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

2
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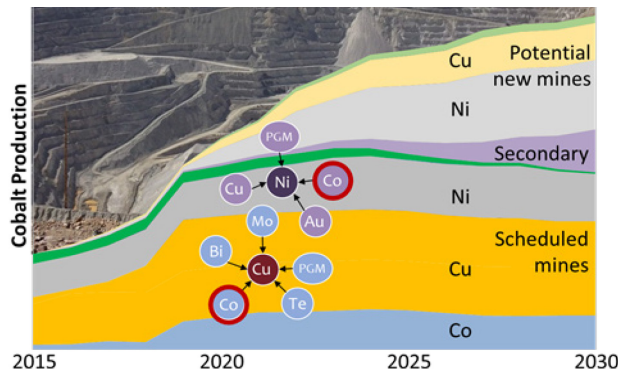
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13 Abstract

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



TOC Art

28 1. Introduction

29 Recent activity in vehicle electrification has led to increased focus on lithium-ion batteries (LIB) and the
30 resulting material system consequences. As many as one million electric vehicles (EVs) were sold in China
31 in 2018.¹ As interest in LIB increases, this invites a number of questions regarding a) the evolution of that
32 demand, b) which types of battery chemistries will be leveraged to meet EV demand, c) the supply chain

33 impacts based on mining and refining capacity, d) the environmental and social impacts of growing mine
34 output, and e) the recycling infrastructure to support end-of-life materials management.

35
36 Economic theory emphasizes that in well-functioning markets, over the long term, imbalances between
37 supply and demand tend to be self-correcting. In the short to medium term, however, markets and prices
38 can be disrupted and volatile. These availability concerns can cause problems for novel technologies, and
39 evolving regulations in response to these concerns can change the economic landscape. There are
40 examples of disruption in materials supply chains that led to profound change in material use², delayed
41 technology implementation, or political instability³ so foresight is critical to planning, management, and
42 action. Moreover, even over the longer term, this view of a material market ignores environmental
43 externalities, functionality constraints around relative substitutability of a material, and feasibility of
44 alternatives in the near term.⁴

45
46 A previous screening analysis by a subset of the authors has shown the importance of Co based on supply
47 chain concentration and its coproduct status.⁵ The majority of Co is produced as a byproduct in mining
48 projects whose revenue comes primarily from copper (Cu) and nickel (Ni) mining. In this study, we address
49 Co availability from 2020-2030. We provide a detailed investigation of new Co supply, the potential role
50 of secondary supply, as well as demand across a variety of applications. We explore how supply of Co will
51 shift to meet this demand through 2030; geographically and by source.

52
53 Demand for Co is based on end uses in LIBs, superalloys, hard materials/cutting tools, and catalysts,⁶ with
54 limited ability to substitute with another element for most applications.⁷ LIB uses, concentrated in
55 consumer electronics and EVs, are currently the largest end use of Co (accounting for 50% of global Co
56 demand).⁸ The market for EVs is expected to increase significantly after 2020, as costs for EVs begin to
57 equalize with those for internal combustion engine vehicles.^{8,9} While projections of extreme EV growth
58 represent sustainable ideals, there are several challenges associated with large increases in EV demand
59 and implementation. Various risk factors have been well documented in recent publications. Pelegov and
60 Pontes indicate production scalability, cost, policy variation across governments, and EV battery recycling
61 impacts (both environmental and economic) as pressing risks to global EV adoption.¹⁰ Additional studies
62 have focused on supply chain concerns, particularly raw material availability and accessibility, as high-risk
63 factors for global EV adoption in the coming years.^{6,9}

64 As detailed in various publications, Co scores highly among potential supply chain disruption drivers
65 including geographically concentrated mining and refining, sociopolitical instability and unrest, by-
66 product production dependence, and cost.^{6,9,11} Primary supply of Co is heavily geographically
67 concentrated, both for mining and refining of the mined materials. Current estimates locate
68 approximately 60% of all mined Co production in the Democratic Republic of the Congo (DRC); this value
69 has been estimated to reach upwards of 65% before 2030.¹² According to the World Governance
70 Indicators developed by the World Bank Group, the DRC has consistently ranked in the lowest 10
71 percentile among all countries it investigates in terms of political stability, government effectiveness, rule
72 of law, and control of corruption.^{13,14,15} Examples of this include political and social issues in the 1970s and
73 1990s that led to supply constraints and subsequent extreme price increases.^{6,16} Supply is more diverse
74 from a company perspective compared to the geographic perspective, and no company has a production
75 share more than 30% on average. Although China has a small share in terms of direct mining production,
76 it indirectly controls 19-26% of mining production through ownership of mining projects mostly located
77 in the DRC.¹⁷

78 Co processing is also heavily concentrated; 2017 numbers indicate that China is responsible for 58% of
79 refined Co, 91% of which originates in the DRC.⁸ Activity in the DRC raises additional concern because of

80 artisanal mining, which is estimated to account for 10% of annual Co production in the country. This
81 unregulated, often unrecorded, practice has led to environmental, social, and health concerns particularly
82 around land contamination, water pollution, child labor, and social unrest.¹⁸

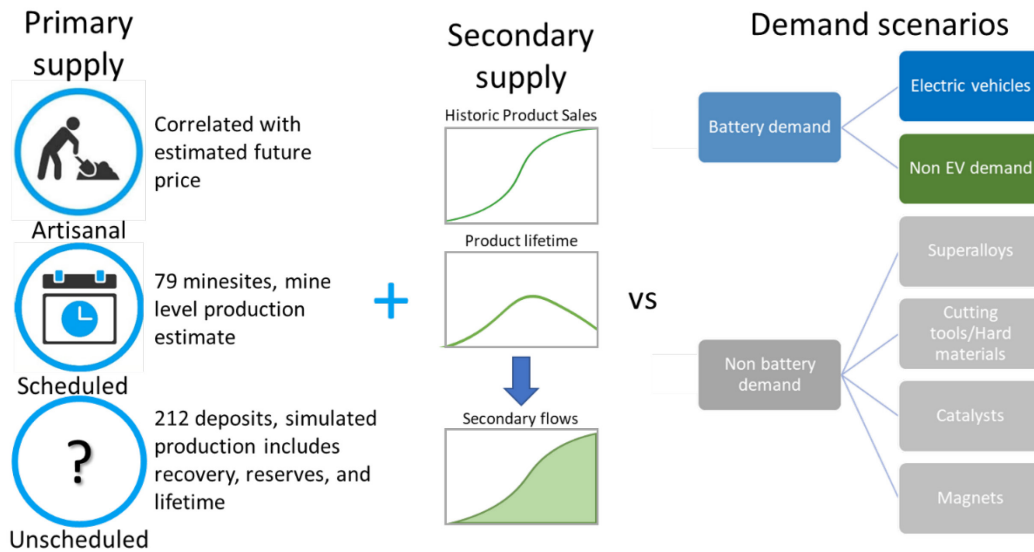
83 Some literature is optimistic about Co futures because assumptions either include proxies for future
84 demand that are more conservative or because they assume aggressive build out of secondary sources.
85 Such studies include those by Tisserant and Pauliuk¹⁹ who conclude that Co supply will easily meet
86 demand out to 2050 and that by-product status has little effect on Co supply in the relatively near future
87 as well as investigations by Sverdrup et al. who consider long-term sustainability of Co out to 2400, where
88 secondary production exceeds primary between 2080 and 2120.²⁰

89 Other works suggest that demand may outpace supply. Valero and coauthors conclude that both Ni and
90 Co demand may outpace reserves in the midterm: Ni could experience bottlenecks as early as 2027, and
91 Co demand is likely to exceed production between 2030 and 2050 with EVs the largest focus of future
92 bottlenecks.⁹ Due to the highly concentrated supply chain of Co and the significant increases in demand
93 that are expected from EV battery implementation, market analysts have also stated that the market for
94 Co will likely continue to remain imbalanced.¹² Future supply consists of significant increases in primary,
95 increases in secondary Co from end of life recycling in the mid- to long-term, and increased Co
96 substitution, (especially in batteries) in the short term. These scenarios are unlikely due to lack of sufficient
97 recycling infrastructure and economic incentives; in 2018 Co contained in scrap represented an estimated
98 30% of consumption.²¹ Substitution may be a viable option in some sectors, however it can often lead to
99 increased prices and decreased performance.

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

106 2. Methods

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



112
 113 Figure 1. Methodology schematic illustrating approach to model primary and secondary supply as well
 114 as demand applications.
 115

116 2.1 Demand Scenarios

117 For Co *demand* up to 2030, we differentiated Co-consuming sectors according to the following, ranked
 118 by market size globally in 2017⁸:

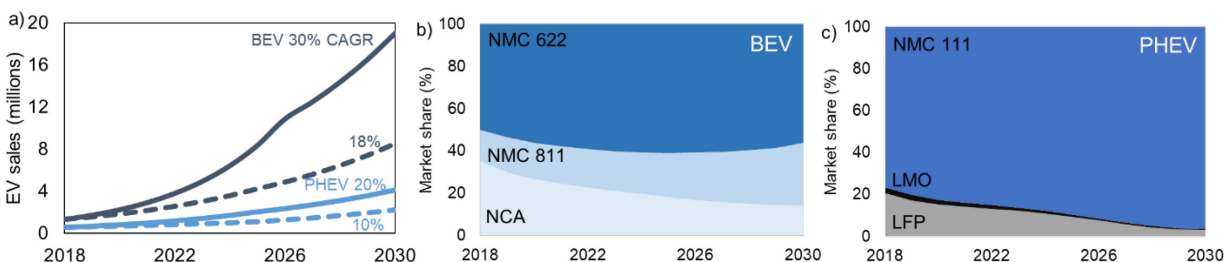
- 119 1. **Battery chemicals demand:** Co is used predominantly as a cathode constituent in LIBs batteries,
 120 53% of total demand for Co. Major applications include consumer electronics (40%), EVs, and
 121 advanced battery energy storage systems (ESS) for grid load leveling to match renewable supply.
 122
- 123 2. **Non-battery demand:** This includes Ni-based superalloys, 16%, used in aircraft engines, turbines
 124 for power generation, and prosthetics. Second highest by quantity, 7%, are hard materials where
 125 Co acts as a binding material in diamond cutting tools and cemented carbide applications for
 126 metal cutting. The catalyst sector is next at 6%, where Co is used in chemical form for
 127 desulfurization from natural gas and petroleum products, synthesis of polyester precursor, and
 128 the hydrogenation of carbon monoxide into liquid fuels. Finally, other smaller uses include
 129 pigments (5%), hardfacing alloys (4%), and magnets (3%).

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

139 Co consumption in EVs depends on market growth rates, the relative fraction of full battery EV (BEV)
 140 versus plug-in and hybrid electric vehicles (PHEV), the pack size, and the battery chemistry for each vehicle
 141 type (we assumed no significant introduction of fuel-cell vehicles, consistent with previous studies²⁷).

142 These parameters were specified over time to link to potential secondary supply, expected to be most
 143 significant for EVs (rather than electronics). For each vehicle type we have reported or estimated vehicle
 144 sales data and projected growth rates from 2018 to 2030.¹ From 2018-2025 these range from 10%-20%
 145 CAGR for PHEVs and 18% to 30% BEVs. Between 2026 and 2030, we assume a constant CAGR of 15%.
 146 Battery pack sizes range from 40 kWh – 75 kWh for BEVs and 10-20 kWh for PHEV, with the expectation
 147 that they will increase over time as battery prices fall.²⁸ International Energy Association historical data
 148 shows that PHEV have dominated global sales but in recent years BEV sales have begun to outpace PHEV;
 149 2015 and 2016 showed BEVs as ~60% of yearly sales.¹ Our assumed cathode chemistry for these vehicles
 150 was a market mix for PHEV and BEV individually, including NMC-622, NMC-811, and NCA (lithium nickel
 151 cobalt aluminium oxide) for BEVs as well as LMO (lithium manganese oxide), LFP (lithium iron phosphate)
 152 and NMC-111 for PHEVs. Figure 2a plots these assumptions for BEV and PHEV adoption in terms of millions
 153 of EV sales including an upper and lower bound with a discontinuity in 2026 with the shifted CAGR. Figure
 154 2b and c show the assumed market share by battery chemistry for BEV and PHEV, respectively. There is
 155 some shift towards lower Co-containing battery chemistries, but over this short timeframe, this shift will
 156 not be significant based on automotive platform lock-in.

157



158

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

161

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

168

169 Table 1. CAGR based on 2005-2017 historical demand and 2017 market share for non-battery Co
 170 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

171

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

176

177 2.2 Supply Scenarios

178 **Secondary supply:** To project the quantity and timing of Co available for recovery from the waste stream
179 after use in the demand sectors described above, a residence-time model based on average product
180 lifetimes was applied to LIBs contained in EVs, laptops, and cell phones. These product categories
181 represent the highest use of Co in a form feasible for recovery, whereas tablets, e-readers, and other
182 mobile electronics are minor volumes, comparatively. Material stocks were inferred from product sales,
183 product lifetimes, and compiled from industry reports and product lifespans.^{22,23,29} The model was
184 initialized with sales data beginning in 2006 when volume of EVs was quite low. Secondary supply focused
185 on battery use because of the significantly longer lifetimes of the non-battery applications for products
186 such as superalloys and magnets, the dissipative nature of their use in the case of pigments, and that Co
187 is not typically recovered from these end products as for use outside of a metal alloying element.
188

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

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

217 We also modeled production from artisanal mining. Artisanal mining has historically shown strong
218 correlation with Co market prices. We assumed production was correlated with our estimated future
219 cyclic scenario of price (see supporting information for details on price), but also assume significant cuts
220 in artisanal mining based on regulatory pressure (40% reduction in 2017 and 6% decrease each year after
221 2017).³⁸ These assumptions are oversimplified, but artisanal mining is not a significant amount of the
222 supply going forward.

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

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

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

257

258 3. Results

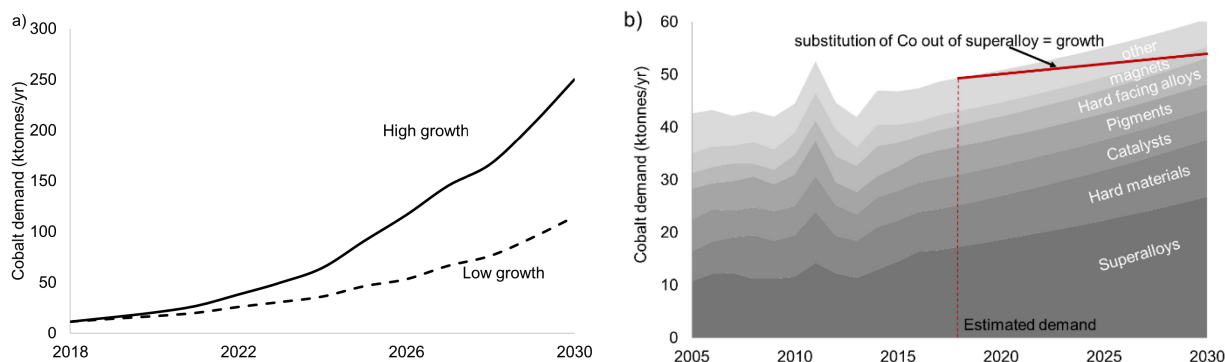
259 3.1 Demand

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

265 Figure 3b shows the demand for non-battery applications, which currently makes up around 47% of Co
266 demand. Superalloys and hard materials sectors have both the largest market share for Co demand and

267 the strongest growth, while demand from catalysts, pigments, magnets and others show a declining trend
 268 in the last decade. The grey segments in figure 3 show the constant CAGR scenario while the red line
 269 indicates the total Co with an aggressive substitution scenario for superalloys. Total Co demand for non-
 270 battery applications in 2030 ranges from 52-60.5 ktonnes. The total Co demand across both battery and
 271 non-battery applications therefore ranges from 235 ktonnes to 430 ktonnes. This aligns with the lower
 272 end of previous published estimates from related publications that looked at estimating demand out to
 273 2050.⁴³

274



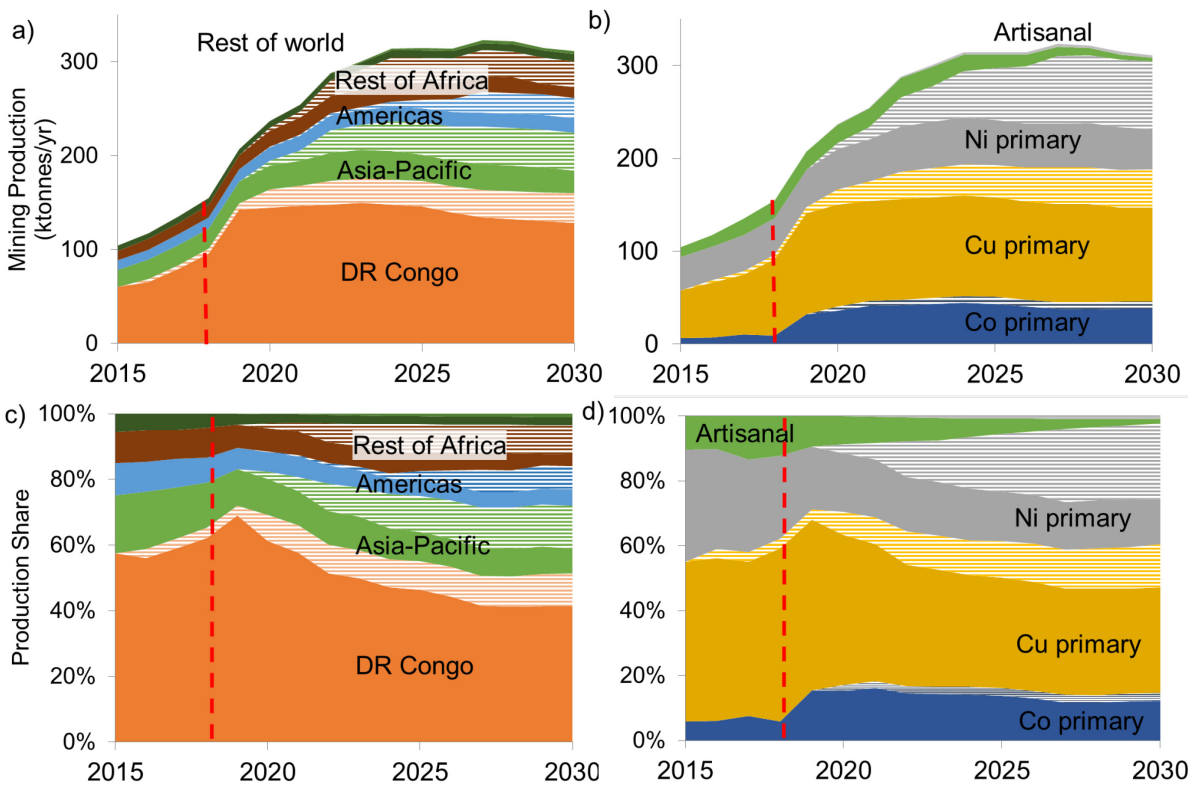
275
 276 Figure 3. Cobalt demand a) EV battery demand for high and low growth scenarios b) Non-battery
 277 demand for Co including breakdown by end use including sector-specific CAGR. Red line indicates overall
 278 demand scenario including sector-specific constant CAGR and substitution out of superalloy demand.
 279 Vertical dashed line indicates historic data versus estimated data.

280

281 3.2 Supply

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

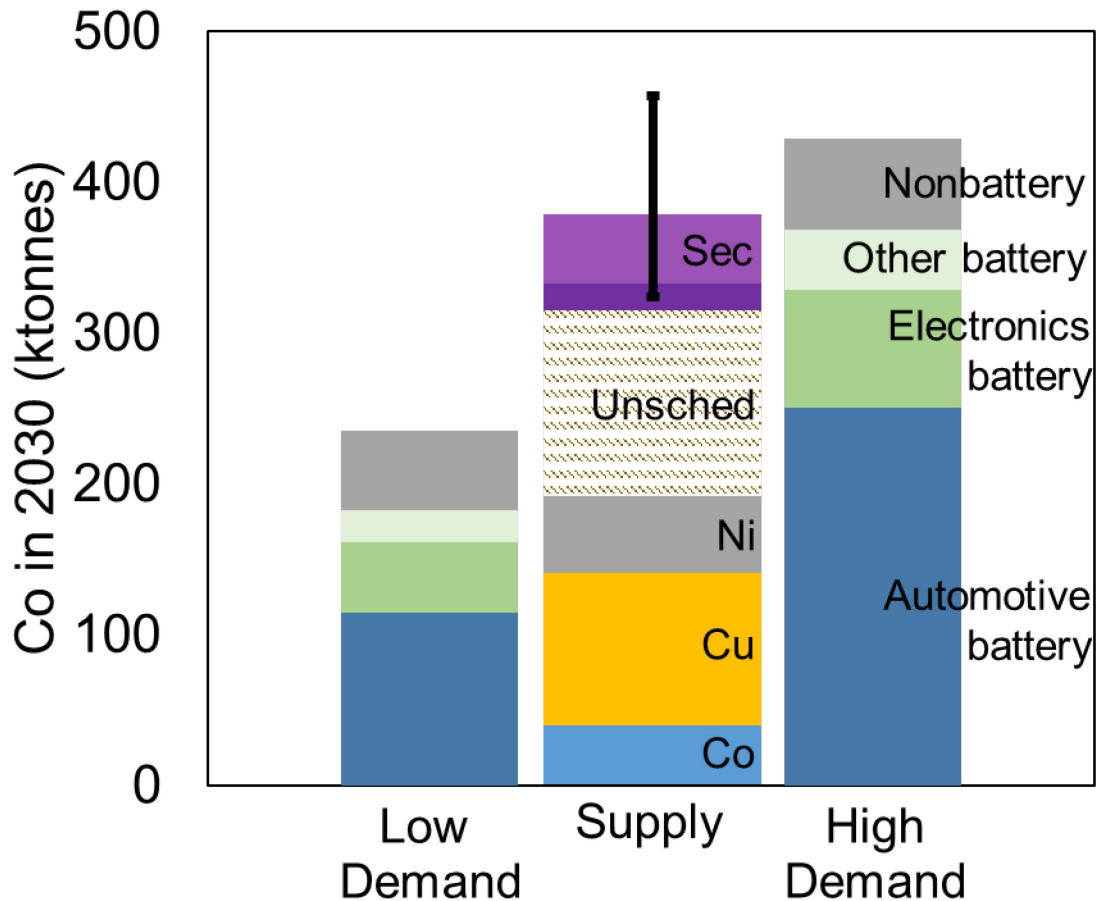
290 Figure 4 shows the share of mining production of Co from 2015 – 2030 broken down by principal metal
 291 and by country and region, showing both quantities of Co (4a and 4b) and percentage shares (4c and 4d).
 292 The striped region within each segment is the median of the simulation model for unscheduled production
 293 and the darker color is for scheduled production (the range for the unscheduled production modeling is
 294 shown in the supporting information). We estimate that Co mining in the DRC will continue to provide 62-
 295 70% of global production from 2018 to 2030. In addition to the DRC, several other countries are also
 296 estimated to contribute significant amounts of Co production (Figure 6b and d). Australia, Canada, Cuba,
 297 Madagascar, Philippines, Russia, and Zambia will each account for 2-6% of global production.
 298



299
 300 Figure 4. Estimates of Co supply from primary mined sources by country (a and c) and principal metal (b
 301 and d) plotted in terms of mining production (a and b) and production share (c and d). The solid region
 302 corresponds to scheduled production for the source or geographic region and the striped segment
 303 corresponds to unscheduled production for each source or geographic region. The vertical dashed line
 304 represents the beginning of estimated results versus reported data.
 305

306 We estimate that during 2015 to 2030, production from Co-principal mines will account for 14-25% of
 307 total mining production. In addition, Cu-principal Co mines with relatively high revenue fraction from Co
 308 (>30% annual average), account for another 24% to 49% of total mining production, Co from these sources
 309 operates more like a coproduct. Together these sources represent over half of the mining production in
 310 this period, which is driven only or in part by the Co market.^{44,45,46} However, we estimate that more Co
 311 will be derived from Ni production in the future rather than Cu, as the unscheduled Ni-principal Co
 312 segment is larger than for Cu. For Ni-principal Co mines, the revenue fraction from Co is much smaller.
 313 Most of these mines receive less than 5% of revenue from Co. Based on industry discussions with Ni mining
 314 companies, even when Co accounts for about 20% gross revenue of a mining project, they are not
 315 responsive to Co prices. Extraction from Ni implies that Co may act more as a byproduct in the future, as
 316 opposed to a coproduct as is the case for Cu-principal Co.
 317

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



324 Figure 5. Low and high scenarios for demand including non-battery, other battery, electronics battery and
 325 automotive battery applications plotted along with supply of Co including secondary sources. Each supply section
 326 represents Co derived from a different source based on scheduled mined production for Co, Cu, and Ni; median
 327 unscheduled across all mined sources in the hashed section (Unsched.) and secondary recovery from EVs and
 328 electronics (Sec). The error bar includes the range of unscheduled production estimates and range in secondary
 329 production based on battery lifetime.
 330
 331

332 4. Discussion

333
 334 Given that these values estimate a relative balance between mined supply and refined demand or even
 335 supply surplus, our analysis suggests Co price will remain relatively stable. However, our lower and upper
 336 bounds on Co demand in 2030 are 160% and 280% of world refinery capacity in 2016, respectively. For
 337 this demand to continue to be met, attention should be paid to sustained investments in refined supply
 338 of Co as well as investments in secondary recovery. High values of Co recovery and secondary supply from
 339 EVs bring supply within reach of demand to 2030. Secondary supply alone is not enough in the short term
 340 to meet demand and would be further delayed if second life options become a preferred route. On the
 341 supply side, there is also opportunity for increased mining efficiency, which at an upper bound could add
 342 another 40 ktonnes of Co. This is estimated by increasing current average recovery for Co-principal to
 343 close to 95% and for byproduct mines to 80%.³⁶ The upper bound on 2018-2030 cumulative Co demand
 344 represents close to 10% of identified terrestrial resources (1.5% also including sea bed resources, see
 345 paragraphs below). The ratio between reserves reported in 2018 and 2030 demand (upper bound) is 16

346 years (termed the static depletion index), compared with 46 years for those same reserves divided by
347 2018 production. The sharp downward trend in this index is further indication of potential supply chain
348 pressure.

349
350 Because of the potential shift in the supply of Co towards more Ni-based sources and the potential to shift
351 to more Ni-based battery chemistries, we comment also on Ni supplies, particularly as it relates to Ni used
352 in battery production. Co can be sourced from either the leaching of Ni-bearing laterite ores or the
353 smelting of Ni sulfide ores.⁴⁷ Only the nickel sulphate route currently yields battery-appropriate grade Ni
354 economically, while instead the current production of Ni has been dominated by expansion of Ni pig iron
355 for stainless steel or ferronickel with fewer ore discoveries that would lead to further sulfide smelting. For
356 the integrated sulfide producers, smelting of sulfide concentrates to produce matte is dependent on
357 investments in new sulfide discoveries (which themselves have a long trajectory). There is potential for
358 hydrometallurgical recovery from laterite ores or as an add-on to sulfates, but the economics are
359 challenging. If increased demand for Co leads to higher prices for the metal, then there would be an
360 additional revenue stream from selling Co byproduct, which in turn could offset more operational costs
361 for a mine. There is potential for disruptive alternatives in the battery-grade Ni from Ni pig iron sources,
362 similar to what was seen for Mg around the Pidgeon process several decades ago.^{48,49} Given the coupled
363 nature of Ni and Co from both a supply and demand perspective, this dynamic is likely to influence the
364 markets for both materials in the near future.

365
366 One source of Co that we have not yet considered is from deep sea mining. Hein et al. estimated that
367 deep sea deposits potentially host a significant amount of recoverable Co which exceed that amount in
368 terrestrial deposits, but the viability of these speculative resources is largely uncertain.⁵⁰ Polymetallic
369 nodules contain 0.25% Co and Co-rich ferromanganese crusts contain around 1 or 2%. Most prospective
370 deep-sea mining discussions revolve around Solwara in Papua New Guinea (hydrothermal vents), Clarion
371 Clipperton Fracture Zone (CCZ) in the central Pacific (nodules), and Cook Islands (nodules).^{51,52} The viability
372 of these sources playing a role before 2030 is unlikely for a variety of reasons stemming from regulatory
373 issues, as few of these sources are in national waters (Cook Islands is an exception). Based on discussions
374 with the industry, we hypothesize that beginning in the mid-2020s there may be 3-5 contractors who are
375 able to extract some Co from this source resulting in around 6 ktonnes per year per contractor (assuming
376 85% recovery). This is not a significant source of Co within the timeframe of interest in this work.

377
378 For a longer-term view on sea bed extraction, CCZ is known to contain over 1.5 million tonnes of Co
379 reserves and resources at an ore grade of 0.25 or 0.3%, making it one of the larger Co deposits in the
380 world. The company, Ocean Minerals, estimated that the Cook Islands has the largest known Co resource
381 in the world, potentially 15-20% of the world's presently known Co resources.⁵³ However, the project's
382 economic viability has not been demonstrated yet; the extent to which that resource could be
383 transformed into economically viable reserves is still in question. There is also significant concern about
384 the potential negative impact of deep sea mining on ecology and biodiversity.⁵⁴

385
386 This work has performed scenario modeling in which the supply and demand scenarios are independent
387 of one another. This is an incomplete perspective, as it neglects how possible supply-demand imbalances
388 lead to price changes and therefore the behavior of both producers and users. A more integrated
389 investigation is the subject of future work, which would include, for example, how demand growth would
390 endogenously influence which mines are developed and at what scale.

391
392 Another area of future study would explore the longer term supply chain considerations required to meet
393 climate goals; research indicates that global emissions of greenhouse gases (GHG) need to be brought

394 down to zero, net of sinks, within the next 50 years.⁵⁵ This transformation will involve all sectors of the
395 economy and has been the subject of several integrated assessments, which provide insight regarding the
396 extent of the transition involved.^{56,57} Relevant to this work, such a major transformation will likely have
397 further implications for demand of Co both for transportation and grid applications. Any analysis which
398 predicts decarbonization approach can apply this analysis of battery chemistries shares within market and
399 Co content to explore more detailed demand scenarios. The upper bound assumption for EV adoption by
400 2030 used in this work aligns with the International Energy Agency (IEA) New Policies scenario. The IEA
401 reports Co EV demand of 350 kt/yr for an EV30@30 Scenario, which reaches 30% market share for EVs by
402 2030 (EV sales reach 43 million).⁵⁸ This demand, combined with other sources of demand (even using our
403 low estimate of those sources), would exceed even our upper bound on supply (470 ktonnes demand
404 versus 458 ktonnes supply). Among scenarios recently presented by the United Nations'
405 Intergovernmental Panel on Climate Change, the transportation sector would increase its share of "low-
406 emission final energy" to 35-65% of the total by 2050 for 1.5 degree limiting scenarios.⁵⁵ The wide range
407 reflects variety in approaches taken to decarbonize the transportation sector. Another important
408 consideration is that many low-carbon transportation technologies involve increased use of Cu conductive
409 wiring. Increased demand for Cu is likely to create a positive feedback loop for Co supply because of their
410 coupled production.⁵⁶

411
412 With the case of Co, we see a strong example of how advanced energy technologies are enabled directly
413 by, or designed around, a set of materials and are therefore subject to the supply chain issues that
414 accompany those materials. Given the demand growth for LIBs, driven by a continued drop in cost, and
415 the societal goal to decarbonize the transportation fleet, attention should be given to the supplies of these
416 materials. There is potential supply chain risk associated with supply of Co given its geographical
417 concentration. Further factors such as political instability in the DRC, small quantities of secondary supply
418 entering the market, the degree of integration among firms within the Co extraction pipeline, potential
419 for hedging and speculation, and rapid demand increases in battery sectors may act to increase the gap
420 between supply and demand past 2030. Beyond this concentration in extraction, there is also concern
421 raised by differential regional capabilities to refine and process battery grade material as 85% of the
422 capability for refining is found in Japan, Korea, and China. The US remains a bystander in the
423 manufacturing supply chains for these materials.

424
425 While these increases in demand for Co do put pressure on the supply chain, if anticipated and planned
426 for, mitigation strategies can be developed. Economic forces will incent, for example, further mining
427 exploration, improved yields in mining and refining, adoption of advanced battery chemistries that use
428 less Co, or recovery from products at end-of-life. The rate of change in emissions needed to reach
429 societally agreed-upon goals remains the same whether society manages the potential resource
430 economics challenges of EV adoption or not. We encourage policy makers to consider material criticality
431 risks not just in isolation, but rather in the context of a) existing risks from maintaining status quo vehicle
432 technology use (e.g. worsening climate change) and b) risks of pursuing other viable decarbonization
433 solutions (e.g. alternate battery compositions, drivetrains, transportation mode shifts, etc.).

434
435
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442

443 Supporting information

444 There is Supporting Information is available free of charge on the ACS Publications website at DOI:
445 Additional details regarding the methodology, scenarios, and tables including chart data throughout the
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447

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