# Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand

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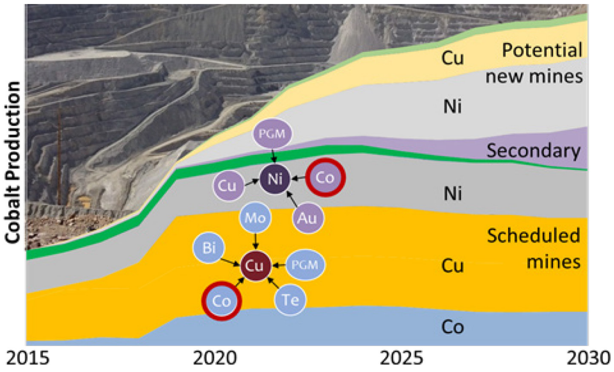
## Abstract

Lithium-ion battery demand, particularly for electric vehicles, is projected to increase by over 300% throughout the next decade. With these expected increases in demand, cobalt (Co)-dependent technologies face risk of significant impact from supply concentration and mining limitations in the short term. Increased extraction and secondary recovery form the basis of modeling scenarios that examine implications on Co supply to 2030. Demand for Co is estimated to range from 235 ktonnes to 430 ktonnes in 2030. This upper bound on Co demand in 2030 corresponds to 280% of world refinery capacity in 2016. Supply from scheduled and unscheduled production as well as secondary production is estimated to range from 320 ktonnes to 460 ktonnes. Our analysis suggests: 1) Co price will remain relatively stable in the short term given that this range suggests even a supply surplus, 2) future Co supply will become more diversified geographically and mined more as a byproduct of nickel (Ni) over this period, 3) for this demand to be met, attention should be paid to sustained investments in refined supply of Co and secondary recovery.



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## 1. Introduction

Recent activity in vehicle electrification has led to increased focus on lithium-ion batteries (LIB) and the resulting material system consequences. As many as one million electric vehicles (EVs) were sold in China in 2018.[1] As interest in LIB increases, this invites a number of questions regarding a) the evolution of that demand, b) which types of battery chemistries will be leveraged to meet EV demand, c) the supply chain impacts based on mining and refining capacity, d) the environmental and social impacts of growing mine output, and e) the recycling infrastructure to support end-of-life materials management.

Economic theory emphasizes that in well-functioning markets, over the long term, imbalances between supply and demand tend to be self-correcting. In the short to medium term, however, markets and prices can be disrupted and volatile. These availability concerns can cause problems for novel technologies, and evolving regulations in response to these concerns can change the economic landscape. There are examples of disruption in materials supply chains that led to profound change in material use[2], delayed technology implementation, or political instability[3] so foresight is critical to planning, management, and action. Moreover, even over the longer term, this view of a material market ignores environmental externalities, functionality constraints around relative substitutability of a material, and feasibility of alternatives in the near term.[4]

A previous screening analysis by a subset of the authors has shown the importance of Co based on supply chain concentration and its coproduct status.[5] The majority of Co is produced as a byproduct in mining projects whose revenue comes primarily from copper (Cu) and nickel (Ni) mining. In this study, we address Co availability from 2020-2030. We provide a detailed investigation of new Co supply, the potential role of secondary supply, as well as demand across a variety of applications. We explore how supply of Co will shift to meet this demand through 2030; geographically and by source.

Demand for Co is based on end uses in LIBs, superalloys, hard materials/cutting tools, and catalysts,[6] with limited ability to substitute with another element for most applications.[7] LIB uses, concentrated in consumer electronics and EVs, are currently the largest end use of Co (accounting for 50% of global Co demand).[8] The market for EVs is expected to increase significantly after 2020, as costs for EVs begin to equalize with those for internal combustion engine vehicles.[8,9] While projections of extreme EV growth represent sustainable ideals, there are several challenges associated with large increases in EV demand and implementation. Various risk factors have been well documented in recent publications. Pelegov and Pontes indicate production scalability, cost, policy variation across governments, and EV battery recycling impacts (both environmental and economic) as pressing risks to global EV adoption.[10] Additional studies have focused on supply chain concerns, particularly raw material availability and accessibility, as high-risk factors for global EV adoption in the coming years.[6,9]

As detailed in various publications, Co scores highly among potential supply chain disruption drivers including geographically concentrated mining and refining, sociopolitical instability and unrest, by-product production dependence, and cost.[6,9,11] Primary supply of Co is heavily geographically concentrated, both for mining and refining of the mined materials. Current estimates locate approximately 60% of all mined Co production in the Democratic Republic of the Congo (DRC); this value has been estimated to reach upwards of 65% before 2030.[12] According to the World Governance Indicators developed by the World Bank Group, the DRC has consistently ranked in the lowest 10 percentile among all countries it investigates in terms of political stability, government effectiveness, rule of law, and control of corruption.[13,14,15] Examples of this include political and social issues in the 1970s and 1990s that led to supply constraints and subsequent extreme price increases.[6,16] Supply is more diverse from a company perspective compared to the geographic perspective, and no company has a production share more than 30% on average. Although China has a small share in terms of direct mining production, it indirectly controls 19-26% of mining production through ownership of mining projects mostly located in the DRC.[17]

Co processing is also heavily concentrated; 2017 numbers indicate that China is responsible for 58% of refined Co, 91% of which originates in the DRC.[8] Activity in the DRC raises additional concern because of artisanal mining, which is estimated to account for 10% of annual Co production in the country. This unregulated, often unrecorded, practice has led to environmental, social, and health concerns particularly around land contamination, water pollution, child labor, and social unrest.[18]

Some literature is optimistic about Co futures because assumptions either include proxies for future demand that are more conservative or because they assume aggressive build out of secondary sources. Such studies include those by Tisserant and Pauliuk[19] who conclude that Co supply will easily meet demand out to 2050 and that by-product status has little effect on Co supply in the relatively near future as well as investigations by Sverdrup et al. who consider long-term sustainability of Co out to 2400, where secondary production exceeds primary between 2080 and 2120.[20]

Other works suggest that demand may outpace supply. Valero and coauthors conclude that both Ni and Co demand may outpace reserves in the midterm: Ni could experience bottlenecks as early as 2027, and Co demand is likely to exceed production between 2030 and 2050 with EVs the largest focus of future bottlenecks.[9] Due to the highly concentrated supply chain of Co and the significant increases in demand that are expected from EV battery implementation, market analysts have also stated that the market for Co will likely continue to remain imbalanced.[12] Future supply consists of significant increases in primary, increases in secondary Co from end of life recycling in the mid- to long-term, and increased Co substitution, (especially in batteries) in the short term. These scenarios are unlikely due to lack of sufficient recycling infrastructure and economic incentives; in 2018 Co contained in scrap represented an estimated 30% of consumption.[21] Substitution may be a viable option in some sectors, however it can often lead to increased prices and decreased performance.

In the work presented here, scenario analysis is used to relate the supply of Co to Co demand in the short term and identify shifts in supply both geographically and by source based on increasing demand. Therefore, this work is differentiated from previous investigations as we focus on a thorough, short term analysis emphasizing the detailed implications for Co supply evolution. The contribution of this work is a detailed treatment of supply, how further primary extraction may meet demand up to 2030, and a discussion of whether Co will be derived primary as a coproducts or byproduct of other metals.

## 2. Methods

We quantified each aspect of the Co materials market to determine viable scenarios for estimating amounts of supply and demand for the metal from 2015 to 2030 according to the method shown in Figure 1. The method for scenario development depended on which segment of the market was being analyzed and supply and demand scenarios operated independently. Here we provide a summary of the methods; interested readers should consult the supporting information for further detail.

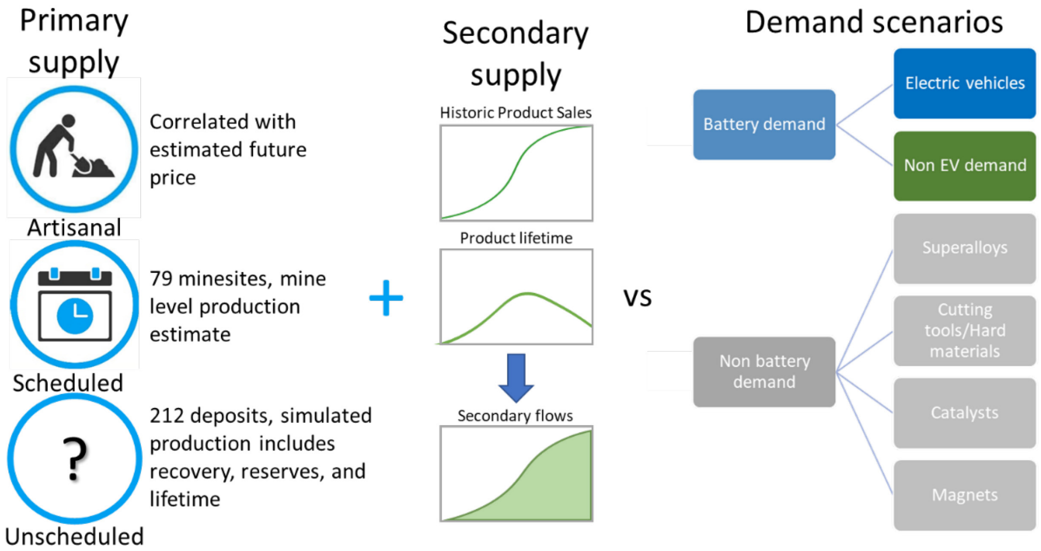

Figure 1. Methodology schematic illustrating approach to model primary and secondary supply as well as demand applications.

## 2.1 Demand Scenarios

For Co *demand* up to 2030, we differentiated Co-consuming sectors according to the following, ranked by market size globally in 2017[8]:

1. **Battery chemicals demand:** Co is used predominantly as a cathode constituent in LIBs batteries, 53% of total demand for Co. Major applications include consumer electronics (40%), EVs, and advanced battery energy storage systems (ESS) for grid load leveling to match renewable supply.
2. **Non-battery demand:** This includes Ni-based superalloys, 16%, used in aircraft engines, turbines for power generation, and prosthetics. Second highest by quantity, 7%, are hard materials where Co acts as a binding material in diamond cutting tools and cemented carbide applications for metal cutting. The catalyst sector is next at 6%, where Co is used in chemical form for desulfurization from natural gas and petroleum products, synthesis of polyester precursor, and the hydrogenation of carbon monoxide into liquid fuels. Finally, other smaller uses include pigments (5%), hardfacing alloys (4%), and magnets (3%).

**Battery chemicals demand**: For the consumer electronics market, we assumed a high and low compound annual growth rate (CAGR) of 5% and 10%, respectively, consistent with previous estimates and a lithium cobalt oxide battery chemistry.[22,23] For ESS applications we used an estimate of 50 and 100 GWh market size in 2030 for low and high demand, respectively, based on projections from both industry and market analysts. ESS installations in 2017 totaled at 2.3 GW, assuming 4-hr storage around 10 GWh.[24,25] We also included an ‘other’ category in LIBs including drones, robots, electric bicycles and other minor applications. From a baseline of 23 GWh total in 2016, we assumed a 5% and 8% CAGR, to provide a low and high scenario, respectively. Grid and ‘other’ applications were assumed to use NMC-622 battery cathode chemistries (where the numbers denote the stoichiometric ratio of Ni, Mn, and Co).[26]

Co consumption in EVs depends on market growth rates, the relative fraction of full battery EV (BEV) versus plug-in and hybrid electric vehicles (PHEV), the pack size, and the battery chemistry for each vehicle type (we assumed no significant introduction of fuel-cell vehicles, consistent with previous studies[27]).

These parameters were specified over time to link to potential secondary supply, expected to be most significant for EVs (rather than electronics). For each vehicle type we have reported or estimated vehicle sales data and projected growth rates from 2018 to 2030.[1] From 2018-2025 these range from 10%-20% CAGR for PHEVs and 18% to 30% BEVs. Between 2026 and 2030, we assume a constant CAGR of 15%. Battery pack sizes range from 40 kWh – 75 kWh for BEVs and 10-20 kWh for PHEV, with the expectation that they will increase over time as battery prices fall.[28] International Energy Association historical data shows that PHEV have dominated global sales but in recent years BEV sales have begun to outpace PHEV; 2015 and 2016 showed BEVs as ~60% of yearly sales.[1] Our assumed cathode chemistry for these vehicles was a market mix for PHEV and BEV individually, including NMC-622, NMC-811, and NCA (lithium nickel cobalt aluminium oxide) for BEVs as well as LMO (lithium manganese oxide), LFP (lithium iron phosphate) and NMC-111 for PHEVs. Figure 2a plots these assumptions for BEV and PHEV adoption in terms of millions of EV sales including an upper and lower bound with a discontinuity in 2026 with the shifted CAGR. Figure 2b and c show the assumed market share by battery chemistry for BEV and PHEV, respectively. There is some shift towards lower Co-containing battery chemistries, but over this short timeframe, this shift will not be significant based on automotive platform lock-in.

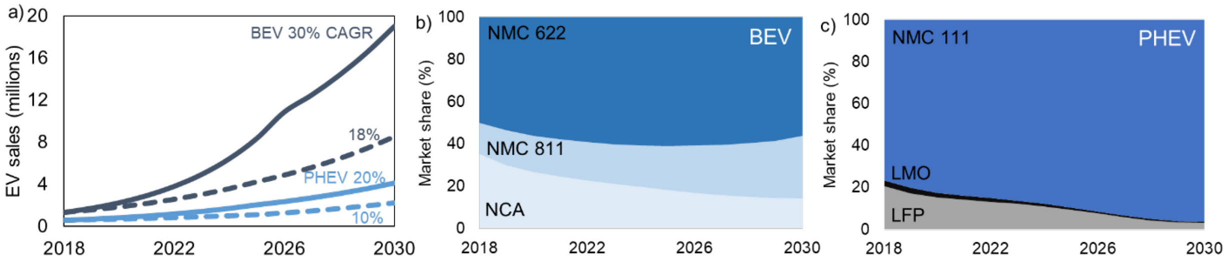

Figure 2. Assumptions for LIB demand in EVs, a) demand for vehicles over time including low and high scenarios in BEV and PHEV, b) assumed chemistry for BEV, and c) PHEV.

**Non-battery demand**: Compared to the use of Co in battery applications, demand growth in non-battery sectors has been much slower. For example, from 2005 to 2017, demand in all seven non-battery sectors only grew from 42.7 ktonnes to 48.7 ktonnes.[8] Therefore, we expect that future demand in these sectors could be forecast from recent trends. Table 1 shows non-battery sector specific compound annual growth rates (CAGR) from 2005 to 2017 using data from the Cobalt Development Institute and Darton Commodities.

Table 1. CAGR based on 2005-2017 historical demand and 2017 market share for non-battery Co consuming sectors.

| | Superalloys | Hard Materials | Catalysts | Pigments | Hardfacing Alloys | Magnets | Others |
|---|---|---|---|---|---|---|---|
| CAGR (%) | 3.70 | 2.64 | -0.20 | -0.79 | 2.07 | -2.27 | -1.44 |
| 2017 Market Share (%) | 16.07 | 7.46 | 5.58 | 5.20 | 3.66 | 2.76 | 6.11 |

We used these sector-specific CAGRs to develop two demand scenarios up to 2030. The first assumes a constant CAGR calculated based on the start year of 2005 (Table 1), while the second assumes that substitution of Co out of superalloys keeps pace with the growth of this segment. This is an aggressive substitution scenario for this end use and was chosen because it is the largest non-battery end use.

## 2.2 Supply Scenarios

**Secondary supply**: To project the quantity and timing of Co available for recovery from the waste stream after use in the demand sectors described above, a residence-time model based on average product lifetimes was applied to LIBs contained in EVs, laptops, and cell phones. These product categories represent the highest use of Co in a form feasible for recovery, whereas tablets, e-readers, and other mobile electronics are minor volumes, comparatively. Material stocks were inferred from product sales, product lifetimes, and compiled from industry reports and product lifespans.[22,23,29] The model was initialized with sales data beginning in 2006 when volume of EVs was quite low. Secondary supply focused on battery use because of the significantly longer lifetimes of the non-battery applications for products such as superalloys and magnets, the dissipative nature of their use in the case of pigments, and that Co is not typically recovered from these end products as for use outside of a metal alloying element.

The residence-time model projected the material expected to reach end of life after a specified product lifespan. Literature states that EV batteries will reach end of life at 80% of their initial capacity,[30] which has been reported to correspond to a range of 5-15 years, with an average around 8-10 years.[31–33] There is much discussion in the literature regarding cascaded use of batteries in grid applications where power density outweighs energy density.[34] For laptop computers, lifespan is reported in a range of 2.9-7.4, with a baseline average around 4 years; for mobile phones including smart phones the range was 1.5-3 years with an average baseline of 2.5 years. These data were used to determine the average and standard deviation for a normal distributed lifespan.[35] Not all Co will be recoverable, particularly due to low collection rates for many of these product categories. However, to account for the maximum possible supply from secondary sources, a 100% collection rate was assumed.

**Mined supply**: We accounted for future Co supply from production of currently operating mines and those for which production schedules have been announced. For both operating mines and mines with scheduled production in the future, we use production estimates from S&P Global Market Intelligence.[36] In cases where these estimates are incomplete or outdated, we update them with the latest company-provided production guidance, found from company annual reports, investor presentations and filings to regulatory bodies. The supporting information contains details on estimates by principal metal including operating or scheduled production estimates. Whether Co is produced as the principal product or the byproduct in a mining project is determined not only by the market price of metals, but also the type of deposit and metal concentrations in minerals. Each mine was labeled based on the metal expected to be the principal source of revenue (based on long-term metal price scenarios, details in the supporting information). We assessed byproduct production based on 71 mines out of which 47 mines are operating as of 2017. The number of operating Cu-principal Co mines in 2017 was one third of that the number of Ni-primary Co mines, but represented five times more Co production by mass. Cu-principal mines are geologically concentrated in the Central African Copperbelt, with 79% of 2017 production coming from DRC and 8% from Zambia.[37] Cu-principal Co mines, especially those that are located in DRC, have a high annual average revenue fraction from Co, between 30% and 50%. Eight projects included in scheduled production are for Co-principal dominated by a single project in the DRC (four are currently operating and four have scheduled production, three of those currently under operation are from tailings and slag).

We also modeled production from artisanal mining. Artisanal mining has historically shown strong correlation with Co market prices. We assumed production was correlated with our estimated future cyclic scenario of price (see supporting information for details on price), but also assume significant cuts in artisanal mining based on regulatory pressure (40% reduction in 2017 and 6% decrease each year after 2017).[38] These assumptions are oversimplified, but artisanal mining is not a significant amount of the supply going forward.

Between now and 2030 there will be new projects for which a production schedule has not yet been announced. For projects without announced schedules, we built a novel simulation approach. Many of those new Co resources are still in the early stages of development (requiring economic and technical assessment), and whether those resources will eventually be mined remains highly uncertain. As the exact amount of Co that would be produced from each mining project remains uncertain for new mining projects, we analyzed mining potential based on resource information to formulate production estimates. Data for reserves were based on Metals and Mining Properties database provided by S&P Global Market Intelligence.[36] We assessed 212 deposits that contain a total of around 10 million tons of Co resources but do not have scheduled production for the period of interest. Within this total we made deterministic estimates for deposits with resources greater than 100 ktonnes (27 out of the 212, totaling 7.2 million tonnes of resources) and performed a simulation for the remaining deposits. For these 27 mines, we found information using production schedules from a previous feasibility study, or production schedule of another metal within the same deposit (for example, Ni).

For the remaining deposits of less than 100 ktonnes, we estimated the supply of Co based on a reserve depletion model which requires estimates of the life of the mine (LOM), recovery rate, reserves, and starting year. The LOM was a truncated distribution from 10-30 years with a mean of 18.25 yrs and a standard deviation of 6.25 based on historic data. Capacity was determined from dividing reserves by LOM multiplied by the recovery rate. For recovery rate, we assumed a mean of 58% and a standard deviation of 24% (based on historical efficiencies for Co recovery). For each deposit, we drew the recovery rate from this distribution non-parametrically. We assumed this rate for 2017 production, and 1% increase every year following 2017. Each of these potential sources was divided among three levels of possibility, low, medium, and high (details for this assignment are provided in the supporting information), which was used to designate a starting year of 2020, 2022, or 2025, respectively. We considered a ramp up period of three years in which production evolves from 25% up to 100% capacity by the third year. For those deposits labeled “low confidence” we assumed a randomly assigned 60% would not be producing at all within the period of interest. When reserves data were not available, the ratio of resources to reserves was drawn from a non-parametric bootstrapping with a mean of 0.59 and a standard deviation of 0.31 based on historic data.

The overall approach taken to model supply is complementary to that taken by others.[39–42] The approach of previous work explicitly focuses on ore grade decline, which provides an appropriate way to provide a long-term production estimate. As the focus in the current work is on the short to medium term, information can be leveraged from company reports and production guidance. Companies consider many factors beyond ore grade in the short term such as market price, profitability, etc. Therefore, a more mine-by-mine approach provides a useful proxy for short term supply.

## 3. Results

### 3.1 Demand

Figure 3a shows the scenarios for projected demand for EV batteries, ranging from 115 and 250 ktonnes in 2030. For other battery demand in 2030, the total Co needed is between 46-78 ktonnes for electronics batteries and between 21-30 ktonnes for other battery applications. Historically, Co use has been dominated by electronics; however, the high CAGR EV scenarios implies that EV LIB Co demand accounts for 70% of battery demand by 2030, a significant shift in the market for Co.

Figure 3b shows the demand for non-battery applications, which currently makes up around 47% of Co demand. Superalloys and hard materials sectors have both the largest market share for Co demand and the strongest growth, while demand from catalysts, pigments, magnets and others show a declining trend in the last decade. The grey segments in figure 3 show the constant CAGR scenario while the red line indicates the total Co with an aggressive substitution scenario for superalloys. Total Co demand for non-battery applications in 2030 ranges from 52-60.5 ktonnes. The total Co demand across both battery and non-battery applications therefore ranges from 235 ktonnes to 430 ktonnes. This aligns with the lower end of previous published estimates from related publications that looked at estimating demand out to 2050.[43]

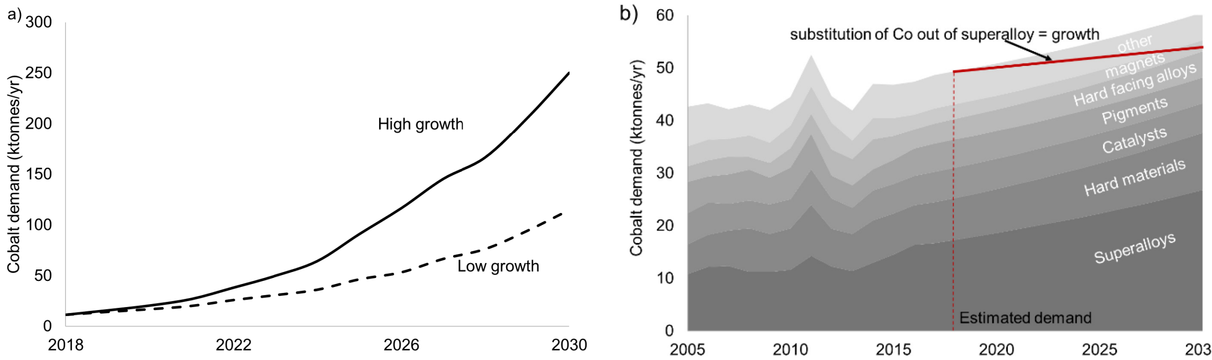

Figure 3. Cobalt demand a) EV battery demand for high and low growth scenarios b) Non-battery demand for Co including breakdown by end use including sector-specific CAGR. Red line indicates overall demand scenario including sector-specific constant CAGR and substitution out of superalloy demand. Vertical dashed line indicates historic data versus estimated data.

## 3.2 Supply

The results of the residence-time model provide an estimate for secondary Co over the period of interest. For an assumed 12-year lifetime, the total Co available from EV secondary sources is less than 30 ktonnes, at the 8-yr lifetime the total ranges from 45-75 ktonnes, on the order of demand from non-battery sources. The 8-yr lifetime is likely a lower bound considering the possibility of second life of batteries. Recovery from electronics recycling adds another 17 ktonnes of Co by 2030. Because of the assumed 100% recovery, this secondary contribution of between 47-92 ktonnes in 2030 is an overestimate. The highest possible supply from secondary sources represents short product lifespans magnifying the demand for more Co and associated minerals.

Figure 4 shows the share of mining production of Co from 2015 – 2030 broken down by principal metal and by country and region, showing both quantities of Co (4a and 4b) and percentage shares (4c and 4d). The striped region within each segment is the median of the simulation model for unscheduled production and the darker color is for scheduled production (the range for the unscheduled production modeling is shown in the supporting information). We estimate that Co mining in the DRC will continue to provide 62-70% of global production from 2018 to 2030. In addition to the DRC, several other countries are also estimated to contribute significant amounts of Co production (Figure 6b and d). Australia, Canada, Cuba, Madagascar, Philippines, Russia, and Zambia will each account for 2-6% of global production.

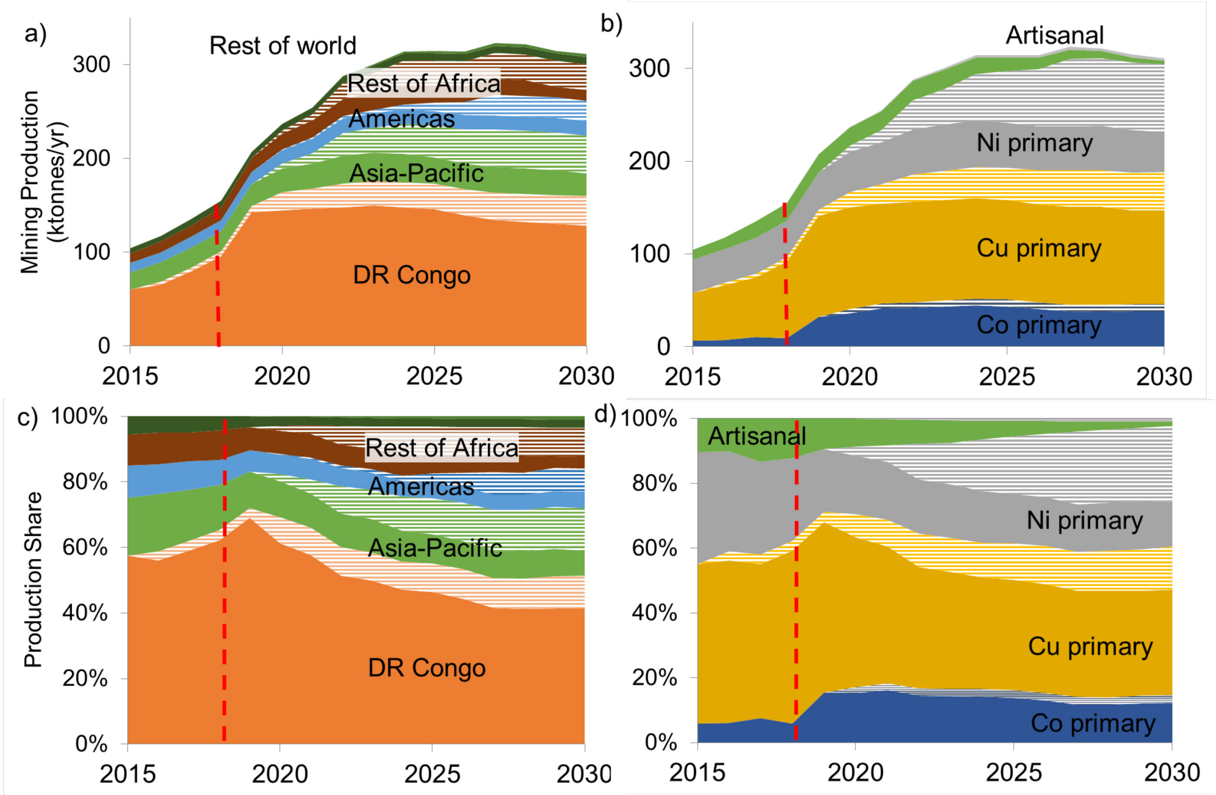

Figure 4. Estimates of Co supply from primary mined sources by country (a and c) and principal metal (b and d) plotted in terms of mining production (a and b) and production share (c and d). The solid region corresponds to scheduled production for the source or geographic region and the striped segment corresponds to unscheduled production for each source or geographic region. The vertical dashed line represents the beginning of estimated results versus reported data.

We estimate that during 2015 to 2030, production from Co-principal mines will account for 14-25% of total mining production. In addition, Cu-principal Co mines with relatively high revenue fraction from Co (>30% annual average), account for another 24% to 49% of total mining production, Co from these sources operates more like a coproduct. Together these sources represent over half of the mining production in this period, which is driven only or in part by the Co market.[44,45,46] However, we estimate that more Co will be derived from Ni production in the future rather than Cu, as the unscheduled Ni-principal Co segment is larger than for Cu. For Ni-principal Co mines, the revenue fraction from Co is much smaller. Most of these mines receive less than 5% of revenue from Co. Based on industry discussions with Ni mining companies, even when Co accounts for about 20% gross revenue of a mining project, they are not responsive to Co prices. Extraction from Ni implies that Co may act more as a byproduct in the future, as opposed to a coproduct as is the case for Cu-principal Co.

Our estimate for total Co demand ranges from 235 ktonnes to 430 ktonnes, which includes scenarios of aggressive substitution in non-battery demand, high and low CAGRs on EVs and electronics, as well as range in GWh for the grid (Figure 5). For supply, the combined total of scheduled supply, electronics and LIB recycling, as well as unscheduled primary, ranges from 323 ktonnes to 458 ktonnes. We conclude that in the short-term scenario-based quantities of Co supply and demand are closely matched.

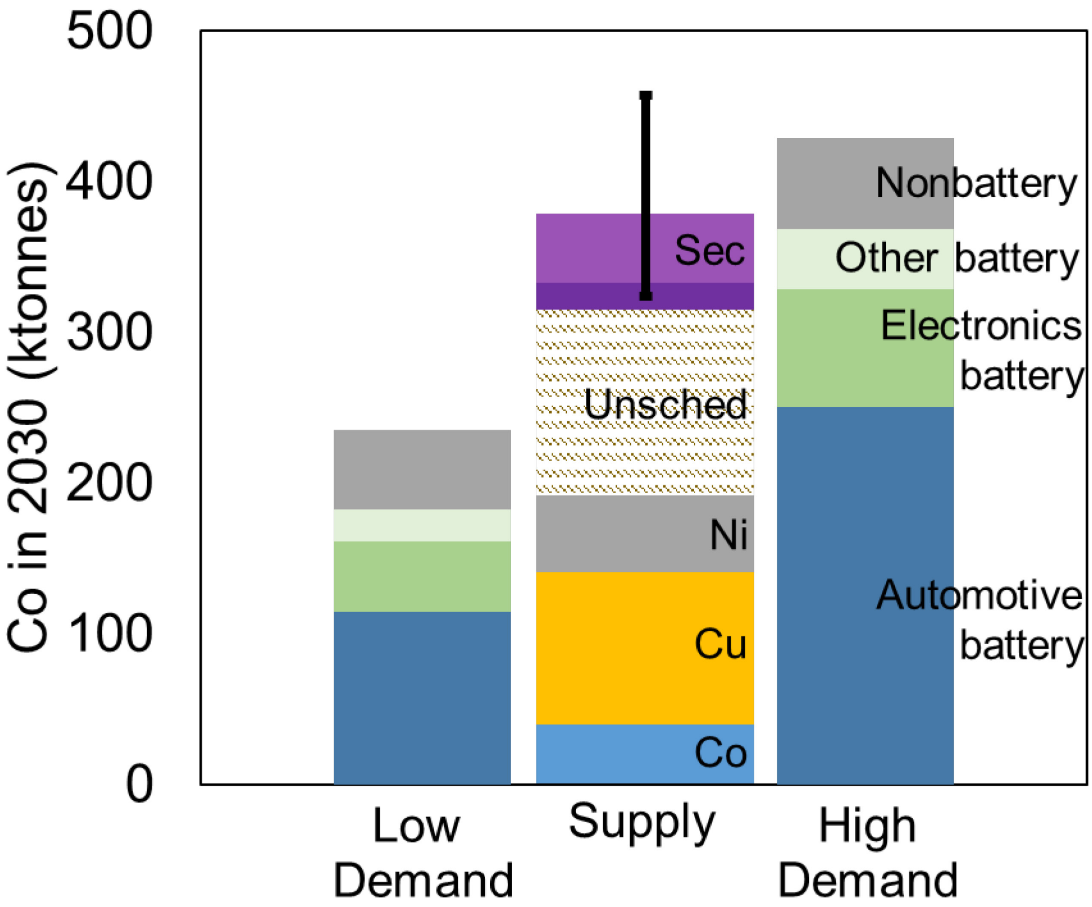

Figure 5. Low and high scenarios for demand including non-battery, other battery, electronics battery and automotive battery applications plotted along with supply of Co including secondary sources. Each supply section represents Co derived from a different source based on scheduled mined production for Co, Cu, and Ni; median unscheduled across all mined sources in the hashed section (Unsched.) and secondary recovery from EVs and electronics (Sec). The error bar includes the range of unscheduled production estimates and range in secondary production based on battery lifetime.

## 4. Discussion

Given that these values estimate a relative balance between mined supply and refined demand or even supply surplus, our analysis suggests Co price will remain relatively stable. However, our lower and upper bounds on Co demand in 2030 are 160% and 280% of world refinery capacity in 2016, respectively. For this demand to continue to be met, attention should be paid to sustained investments in refined supply of Co as well as investments in secondary recovery. High values of Co recovery and secondary supply from EVs bring supply within reach of demand to 2030. Secondary supply alone is not enough in the short term to meet demand and would be further delayed if second life options become a preferred route. On the supply side, there is also opportunity for increased mining efficiency, which at an upper bound could add another 40 ktonnes of Co. This is estimated by increasing current average recovery for Co-principal to close to 95% and for byproduct mines to 80%.[36] The upper bound on 2018-2030 cumulative Co demand represents close to 10% of identified terrestrial resources (1.5% also including sea bed resources, see paragraphs below). The ratio between reserves reported in 2018 and 2030 demand (upper bound) is 16 years (termed the static depletion index), compared with 46 years for those same reserves divided by 2018 production. The sharp downward trend in this index is further indication of potential supply chain pressure.

Because of the potential shift in the supply of Co towards more Ni-based sources and the potential to shift to more Ni-based battery chemistries, we comment also on Ni supplies, particularly as it relates to Ni used in battery production. Co can be sourced from either the leaching of Ni-bearing laterite ores or the smelting of Ni sulfide ores.[47] Only the nickel sulphate route currently yields battery-appropriate grade Ni economically, while instead the current production of Ni has been dominated by expansion of Ni pig iron for stainless steel or ferronickel with fewer ore discoveries that would lead to further sulfide smelting. For the integrated sulfide producers, smelting of sulfide concentrates to produce matte is dependent on investments in new sulfide discoveries (which themselves have a long trajectory). There is potential for hydrometallurgical recovery from laterite ores or as an add-on to sulfates, but the economics are challenging. If increased demand for Co leads to higher prices for the metal, then there would be an additional revenue stream from selling Co byproduct, which in turn could offset more operational costs for a mine. There is potential for disruptive alternatives in the battery-grade Ni from Ni pig iron sources, similar to what was seen for Mg around the Pidgeon process several decades ago.[48,49] Given the coupled nature of Ni and Co from both a supply and demand perspective, this dynamic is likely to influence the markets for both materials in the near future.

One source of Co that we have not yet considered is from deep sea mining. Hein et al. estimated that deep sea deposits potentially host a significant amount of recoverable Co which exceed that amount in terrestrial deposits, but the viability of these speculative resources is largely uncertain.[50] Polymetallic nodules contain 0.25% Co and Co-rich ferromanganese crusts contain around 1 or 2%. Most prospective deep-sea mining discussions revolve around Solwara in Papua New Guinea (hydrothermal vents), Clarion Clipperton Fracture Zone (CCZ) in the central Pacific (nodules), and Cook Islands (nodules).[51,52] The viability of these sources playing a role before 2030 is unlikely for a variety of reasons stemming from regulatory issues, as few of these sources are in national waters (Cook Islands is an exception). Based on discussions with the industry, we hypothesize that beginning in the mid-2020s there may be 3-5 contractors who are able to extract some Co from this source resulting in around 6 ktonnes per year per contractor (assuming 85% recovery). This is not a significant source of Co within the timeframe of interest in this work.

For a longer-term view on sea bed extraction, CCZ is known to contain over 1.5 million tonnes of Co reserves and resources at an ore grade of 0.25 or 0.3%, making it one of the larger Co deposits in the world. The company, Ocean Minerals, estimated that the Cook Islands has the largest known Co resource in the world, potentially 15-20% of the world's presently known Co resources.[53] However, the project's economic viability has not been demonstrated yet; the extent to which that resource could be transformed into economically viable reserves is still in question. There is also significant concern about the potential negative impact of deep sea mining on ecology and biodiversity.[54]

This work has performed scenario modeling in which the supply and demand scenarios are independent of one another. This is an incomplete perspective, as it neglects how possible supply-demand imbalances lead to price changes and therefore the behavior of both producers and users. A more integrated investigation is the subject of future work, which would include, for example, how demand growth would endogenously influence which mines are developed and at what scale.

Another area of future study would explore the longer term supply chain considerations required to meet climate goals; research indicates that global emissions of greenhouse gases (GHG) need to be brought down to zero, net of sinks, within the next 50 years.[55] This transformation will involve all sectors of the economy and has been the subject of several integrated assessments, which provide insight regarding the extent of the transition involved.[56,57] Relevant to this work, such a major transformation will likely have further implications for demand of Co both for transportation and grid applications. Any analysis which predicts decarbonization approach can apply this analysis of battery chemistries shares within market and Co content to explore more detailed demand scenarios. The upper bound assumption for EV adoption by 2030 used in this work aligns with the International Energy Agency (IEA) New Policies scenario. The IEA reports Co EV demand of 350 kt/yr for an EV30@30 Scenario, which reaches 30% market share for EVs by 2030 (EV sales reach 43 million).[58] This demand, combined with other sources of demand (even using our low estimate of those sources), would exceed even our upper bound on supply (470 ktonnes demand versus 458 ktonnes supply). Among scenarios recently presented by the United Nations' Intergovernmental Panel on Climate Change, the transportation sector would increase its share of "low-emission final energy" to 35-65% of the total by 2050 for 1.5 degree limiting scenarios.[55] The wide range reflects variety in approaches taken to decarbonize the transportation sector. Another important consideration is that many low-carbon transportation technologies involve increased use of Cu conductive wiring. Increased demand for Cu is likely to create a positive feedback look for Co supply because of their coupled production.[56]

With the case of Co, we see a strong example of how advanced energy technologies are enabled directly by, or designed around, a set of materials 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 the societal goal to decarbonize the transportation fleet, attention should be given to the supplies of these materials. There is potential supply chain risk associated with supply of Co given its geographical concentration. Further factors such as political instability in the DRC, small quantities of secondary supply entering the market, the degree of integration among firms within the Co extraction pipeline, potential for hedging and speculation, and rapid demand increases in battery sectors may act to increase the gap between supply and demand past 2030. Beyond this concentration in extraction, there is also concern raised by differential regional capabilities to refine and process battery grade material as 85% of the capability for refining is found in Japan, Korea, and China. The US remains a bystander in the manufacturing supply chains for these materials.

While these increases in demand for Co do put pressure on the supply chain, if anticipated and planned for, mitigation strategies can be developed. Economic forces will incent, for example, further mining exploration, improved yields in mining and refining, adoption of advanced battery chemistries that use less Co, or recovery from products at end-of-life. The rate of change in emissions needed to reach societally agreed-upon goals remains the same whether society manages the potential resource economics challenges of EV adoption or not. We encourage policy makers to consider material criticality risks not just in isolation, but rather in the context of a) existing risks from maintaining status quo vehicle technology use (e.g. worsening climate change) and b) risks of pursuing other viable decarbonization solutions (e.g. alternate battery compositions, drivetrains, transportation mode shifts, etc.).

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## Supporting information

There is Supporting Information is available free of charge on the ACS Publications website at DOI: Additional details regarding the methodology, scenarios, and tables including chart data throughout the manuscript.

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