related to supply chain concentration, this heavy concentration in the DRC raises additional questions of materials availability: Cobalt is mined primarily as a by-product of copper and nickel production and the DRC consistently ranks in the lowest group for country specific political stability. Examples of this include political and social issues in the 1970s and 1990s that led to supply constraints and subsequent extreme price increases (Shedd).

Mining in the DRC raises additional concern because of extensive artisanal mining, which is estimated to account for up to 20% of annual cobalt production in country. This unregulated, often unrecorded mining practice has led to widespread environmental, social, and health concerns by outside research and social groups. Land and water pollution, child labor, and social disruption have been documented. Adverse health effects associated with handling cobalt containing ores have been studied in areas where artisanal mining has become a main form of employment. High levels of cobalt and other metals associated with ores, such as uranium, have been found to be particularly high in children in these areas. Extended, high levels of cobalt exposure can lead to oxidative DNA damage (already indicated for children in studied areas), heart, lung, and thyroid problems (Nkulu). Artisanal mining, and its lack of regulation, raises more questions for the overall sustainability of the heavily concentrated cobalt supply chain.

Concerns over production concentration and mining have led researchers to explore the primary supply of critical metals such as cobalt in more detail. Although cobalt is primarily mined as a by-product of technologically and societally significant metals such as copper and nickel, its own technological importance in large demand sectors (aerospace, consumer electronics, EVs) has led to increased interest and concern about cobalt resource quantities and recovery efficiency (Mudd Weng Jowitt, Mudd Jowitt, Mudd Weng Jowitt Turnbull Graedel). Supply and demand projections are becoming increasingly common and important for assessing material critically for irreplaceable materials such as cobalt in these technologically important sectors.

Tisserant and Pauliuk ran such analyses for cobalt supply and demand out to 2050 (Tisserant and Pauliuk). In this analysis, supply models considered the by-product status of cobalt and mining risk based on geographical location, political stability, and mine-type; demand models were based entirely on GDP growth projections, giving a rough, likely low estimate of actual future cobalt demand. Despite this, under relatively stable conditions moving forward, Tisserant and Pauliuk conclude that cobalt supply will easily meet demand out to 2050 and that by-product status has little effect on cobalt supply in the relatively near future. Based on these projections, demand would outpace supply (by up to 20%) only under extreme conditions such as the total cut-out of African cobalt supply for a 15 year period (Tisserant and Pauliuk). To complete and expand these previous models for cobalt supply and demand in the short to midterm, trade patterns, technological demand structures, and product specific growth projections would need to be accounted for.

Similar ideas have been explored by Sverdrup, Ragnarsdottir, and Koca, who consider the sustainability of supply and demand modeling for cobalt in the long term, out to 2400. Values of and scenarios concerning ultimately recoverable resources of cobalt (both known and hidden, on land and undersea), population growth statistics, recycling rates, and government policies are considered. Various models are used to assess how and when cobalt supply will be exhausted. In these models, cobalt recycling is based entirely on market price, and becomes especially important between 2080 and 2120, after which it is likely to outpace mined extraction. Depending on scenario, Sverdrup, Ragnarsdottir, and Koca conclude cobalt supply will be exhausted after 2200, unless significant policy decisions and changes are implemented (Sverdrup, Ragnarsdottir, and Koca).

Valero, Valero, Calvo, and Ortego also explore criticality of cobalt, along with twelve other materials, out to 2050. In these analyses, cumulative raw material demand with currently available reserves and resources, expected raw material demand, and production projections are considered for both cobalt and nickel. Conclusions indicate that both nickel and cobalt demand may outpace reserves (but not resources) in the midterm: nickel could experience bottlenecks as early as 2027, and cobalt demand is likely to exceed production between 2030 and 2050. Both of these materials are indicated as having high to medium risk for constraints in the medium term, with EVs the largest focus of future bottlenecks (Valero). For this analysis, a Hubbert peak bottom-up modeling approach was taken to predict supply, which introduces uncertainty for by-product metals such as cobalt due to poor Gaussian fitting. Top down approaches for modeling material usage and demand are also included, however, a full understanding of potential material bottlenecks would need to take growth in all sectors into account. Recycling potentials are also touched on, however, more complete models for predicting its impact on primary cobalt demand are still needed.

Batteries and battery materials have also specifically been assessed. Various battery chemistries, both containing high and low amounts of nickel and cobalt, have been assessed based on aggregated relative supply risk, using eleven different indicators, out to the medium term. Discussed battery chemistries include NMC-C, LCO-C, LMO-C, NCA-C, LFP-C, and LFP-LTO. Due to the heavy overlap of elements in both the anode and cathode of all lithium ion battery chemistries currently in use, no conclusions can be drawn about which of these cathode materials may prove to be the most susceptible to supply chain problems. Many studies indicate the need for further research in these areas and its heavy impact on governmental policy and sustainable technology adoption (Valero, Schmidt).

Due to the highly concentrated supply chain of cobalt and the huge increases in demand that are expected from EV battery implementation, the economic market for cobalt is likely to become unbalanced, if it is not already, according to Colin Hamilton, a BMO Capital Markets analyst (Hamilton-BMO). In his December 2017 report, he concludes that cobalt prices are likely to see large increases in the near future, peaking in 2019, if the market is to move closer to a supply-demand balance. This balance would also require dramatic scenarios of significant increases in secondary cobalt supply from end of life recycling and increased cobalt substitution, especially in batteries in the short term (to 2025). These scenarios are unlikely based on current recycling infrastructure and economic incentives (between 10% and 32% of cobalt is currently recycled), and on the EV market’s focus on increased energy density, power to weight ratio, and chargeability (all of which increase for cobalt containing cathodes as compared to alternatives) (Valero). Recycling rates are low, depend heavily on the type of cobalt ore used, and may be outweighed by the effort necessary, specifically for battery materials (Schmidt). Substitution may be a viable option in some sectors, however it can often lead to increased prices and decreased performance (Shedd).

Along with assessments such as this, it is evident that market responses will not be enough to balance the increasingly critical nature of materials such as cobalt. Recent publications indicate the need for extreme government regulation before significant problems arise for the cobalt and EV battery markets. These indicate the need for expansion of the education and research sectors, particularly on topics such as supply, free market transparency, environmental impacts, manufacturing, and recycling of critical materials. If EVs are to play a large role in sustainable development in both the short and long terms, governments and policy makers need to play a larger role than simply advocating for increased EV adoption (Eggert).

In the work presented here, scenario analysis was used to determine when the supply of cobalt becomes a limiting factor for cobalt demand in the short term, how this supply will meet demand, and what shifts will need to occur both geographically and by source to meet increasing demands. Therefore, this work is differentiated from previous papers because we focus on a short-term analysis versus previous work which has extended out to much further. Our primary contribution is a detailed treatment of supply including primary mines and how further primary extraction will meet demand in the short term and discussion of whether those will be operated as coproducts or byproducts for cobalt. We link the demands for cobalt within LIBs to the potential for secondary supply. Finally, we explore the impact of substitution within non-battery sources of demand.

**NOTES**

**Brief background on cobalt**



Primary supply of cobalt is heavily geographically concentrated, both for mining/production and processing of the mined materials. Current estimates put approximately 60% of all mined cobalt production in the Democratic Republic of Congo (DRC); this value is expected to reach upwards of 65% before 2030 [1]. Cobalt processing is also heavily concentrated; 2017 numbers indicate that China is responsible for 58% of refined cobalt, 91% of which originates in the DRC [2]. More concentrated because DRC increase worldly share even more than everywhere else and despite their increases lose percent of total.

Apart from problems directly related to supply chain concentration, this heavy concentration in the DRC could cause specific issues. These stem from political instability, high governance risks, social unrest. Example from 1978 and the 1990s where political issues led to extreme price increases and supply chain issues. Expand on these issues using the supply risk criteria here.

Other issues associated with the supply of cobalt include its by-product nature (by-product of mines producing Ni and Cu primarily, also some PGM mines). DRC also raises concern because of its artisanal mining of cobalt, which is estimated to account for up to 20% of their annual cobalt production. Not only have their been concerns raised about the environmental impact of this, but also about the health impacts on the workers, their families, and the people living near these artisanal mining opporations, some of which are directly adjacent to large metropolitan areas. Actual health risks associated with this – higher levels of cobalt, particularly in children, as well as other elements associated with ore which cobalt comes from, including uranium, which can have severe health impacts moving forward. This is one more aspect leading to the questionable sustainability of the cobalt supply chain.

Primary demand of cobalt is based on end uses in lithium ion batteries (LIB), other, non-battery superalloys, hard materials/cutting tools, and catalysts. LIB, concentrated in consumer electronics and electric vehicles (EVs), are currently the largest end use of cobalt (accounting for 50% of the global cobalt demand). Consumer electronics and superalloy demand for cobalt are projected to remain constant in the coming years. The market for EVs is expected to increase exponentially after 2020, as costs for EVs equalize with those for traditional ICE vehicles [2]. Along with cost, country-specific policy decisions are limiting the production and sell of traditional vehicles in favor of a more sustainable alternative, such as EVs. These regulations, along with increased EV demand, will likely affect the geographic distribution of cobalt demand in the coming years. This could be further exacerbated by potential mineral stockpilings for political and economic reasons, of which evidence has already been documented by multiple research groups. Lots of potential issues with this giant increase in EV demand/adoption. Biggest issues are scaling up production, decreasing cost, and recycling , as well as raw material availability and accessibility. Risks also in Shedd

There has also been calls for extreme government regulation and rules, particularly expansion of education and research into critical materials . Market responses are not enough, government responses need to outpace the potential problems. Competition for cobalt sources existing will lead to tech advantages for increased recovery, possible substitution, decreased demand/consumption, increased recycling.

Along these lines, due to the highly concentrated supply chain of cobalt and the huge increases in demand that are expected from EV battery implementation, the economic market for cobalt is likely to become unbalanced, according to Colin Hamilton, a BMO Capital Markets analyst [1]. In his December 2017 report, he concludes that cobalt prices are likely to see large increases in the next few years, peaking in 2019, if the market is to move closer to a supply-demand balance. This balance would also require dramatic scenarios of significant increases in secondary cobalt supply from end of life recycling and increased cobalt substitution, especially in batteries in the short term (to 2025). These scenarios are unlikely based on current recycling infrastructure and economic incentives (only 10% of cobalt is currently recycled), and on the EV market’s focus on increased energy density, power to weight ratio, and chargeability (all of which increase for cobalt containing cathodes as compared to alternatives).

Despite low levels of current recycling, cobalt is one of the most recyclable of the materials used in batteries – where 32% of it can be recycled and reused. Up to 15% of environmental impacts comes from manufacturing – potential to balance w recycling but only if it makes sense! Co and Ni up to 30% from primary production. There are issues with substitution particularly because it can lower the performance of many of the products in question. Recycling mostly very low and not pay off.

Although cobalt is primarily mined as a by-product of technologically and societally significant metals such as copper and nickel, its own technological importance in large demand sectors such as aerospace, consumer electronics, and electric vehicles has led to increased interest and concern about cobalt resource quantities and recovery efficiency in the near future [3-5]. Supply and demand projections are becoming increasingly common and important for assessing material critically for irreplaceable materials such as cobalt in these technologically important sectors.

Tisserant and Pauliuk ran such analyses for cobalt supply and demand out to 2050 [6]. In this analysis, supply models considered the by-product status of cobalt and mining risk based on geographical location, political stability, and mine-type; demand models were based entirely on GDP growth projections, giving a rough, likely low estimate of actual future cobalt demand. Despite this, under relatively stable conditions moving forward, Tisserant and Pauliuk conclude that cobalt supply will easily meet demand out to 2050 and that by-product status has little effect on cobalt supply in the relatively near future. Based on these projections, demand would outpace supply (by up to 20%) only under extreme conditions such as the total cut-out of African cobalt supply for a 15 year period [6]. To complete and expand these previous models for cobalt supply and demand in the short to midterm, trade patterns, technological demand structures, and product specific growth projections would need to be accounted for.

Similar ideas have been explored by Sverdrup, Ragnarsdottir, and Koca, who consider the sustainability of supply and demand modeling for cobalt in the long term, out to 2400. Values of and scenarios concerning ultimately recoverable resources of cobalt (both known and hidden, on land and undersea), population growth statistics, recycling rates, and government policies are considered. Various models are used to assess how and when cobalt supply will be exhausted. In these models, cobalt recycling is based entirely on market price, and becomes especially important between 2080 and 2120, after which it is likely to outpace mined extraction. Depending on scenario, Sverdrup, Ragnarsdottir, and Koca conclude cobalt supply will be exhausted after 2200, unless significant policy decisions and changes are implemented.

Data for the medium term = out to 2050 also predicts a medium to high risk of bottlenecks in both the Ni and Co sectors, particularly due to the increase in electric vehicle demand. In almost all of the reports written concerning cobalt criticality, it is considered critical. Constraints of the market is likely from battery manufacturing. Ni as soon as 2027, Co between 2030-2050. Demand in other sectors constant which is likely not the case.

Certain studies have considered battery materials specifically. Type of ore important in which materials are used for which applications. Nickel could actually prove more of an issue than cobalt in terms of production. Understanding material flows has a huge impact on policy and there is a large call for continuous updates and greater understanding in this area. Batteries demand largest quantity of Co. Specific battery chemistries, both cobalt and nickel heavy and some including neither of those materials, have also been assessed, however no solid conclusions can be drawn about which of these cathode materials may prove to be the most susceptible to supply chain issues. These tend to concern over cobalt availability as well as nickel. Call to assess environmentally impacts more precisely based on actual inputs and outputs.

In the work presented here, scenario analysis was used to determine when the supply of cobalt becomes a limiting factor for cobalt demand in the short term, how this supply will meet demand, and what shifts will need to occur both geographically and by source to meet increasing demands. Therefore, this work is differentiated from previous papers because we focus on a short term analysis versus previous work which has extended out to much further. Our primary contribution is a detailed treatment of supply including primary mines and how further primary extraction will meet demand in the short term and discussion of whether those will operated as coproducts or byproducts for cobalt. We link the demands for cobalt within LIBs to the potential for secondary supply. Finally, we explore the impact of substitution within non-battery sources of demand.

Helbig

Eggert

Shedd

Pelegov

Valero

Schmidt

Nkulu

**Outline Ideas**

Cobalt uses and importance

Sectors, specifically batteries!

Huge demand increases because of EVs

EV specific details – types of cathode lists

Played up because of government intervention

May need to increase more to meet environmental goals

So cobalt is important but what is the problem?

Supply concentration – DRC specifically

a big issue maybe because of increased demand

All the reasons the DRC has issues

Political, social, etc

Cobalt production specific problems

By product status, artisanal mining, etc.

Problems specifically related to applications

Cathodes and which may pose more problems (EVs)

Recycling (EVs)

Substitution (EVs and other sectors)

Country stockpiling (adds to geographical concentration and supply issues in future)

While all true for Co, also a problem for Ni

Could be even more of a problem for Ni than Co actually

Potentially dependent on battery cathode type

Because of increased demand and future supply questions lots of studies and concern about this!

Lots of studies with all different times frames and specific analyses

Tisserant and Pauliuk

Sverdrup

Valero

Among others

Studies like these also indicate

Cobalt criticality high potential coming up

Call for increased gov intervention

Recycling issues and substitutability

Question of when problems will arise not if

Focus of our study

Short term

Supply specific – location, firms, potential future supply from resources and reserves

Secondary supply potential

Effect of extreme substitution