

1 **Circular economy strategies for electric vehicle batteries reduce raw material reliance**

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14 **Abstract**

15 The wide adoption of lithium-ion batteries used in electric vehicles (EVs) will require increased
16 natural resources for the automotive industry. The expected rapid increase in batteries could
17 result in new resource challenges and supply chain risks. To strengthen the resilience and
18 sustainability of automotive supply chains and reduce primary resource requirements, circular
19 economy strategies are needed. Here we illustrate how these strategies can reduce primary raw
20 material extraction i.e. cobalt supplies. Material flow analysis is applied to understand current
21 and future flows of cobalt embedded in EVs batteries across the European Union. A reference
22 scenario is presented and compared with four strategies: technology driven substitution and
23 technology driven reduction of cobalt, new business models to stimulate battery
24 reuse/recycling and policy driven strategy to increase recycling. We find that new technologies
25 provide the most promising strategies to reduce the reliance on cobalt significantly but could
26 result in burden shifting such as an increase in nickel demand. To avoid the latter, technological
27 developments should therefore be combined with an efficient recycling system. We conclude
28 that more ambitious circular economy strategies, at both government and business levels, are
29 urgently needed to address current and future resource challenges across the supply chain
30 successfully.

31

32 **Introduction**

33 The global adoption of low-carbon sustainable energy technologies and infrastructures result
34 in mineral resource challenges. These challenges are well illustrated in the case of Electric
35 Vehicles (EVs), which are considered as one of the key technologies to climate change
36 mitigation efforts in the transport sector. With a global record-breaking amount of EVs sales
37 in 2019 and continuous policy and business support, this disruptive technology needs careful
38 consideration in terms of natural resource challenges. International policy efforts to integrate
39 Circular Economy Strategies (CES) may be a way forward to foster a sustainable use of global
40 resources whilst meeting climate and Sustainable Development Goals. This study quantifies
41 opportunities and limitations of CES for lithium-ion batteries (LIB) in EVs raw material
42 supplies, with a focus on Cobalt (Co). Cobalt is an excellent case as its market is prone to three
43 major supply risks¹.

44 First, Co is primarily mined as a by-product of nickel and copper (43% and 44% in 2015) and
45 therefore relies on both markets for the expansion of new mines². Second, the Co market has a
46 high centralisation of mine production and reserves, located in the Democratic Republic of the
47 Congo (DRC) as well as the increasing role of Chinese refining and mining ownership³. Figure
48 1 shows price peaks associated with events happening in the DRC and the recent market trends
49 with prevailing DRC hegemony. Finally, substitution of Co whilst maintaining product
50 performance is challenging and time consuming in applications such as hard facing materials,
51 pigments, catalysts, super-alloys and LIB⁴. For LIB, new chemistries partly substituting Co
52 with Nickel (Ni) have been commercialized faster than expected⁵. However, the comparatively
53 long path between lab scale innovations and commercialisation in the electro chemical energy
54 industry⁶ and the essential role of Co to provide high energy density and stable batteries, as
55 well as the safety and performance improvement required by the automotive industry^{7,8}, makes
56 it unlikely for Co to be entirely substituted from LIBs in the foreseeable future.

57 INSERT FIGURE 1

58

59 **Figure 1. Annual cobalt price and production from 1950 until 2019.** Price line reflects the annual real price of
60 cobalt in dollar per tonne based on the 2019-dollar value. The dark blue shaded area represents global annual
61 cobalt mine production and the light blue areas annual cobalt production of the DRC. The large price peak in 1979
62 was due to the insurgency in the cobalt mining province Katanga (DRC), the resulting concerns for supply
63 availability and speculation on the cobalt market⁹. Production and price data compiled from USGS Yearbooks
64 ^{10,11}

65 Governments and industry are increasingly aware of Co supply risks and formulate critical
66 material strategies to mitigate risks, e.g. in the United States¹², Japan¹³ and the European
67 Union¹⁴. Most of these strategies point to the need of new sourcing avenues to ensure a stable
68 supply of Co and address concerns over social scrutiny of mining practices, as evidenced
69 through recent lawsuits filed against large tech companies over child labour¹⁵. Adopting CES
70 has become popular in recent years to contribute to reducing primary extraction and to a more
71 resilient and green supply chain for EV batteries. Based on the literature, we identified four
72 relevant CES for LIBs in EVs. The first and second strategy focus on reducing or eliminating
73 Co from current chemistries, e.g. through commercialisation of ground-breaking battery
74 technologies¹⁶ or a switch to high nickel (Ni) chemistry reducing the Co content. A third
75 strategy aims to promote the re-use market for EV batteries in less demanding applications
76 such as residential buildings¹⁷ or communication base stations¹⁸. The fourth strategy is based
77 on a closed loop battery recycling system, whereby waste batteries are a new source of
78 secondary materials for new battery production. Although obstacles for such system still
79 exist¹⁹, the potential of recycling is promising²⁰⁻²² and has already an important impact for the
80 battery material industry in countries with battery production at scale such as China and South
81 Korea²³.

82 To underpin these strategies and overcome the lack of granularity of established datasets²⁴, we
83 develop a detailed model of the current and future passenger vehicle fleet. We have
84 incorporated novel data sources to allow for a more detailed understanding of the current and
85 future Co demand and secondary supply. Due to the availability of such detailed data, the

86 geographical scope of this study is limited to the European Union. The data of EVs was
87 gathered and combined with company specific data on upstream battery production, Co
88 refining, mining production and trade data to establish a static material flow analysis for 2017
89 (see the Supportive Information (SI) and Methodology for all details and data).

90

91 Based on expected future EV adoption rates to reach the new EU vehicle emission targets^{25,26},
92 prospective Co demand is modelled. We adopt an explorative and strategic scenario approach
93 to investigate a range of possible outcomes. Secondary data is complemented with stakeholder
94 interviews, and site visits to battery recycling facilities, both framed within a variety of
95 literature sources, to develop a reference scenario. The reference scenario portrays the current
96 technology and battery recycling situation in the EU, illustrating a closed-loop recycling
97 system under the current economic and institutional framework. This serves as basis for
98 comparison to assess (and quantify) key opportunities and challenges across the different
99 scenarios. Four CES are modelled to quantify circular resource management options,
100 including: 1) technology driven Co substitution; 2) technology driven Co reduction; 3) new
101 business models based on reuse; and 4) policy-driven promotion of recycling. We find that the
102 gross demand of Cobalt for EVs in Europe in 2017 is relatively small, but an increase of 20 to
103 30 times is expected by 2035. The scenario results illustrate that CES could significantly
104 contribute to the saturation of primary Co consumption by the automotive industry.

105

106 **Results**

107 *EV Sales and the Flow of Cobalt in 2017*

108 The 2017 Co supply chain, from mined Co to EV use in the EU, is illustrated in Figure 2. Mine-
109 specific data of 2017 suggests that most Co is a by-product of copper (~63%) and Ni (~30%)
110 with the rest being copper-nickel, polymetallic and Co mines. In 2017, the total EU mined
111 production was 2.3 kt, all of which came from Finland. Total refined Co suitable for battery
112 production (Co powders, broken cathodes and briquettes) was 84.95 kt in 2017, which was
113 primarily produced in China (64%), followed by the EU (15%). Our analysis suggest that
114 consumption of these refined Co products is centralised around four countries consuming ~81
115 kt (94% of global production of Co powders, broken cathodes and briquettes). This includes
116 China (57 kt), Japan (10 kt), South Korea (8 kt) and the USA (6 kt). These are also the countries
117 producing cathode materials for EVs in the EU in 2017. We found that in 2017, the 218,850
118 battery electric (BEVs) and plug-in hybrid (PHEVs) passenger vehicles registered in the EU
119 (accounting for 1.4% of the total vehicles sales) consumed 1.2kt Co, accounting for 1% of the
120 global Co mine production. Data for 2016 highlights a total consumption of 34.9kt of Co in the
121 EU, with LIBs for portable devices accounted for the largest consumption (14.8kt) followed
122 by hard metals (7.9kt) and superalloys (7.1kt)²⁷. Co embedded in EVs in the EU is therefore
123 still comparatively small.

124 INSERT FIGURE 2

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126

127 **Figure 2. Global cobalt flows from mine to European electric vehicle in 2017 (a).** Cobalt flows 2017 from
128 mine to refined material suitable for battery production. Mines for the Democratic Republic of the Congo (DRC)
129 are included to illustrate the high mine centralisation. The refining stage only includes powders, chemicals, broken
130 cathodes and briquettes as these are identified as the main inputs for the battery industry. The exception is cobalt
131 metals produced in Japan as an unknown amount is used in cathode production. **(b) Normalised** cobalt flows, this
132 only accounts for cathode production for registered EVs in the European Union (2017). All underlying data and
133 assumptions can be found in the methodology and Supplementary Tables 2-11.

134

135 *Future Cobalt Demand and Circular Economy Strategies*

136 In the reference scenario, trends regarding future EV registration and new battery
137 developments are taken into consideration. Secondary supply, however, is restricted to 2017
138 EU battery and vehicle collection and Co recovery rates. Future EVs registrations are based on
139 new EU emissions regulations, whereby the annual EU passenger EV sales by 2050 are
140 expected to be between 65% and 85% of the total vehicle sales²⁸. We consider nine different
141 passenger vehicle segments for which the battery characteristics are based on data from 2017
142 vehicles and trends around future battery chemistries and specific energy (Table 1). For future
143 chemistries, we included a trend towards high Ni and low Co cathodes. The adaption of high
144 Ni and low Co chemistries has been faster than expected⁵, with the first mass produced EV
145 using such cathode being delivered in 2019⁷. Despite the recent revival of the LFP chemistry,
146 high Ni chemistries have the greatest potential to reach the desired range for most vehicle
147 segments^{8,29}. We also assumed the specific energy (Wh/kg⁻¹) will increase to 235 Wh/kg⁻¹ on
148 the pack level (the goal stated by US Department of Energy to make EVs commercially
149 viable³⁰), primarily driven by to the continuous evolvments of solid-state lithium metal
150 batteries³¹. With the increase in specific energy as well as the higher market share of SUVs
151 which require larger batteries, we estimate that the average BEV by 2030 has 86 kWh battery,
152 up from 42 kWh in 2017. Despite the doubling in capacity, average Co content in BEVs is
153 expected to only increase from 6.4 kg in 2017, to 10.3 kg in 2030 due to the shift in chemistry.

154

155

156 **Table 1. Battery characteristics of the future vehicle fleet.** Current and future battery characteristics for BEVs
 157 assuming battery weight and energy consumption remains the same as in 2017 and specific energy increased to
 158 235 Wh/kg⁻¹ for all segments based on US Department of Energy target³⁰. Market share by segment are based
 159 on 2017 values³². Battery weight and energy consumption for 2017 is based on newly registered BEVs in the
 160 EU in 2017. All PHEV models are expected to have a future capacity of 15 kWh. Further data sources and
 161 calculations can be found in the methodology and SI.

Vehicle segment	Future market share	2017 Specific energy (kWh/kg ⁻¹)	2050 Specific energy (kWh/kg ⁻¹)	2017 capacity (kWh)	2050 capacity (kWh)	Battery weight (kg)
Mini	7.9%	0.104	0.235	17	41	174
Small	20.9%	0.118	0.235	36	69	294
Lower Medium	28%	0.115	0.235	33	73	310
Medium	7.6%	0.133	0.235	52	103	438
Upper Medium	2.6%	0.151	0.235	72	133	566
Luxury	0.2%	0.160	0.235	100	115	490
Sport	1.3%	0.146	0.235	82	132	562
Van	2.6%	0.083	0.235	27	69	294
SUV	28.7%	0.142	0.235	77	116	492

162

163 Based on expected EV demand and battery trends, total Co demand for EU EVs could reach
 164 26.2 kt in 2030 and 57.4 kt in 2050, equal to 22% and 48% respectively of global Co mine
 165 production in 2017 (Figure 4). Estimates of total Co reserves of current mines and ongoing
 166 late stage exploration projects have identified a total Co reserves in Europe of 58 kt³³. These
 167 reserves are in Finland and to a lesser extent in Sweden, Spain and Germany. Future supply
 168 projections based on cost of primary extraction and mine capacity estimate the future global
 169 annual mine supply capacity to be between 225-235 kt by 2025³⁴, and 190 kt with upper bounds
 170 between 237³³ and 311 kt³⁵ by 2030. All studies highlight that the dominant role of the DRC
 171 in future Co supply is likely to continue within the next decade, accounting for 60-75% of
 172 global mine production. In our reference scenario, secondary Co supply originating from
 173 batteries is limited to the 2017 vehicle collection and Co recovery rates. This results in a

174 secondary Co supply of 5.9kt by 2040 and 17.4kt by 2050, assuming a 96% recovery rate. With
175 the ongoing increase in EU battery production facilities (based on current production facilities
176 and recent announcements, annual production capacity in the EU by 2030 would be 6.1 million
177 EV batteries, enough to supply 40% of all vehicles registered in 2030 (including internal
178 combustion engines) with a battery (Supplementary Table 20 for compiled data on current and
179 future EU battery production), the recycling and material supply chain will have to scale up
180 continuously within the next two decades to align with increased production capacity.

181 ***The impact of Circular Economy Strategies (CES)***

182 Five parameters are considered to model potential improvements in reducing primary Co
183 requirements in comparison to the reference scenario (Table 2). The first parameter, batteries
184 replaced, indicates the percentage of batteries replaced after 8 years. OEMs typically provide
185 an eight-year warranty on LIB. However, given the limited economic incentives for vehicle
186 owners to replace batteries prior to the end-of-vehicle³⁶, and the often sufficient performance
187 left beyond the warranty levels to meet travel needs for many drivers³⁷, it is unlikely that
188 batteries will be replaced prior to the expected end-of-life of the vehicle (ELV). The second
189 and third parameters refer to ELV and battery collection rates. Current ELV collection rate is
190 low due to the large amount of ‘missing vehicles’ (39%) and exports (9.6%)³⁸. Battery
191 collection rate is set to 95% in the reference scenario, based on the European Commission
192 Product Environmental Footprint Category Rules³⁹. The fourth parameter refers to Co
193 recovery rate from LIB recycling. In the reference scenario, this is based on current installed
194 LIB recycling technologies in the EU. The final parameter, rate of adoption of new
195 chemistries, estimates market penetration of new battery chemistries over time. “High”
196 indicates a quick adoption of new chemistries with little to non-Co whereas “Low” indicates
197 a slower adoption.

Table 2. Overview of circular economy strategies, scenario narratives and main assumptions. The difference between each scenario is based on the value of the five parameters, including: batteries replaced, end-of-life vehicle (ELV) collected, batteries collected, and the adoption of new chemistries.

Strategies	Reference (REF)	Technology Driven Substitution (TDS)	Technology Driven Reduction (TDR)	Business Model Driven Reuse/Recycle (BDR)	Policy Driven Recycle (PDR)
Scenario narrative	EV sales continues to grow but no changes from the end of life situation in 2017 are expected, resulting in resource loss and low recycling capacity	Entire substitution of Co from batteries by technological breakthrough resulting in chemistries with zero Co by 2050.	Reducing Co demand through a rapid adoption of chemistries with high nickel and low cobalt content (less than 5%).	Batteries are leased to the vehicle owner and replaced after 9 years, resulting in a high amount of batteries fit for a second life in less demanding applications	Stronger policies that improve the waste management of EV batteries will result in increased collection and recycling rates.
Parameters	REF	TDS	TDR	BDR	PDR
1. Batteries replaced prior to ELV	Small amount replaced (5%)	Small amount replaced (5%)	Small amount replaced (5%)	High early replacement (95%)	Small amount replaced (5%)
2. ELV collection	High amount of ELV statistically missing or exported (51%)	High amount of ELV statistically missing or exported (51%)	High amount of ELV statistically missing or exported (51%)	All ELV collected (100%)	All ELV collected (100%)
3. Battery collection	95%	95%	95%	100%	100%
4. Co recovery rate	96%	96%	96%	96%	99%
5. New chemistry adoption	NCM811 & NCA dominant chemistry (60% by 2030, 100% by 2050)	Co chemistries phased out from 2030	100% adoption NCA/NCM9.5.5 by 2050	NCM811 & NCA dominant chemistry (60% by 2030, 100% by 2050)	NCM811 & NCA dominant chemistry (60% by 2030, 100% by 2050)

203 The Technology Driven Substitution (TDS) scenario aims to reduce the total amount of Co in
 204 EV batteries through new technological developments. Co content in batteries is substituted
 205 entirely due to new battery technology developments. As a result of the full commercialisation
 206 of chemistries without Co, such as sodium-ion batteries¹⁶, lithium sulphur (Li/S)⁴⁰, lithium iron
 207 phosphate (LFP) or lithium nickel oxide (LNO)⁴¹, total demand of primary Co could reach its
 208 peak by 2032 with total demand of 10.4kt and decline thereafter. This strategy is highly

209 depended on the breakthrough of new technologies and full commercialisation of new
210 chemistries. In the Technology Driven Reduction (TDR) scenario, Co content is reduced
211 significantly due to the rapid adoption of low Co and high Ni chemistries containing less than
212 5% Co in the cathode. This strategy reduces total cumulative demand for primary Co between
213 2017 and 2050 by 54.6% compared to the reference scenario. However, Ni demand would
214 increase significantly, reaching 172 kt in 2030 and 540 kt in 2050 (Figure 3).

215

216 INSERT FIGURE 3

217 **Figure 3. Cobalt and nickel demand for European electric vehicles in a rapid adoption of high nickel**
218 **cathodes.** The values represent annual nickel and cobalt demand for EU BEVs and PHEVs. The scenario
219 assumes a 100% adoption of NCM9.5.5/NCA-II cathodes for all BEV and PHEV sales by 2050.

220

221 In the Business model Driven Reuse (BDR) scenario, EV producers adopt a product-service-
222 system business model. This means that they bundle of product and services to create customer
223 utility, provide performance and generate value and ownership of materials remain with the
224 manufacturer⁴². To increase the reuse of EV batteries, most vehicles require two batteries over
225 their lifetime, resulting in a higher Co demand compared to the reference scenario. With only
226 8 years in the vehicle, some modules and cells originating from BEV battery packs will have
227 enough capacity left to be directly reused in EV application for repair and remanufacturing
228 purposes. From an energy systems perspective, a much larger amount of spent first life BEV
229 batteries could be reused in Energy System Storage (ESS) applications where the decrease in
230 capacity is less of an issue. Whilst the current energy storage market (excluding pumped hydro
231 storage) in Europe is estimated to be 1.6 GWh⁴³, in the business model scenario an additional
232 175 GWh in 2040 alone would be available for ESS applications. Considering that the
233 estimated amount of battery based ESS worldwide is expected to be 2,850 GWh by 2040⁴⁴ a
234 large amount of this could be supplied by second life EV batteries. However, several safety,

235 regulatory, economic and technical barriers exist to repurpose used EV batteries into ESS
236 applications⁴⁵. New batteries for specific ESS applications might, therefore, be a more viable
237 alternative.

238 In the Policy Driven Recycling strategy (PDR), the EU adopts a more stringent waste
239 management policy framework for priority waste streams. Secondary Co from EV batteries
240 becomes an important source of supply (through increased recycling). Secondary Co only starts
241 to flow back into the system from 2032 onwards after the first large volume of EVs reach their
242 technical end of life and it is expected to stabilise primary Co from 2040 onwards. This requires
243 a gradual expansion of the installed recycling capacity. Current global annual LIB recycling
244 capacity is estimated to be over 300 kt of batteries⁴⁶, of which the EU has an annual processing
245 capacity of around 30 kt for all batteries including mechanical processing of materials which
246 is further refined abroad (for compiled data for the EU, see Supplementary Table 19). To
247 process and recycle increasing end of life (EOL) EV batteries, European recycling capacity
248 must increase five times the current size by 2035, and 45 times by 2050, to recycle all LIBs.

249 **Discussion**

250 *Achieving circular economy strategies for batteries*

251 Figure 4 illustrates that all circular economy inspired scenarios could reduce Europe's demand
252 for imported primary Co significantly compared to the reference scenario. The following
253 section discusses implications for the different strategies and implications for decision-making
254 across the supply chain, as well as possible synergies across different scenarios.

255 INSERT FIGURE 4

Figure 4. Total demand and supply of cobalt for EVs in the EU for all strategies. Cobalt is supplied through primary mine production, recycled EV batteries or through the direct re-use of spent EV batteries in new EVs. Primary cobalt mine production does not include losses during the mining and refining stage. In the Technology Driven Substitution scenario (b) Co is entirely substituted by 2050, in the Technology Driven Reduction scenario (c) Co is rapidly replaced by high Ni chemistries but not entirely substituted, in the Business Model Driven Re-use/Recycle scenario (d) batteries are replaced after 8 years in the vehicle resulting in high collection rates, in the Policy Driven Recycling scenario (e) improvements in collection results in a reduction in primary requirements.

256

257 Following the analysis, the adoption of new chemistries reducing and eventually substituting
258 Co from LIB looks compelling. The alternative chemistries such as sodium-ion cells prove to
259 be cheaper, more abundant and less toxic than current technologies¹⁶. However, we consider
260 the likelihood of these chemistries beyond current LIB being fully commercialised within the
261 next decade rather small in light of several technological drawbacks for these new chemistries
262 despite improved energy density and/or cost. For instance, Li-S has a lower technical cycle life
263 and reduced performance⁴⁰; sodium-ion suffers from low energy density¹⁶ and there are
264 continuous stability issues related to LNO batteries, despite two decades of intensive research.
265 Our results show that substituting Co by Ni, currently the dominant strategy by OEMs, could
266 see a 60 times increase in Ni demand for EU EVs compared to 2017 by 2030 and up to 190
267 times by 2050. Ni chemicals suitable for batteries are derived from Class 1 Ni products
268 (containing more than 99.8% Ni) which are primarily produced from sulfide and to small extent
269 (10% in 2011) limonite deposits⁴⁷. In 2015, global Ni sulphide production was 593 kt⁴⁸ whilst
270 the TDR scenario results illustrate a primary Ni demand for European EVs of 172kt by 2030.
271 The Ni supply chain requires therefore further investigation to reflect on the implications of
272 such large increase in demand.

273

274 The business model innovation strategy requires tighter demand management but provides
275 higher resilience. It does not necessarily lead to lower Co demand due to the early replacement
276 of batteries. A large amount of batteries, though, could be reused in less demanding

277 applications such as ESS. EES could help to balance energy supply and increase required
278 flexibility in increasingly decarbonised electricity systems. However, this may represent a
279 suboptimal use of Co in the long run. For EV applications, batteries require a high energy
280 density to reduce size and weight and enhance the range which is less of an issue for batteries
281 in ESS application. Due to their longer lifetime with high cycle stability, the high safety
282 standards and lower costs, LFP chemistries are increasingly favoured in ESS applications⁴⁹,
283 although several large ESS vendors still using NCM. Additionally, a small share could be
284 directly reused and/or remanufactured for EV applications. This is already happening at scale
285 with most car makers having implemented either proprietary or third-party programs for
286 remanufacturing.

287 In all scenarios, an efficient recycling system is a key requirement to reduce primary demand.
288 Achieving CES for batteries will require improving the current recycling system. Historically
289 a high number of LIBs has been lost at the end of life without becoming available for European
290 recyclers. Most of these batteries are portable batteries which primarily are exported as part of
291 their original devices such as mobile phones, tablets, and portable computers. Whilst research
292 to investigate future trade with EV batteries at scale has yet to be undertaken, data suggests
293 that vehicles might be exported for either, second hand markets or for the re-use of their
294 components⁵⁰. This could mean that EV batteries are lost in similar way as portable batteries
295 and could potentially create concerns of inadequate handling and processing with associated
296 environmental impacts⁵¹. In addition, material leakages also occur due to the poor vehicle
297 traceability system in the EU, resulting in a high level of statistically missing vehicles (4.7
298 million vehicles in the EU in 2014)⁵⁰. Clearly business viability of improved recycling will
299 need to address unfavourable market conditions and economic uncertainties. Although our
300 scenarios make reasonable assumptions based on detailed analysis, the volatility of the primary
301 commodity markets, especially those on the Ni and Co market, have direct impacts on

302 recycling. In addition, with Co being currently the main economic driver for battery
303 recycling⁵², the shift towards high Ni and low Co chemistries might impact the economic
304 viability of recycling, which may then become more dependent on the price of Ni. In
305 unfavourable market conditions, policy action might be required to incentivize recycling and
306 ensure minimisation of negative environmental impacts or critical material depletion
307 associated to inadequate end of life treatment of EVs batteries. Similar proposals have been
308 made to enhance a circular flow of yttrium recovered from electronic waste⁵³ and could be
309 expanded to EV batteries.

310 ***Outlook***

311 In this study we presented four different Circular Economy Strategies (CES) that decreased the
312 reliance of the automotive industry on Co production. Action points that need to be considered
313 include continuous research into material substitution developed in collaboration between
314 material science and industry as a long-term option. We have illustrated resource implications
315 associated with existing battery chemistries and Co supplies, yet more research is required to
316 expand the methodology to other resources and alternative battery chemistries. Considering the
317 long lead times, promoting new business models and innovation that enhance re-use of EV
318 batteries offer rapid replacement options and integration with energy storage systems using
319 remaining capacity in EOL EV batteries. It seems clear, that under current EU policy
320 frameworks, there will be developments favouring markets for secondary battery resources,
321 which may consequently strengthen industrial capacities for battery and cathode production
322 are recycling in the EU. These suggestions need to be underpinned with additional research

323 considering the environmental and economic implications of different new battery recycling
324 processes and the advantage compared to primary raw material extractions.

325

326 Without stretching the scope of this paper too far, it can also be said that policies e.g. Extended
327 Producer Responsibility (EPR) are both feasible and triggers for change that will encourage
328 recycling and enhance collection rates of EV batteries. Likewise, efforts towards more
329 integrated and resilient supply chains are needed. Because of those broader conditions, the four
330 CES that we modelled should be framed under a mission-oriented policy approach that promote
331 the transition towards a more circular economy. Mineral resource implications should be
332 central to government-funded battery research. New policies should encourage increased
333 accountability, traceability and create favourable market conditions for the emergence of new
334 business models. The improvements in vehicle end of life traceability, collection rates and
335 battery design will leverage a stronger recycling industry and ensure supply security for critical
336 materials, whilst also providing incentives for the development of an EU battery production
337 industry. This and future research can contribute to the evidence base to develop a roadmap
338 towards sustainable batteries, with key milestones and activities that are applicable at different
339 stages of any raw material supply.

340 **Methods**

341 **Methodology overview and model structure**

342 We used Material Flow Analysis (MFA) to analyse current and future stocks and flows of Co
343 for EV batteries. The MFA approach applied in this study consists of a static MFA for Co flows
344 in 2017 and a dynamic MFA of Co flows between 2017-2050⁵⁶. The aim of the static MFA is
345 to understand the global flows of Co (mine to production) and Co flows (consumption to EoL)
346 for EVs registered in the EU in 2017. Data has been compiled from a wide variety of sources
347 including secondary data sets from governmental statistics, company reports and primary data,

348 collected through interviews and site visits to recyclers- see main manuscript and the SI. Based
349 on the 2017 EV fleet characteristics and reference static MFA, a dynamic MFA model was
350 established to project future EVs and Co stocks and flows. A reference business as usual
351 scenario for 2017-2050 was then generated to project future trends and estimate future Co flows
352 when little change in institutional conditions and end-of-life management from 2017 is
353 expected but incorporating some technological changes (details in SI). Four circular economy
354 scenarios were modelled modifying different parameters to compare potential resource savings
355 from the reference scenario. The inputs to the 2017 base year and key features of the MFA
356 model are described below. A more detailed on the model inputs can be found in the SI.

357 *Calculating cobalt flows for 2017*

358 The static MFA was developed by tracing the upstream flows of Co embedded in EU EVs in
359 2017. Flows were divided into seven processes including vehicle use, battery cell assembly,
360 cathode production, Co consumption, refining, intermediate refining, and Co mine production
361 (see Supplementary Figure 1 for the complete MFA system). Vehicle use: Due to the different
362 chemistry types and varying sizes used for EVs, the Co content within batteries varies
363 significantly. To include this heterogeneity of chemistries and size, vehicle specific details
364 were considered. Vehicle registrations for all BEV and PHEV models in the EU in 2017 were
365 derived from the CO₂ monitoring dataset by the European Environmental Agency⁵⁷. All 28 EU
366 member states are obliged to provide a wide variety of detailed information on each new
367 passenger vehicle registration, including the manufacture name, vehicle type, model, CO₂
368 emissions, vehicle mass and other details. Due to the limitations of the dataset, several steps
369 had to be taken to filter out both BEVs and PHEVs (see SI). For each individual model the
370 battery capacity, weight, chemistry, specific energy, and battery producer were estimated based
371 on a variety of sources. A full list of all vehicles and the battery details can be found in
372 Supplementary Table 10 and 11. Co content per vehicle model was calculated based on the size

373 of the battery (kWh) and material content for the considered chemistries derived primarily from
374 the BatPaC model version 3.1 by the Argonne National Laboratory⁵⁸. As most LMO
375 chemistries are used with a blend of NCM⁵⁹, the LMO-NCM distribution was based on a
376 teardown of a commonly used LMO cell⁶⁰. Currently three major types of NCM chemistries
377 are used, NCM 333, NCM 622, NCM 811, whereby the number indicates the content of Ni,
378 manganese, and Co in the battery. Limited information is available describing which NCM
379 type is used. As a higher Ni content increases the specific energy (Wh/kg⁻¹)⁸, the specific
380 energy per vehicle, obtained from the US Environmental Protection Agency – Clean Air Act
381 certification summaries⁶¹, was used to determine if the battery is a NCM 622/532 or 333 (NCM
382 811 was introduced for the first time in 2019⁷). Our data suggest that PHEVs have a lower
383 specific energy than BEVs, which can be explained since battery cells for hybrid vehicles are
384 optimised for high power requirements. The low specific energy in PHEVs makes it
385 challenging to filter out the chemistry type. We therefore assumed that most PHEVs had an
386 NCM 333 cathode if not reported differently in the literature.

387

388 Cell assembly. The location and capacity of cell suppliers determined the flows of cell
389 assembly (Supplementary Table 9). However, some vehicle specific information was available
390 to determine the location of cell assembly (GM, Ford and Chrysler batteries produced by LG
391 Chem plant in the USA and AESC/Envision producing the Nissan Leaf battery for the EU
392 market). Cathode production. It was assumed that most cathodes were produced in the same
393 countries as the cells based on several sources of information as described in SI. These were
394 the USA, Japan, South Korea and China. Due to the lack of data on cathode and cathode
395 material trade statistics, trade of these products is not considered. Refined Co consumption. To
396 include further upstream flows, the total Co consumption by the four cathode producing
397 countries was calculated based on apparent consumption (refined production + refined imports

398 – refined exports). Here we only included refined Co products that are used for batteries,
399 including Co chemicals and powders⁴⁷ as well as broken cathodes, briquettes and ingots⁶². All
400 data sources for refined production and trade flows can be found in the Supplementary Tables.
401 Refining. Total refined Co production in 2017 of Co chemicals, powders and metals is based
402 on data by Darton Commodities, provided by Bloomberg⁶³. The refined Co metal data is further
403 disaggregated into broken cathodes, briquettes and ingots based on company reports and trade
404 brochures. Trade statistics were further used to determine the upstream flows of Co consumed
405 by South Korea, Japan, USA and China. Trade flows are based on several Harmonised System
406 trade codes using the UN Comtrade database, using different Co contents for each trade flow
407 (see Supplementary Methods for more information on data extraction). Intermediate refining.
408 Intermediate refining was estimated based on mass balance (mine production plus ore import
409 minus ore export). Mine production. Mine specific data on global primary Co production in
410 2017 was compiled from company and governmental reports. This dataset was compared with
411 geological survey data by the British Geological Survey (BGS) and the United States
412 Geological Survey (USGS) to adjust for gaps were needed. See Supplementary Table 2 for the
413 entire list of Co mines. Recycled Co is not taken into consideration due to the limited amount
414 of available data. However, all European LIB recycling facilities are listed in Supplementary
415 Table 19. Co losses during cell assembly, the cathode production, refining, and mining are also
416 not considered in the analysis.

417

418 ***Dynamic material flow analysis for cobalt in EU EVs 2017-2050***

419 To forecast potential Co demand growth and end of life implications and solutions, a dynamic
420 MFA scenario model was established. Central to the model is the mass balance principle and
421 stock-flow relations⁶⁴. An inflow-driven approach is adopted, with future vehicle inflows as
422 the primary variable. We justify this approach based on the saturation of vehicle ownership in

423 the EU⁶⁵, and no significant increase in ownership (vehicles per capita) is expected in the
424 future. Annual vehicle inflows are therefore based upon the 2017 vehicle registration rate and
425 population dynamics. The dynamic MFA system, including parameters, is illustrated in
426 Supplementary Figure 2.

427

428 *Calculating future cobalt demand*

429 Annual Co demand at time t (1), is calculated based upon the inflow of vehicles in units (EV),
430 the vehicle type and corresponding battery size in kWh (i), the battery chemistry (j) and the
431 material intensity (MI) in kg/kWh.

$$Demand_{Co}(t) = EV_{i,j}(t) \cdot MI_j \quad (1)$$

432 Future Co demand is driven by the expected annual sales of BEVs and PHEVs in the EU.
433 Future EV registrations are expected to increase according the recent EC proposal for post-
434 2020 CO₂ targets for cars²⁵. The BEV and PHEV rates to achieve these targets are based on a
435 study by Ricardo²⁸. This study however only indicates the percentage BEVs and PHEVs of the
436 entire passenger vehicle fleet required to meet the emissions targets. Future vehicle
437 registrations are therefore calculated based upon historic car sales rate (annual sales of
438 vehicles/population), assuming this remains the same until 2050 and including population
439 projections of the EU28⁶⁶. To account for the differences in battery size of BEVs, the future
440 vehicle fleet model is categorised into different vehicle segments. The vehicle segmentation
441 from the International Council for Clean Transport (ICCT) is used, which include 9 categories:
442 mini, small, lower medium, medium, upper medium, luxury, sport, Van and SUV. All 2017
443 BEV models were categorised into these segments to include the battery size, weight, specific
444 energy and range for each vehicle segment (see Supplementary Table 15). In the model it is
445 expected that specific energy of all vehicle segments will gradually increase to 235 Wh/kg⁻¹
446 (pack level) by 2030 as set by the Electrochemical Energy Storage Technical Team Roadmap

447 by the US Department of Energy³⁰. It is assumed that the increase in energy density is primarily
448 driven by the use of a lithium metal anode and solid-state electrolyte^{29,31}.

449

450 Battery and vehicle weight per segment are assumed to remain the same as in 2017. As a result,
451 battery capacity will increase whilst the energy efficiency of the vehicle (km/kWh) is assumed
452 to remain the same for all vehicle segments as in 2017. With an increase in specific energy,
453 most vehicles would provide a range of 480 km or more, acceptable to 60 to 90% of consumers
454 according to market studies⁶⁷. It is assumed that by 2030, EVs will be cost competitive with
455 ICE and BEV market shares of the different vehicle segment will be the same as all vehicles
456 in 2017 in the EU as provided by ICCT³². Due the limited variety in battery capacity of PHEVs
457 in 2017 and range being less of an issue, future battery capacity for all PHEV models increases
458 to 15 kWh as used by the IEA⁶⁸. Future market share of different chemistries were included
459 based on different sources and technology roadmaps. Supplementary Table 16 illustrates the
460 assumed future market share for each chemistry. Co and Ni content of batteries are calculated
461 the same as in the static MFA except for the NCA chemistry. It is assumed that new NCA
462 chemistries will be solely based on the low Co NCA technology (referred to as NCA-II in the
463 SI) based on Wentker, et al.⁶⁹. Material content (kg/kWh) per chemistry can be found in
464 Supplementary Table S14.

465

466 **Calculating future secondary supply**

467 In the model, Co is supplied through three routes: primary Co (p) and reused (u) and recycled
468 EV batteries (r). Annual primary Co supply is based on the difference between Co demand in
469 t and secondary supply. Secondary supply is calculated based upon the total outflow of batteries
470 in time t (2).

$$Outflow_i(t) = \sum_{t'=0}^t EV_i(t') + ESS_i(t') \cdot f(t - t') + Repl_i(t') \quad (2)$$

471 Where annual outflow is based upon the lifetime of the vehicle fleet and reused EV batteries
 472 in energy system storage (ESS_i) in time t' , and the replacement rate of batteries in EV ($Repl_i$).

473

474 Outflow. Two different battery end of life routes for BEVs and one for PHEVs are included.

475 In the first route for BEVs, batteries retire simultaneously with the vehicle, the second route
 476 assumes that batteries are replaced prior to the end of vehicle life. Due to the lack of real-life

477 battery degradation data, lifetime distributions for batteries and EVs are not available. A static

478 vehicle and battery lifetime were therefore included. Vehicle lifetime was set to 15 years based

479 on an European study on vehicle lifetime distance travelled and vehicle mass⁷⁰. Some BEV

480 batteries will be replaced after 8 years, a proxy for current calendar life warranty periods⁷¹.

481 PHEV batteries are assumed to remain in the vehicle due to the limited incentive for

482 replacement and thus have a lifetime of 15 year. Despite the lack of certainty around second

483 life LIB aging⁷², the lifespan of indirect reused LIB is assumed to be 10 years³⁶

484

485 PHEV batteries are assumed to be directly recycled due their high degradation as a result of

486 the long lifetime (batteries are not replaced) and high cycling rate (charge and discharge).

487 Batteries from end-of-life BEVs are either reused directly in EV applications, reused indirectly

488 in ESS or recycled in closed-loop and open loop systems. The state of health (SOH), the

489 remaining capacity of the battery after its first life, determines the end-of-life (EOL) route of

490 BEVs. To estimate the SOH, annual capacity fade of batteries is based upon calendric aging

491 and total charging cycles. Due to the missing long-term experiences of EV battery calendar

492 aging and uncertainties in battery aging models⁷³, a simplified approach regarding calendar age

493 is taken based on Schmidt, et al.⁷⁴. All battery chemistries are expected to reach 80% of their

494 initial capacity within 12 years, a capacity loss of 1.67% per year. Cycling degradation is
495 defined for each vehicle segment and chemistry based on annual charging cycles and depth of
496 discharge. Average cycling lifetime per chemistry, defined as amount of cycles until the battery
497 reaches a SOH of 80%, is based on the consolidation of a wide range of scientific and industry
498 data sources on lithium-ion batteries provided by Peters, et al.⁷³. Annual charging cycles are
499 based on the depth of discharge, vehicle range and annual km driven. DoD for all BEV
500 segments are assumed to be 40% based on a European average⁷⁵. Annual KM driven for each
501 segment is based upon the correlation between vehicle mass and KMs driven⁷⁰. The
502 calculations and sources used can be found in the SI. Batteries with a SOH below 80% are
503 directly recycled and those between 85% and 80% are reused in less-demanding energy system
504 storage (ESS). Batteries with a SOH larger than 85% might still be fit to be reused in smaller
505 EV batteries, where range is less of an issue or used to replace damaged cells⁷⁶. However, as
506 individual cells under equal conditions age differently^{77,78}, not all cells can be reused. BEV
507 battery packs with a SOH above 85% are assumed to be dismantled to cell level and further
508 tested for reuse as currently done with EOL Nissan Leaf batteries⁷⁹. A dataset on cycling
509 degradation of 24 LIB cells⁷⁷ is used to determine the percentage of individual cells in a battery
510 pack with a SOH >85% can be directly reused.

511

512 **An overview of the circular economy strategies (CES)**

513 We model four future scenarios to understand the potential of the four CES to reduce and
514 replace primary Co for EVs. Five parameters are altered to change the outcome of the model
515 in the four scenarios. These include battery chemistry, end-of-vehicle life and battery collection
516 rates, Co recovery rates and batteries replaced prior to vehicle end of life. In the reference
517 scenario (REF) EV adoption will continue to increase and lower Co, higher Ni chemistries will
518 be adopted based estimates from the IEA⁸⁰, reflecting the higher than previously expected

519 adoption of high Ni cathodes⁵. Secondary Co from recycled batteries in this scenario is
520 constrained by current limited collection and recovery rates in the EU. In this scenario, all
521 batteries are assumed to reach end of life simultaneously with the vehicle given the limited
522 economic incentives for vehicle owners to replace batteries before that³⁶. The goal of this
523 scenario is to define the business as usual conditions against which to simulate savings
524 associated with more circular flow of materials.

525 In the technology driven substitution (TDS) scenario, novel battery technologies substituting
526 Co entirely are adopted, following the compilation of technology roadmaps by the IEA⁶⁸. By
527 2030, it is assumed that chemistries with less than 5% Co in the cathode (NCA-II or NCM9.5.5)
528 will be the dominant technology. Beyond 2030, it is expected that new chemistries without Co
529 such as Li-Sulphur and Li-Air are commercialised and used in passenger EVs. In the
530 technology driven reduction (TDR) scenario, Co content is rapidly reduced but not entirely
531 substituted. Here low Co and high Ni (NCA-II/NCM9.5.5) chemistries are the dominant
532 technology by 2050.

533

534 In the business model driven reuse scenario (BDR), EV producers adopt a product service
535 system business model, whereby a bundle of product and service aim to create customer utility
536 and generate value⁴². It is assumed that 95% of all EV batteries are now leased to consumers,
537 whereby the battery ownership remains with the car manufacturer or a third party. The
538 consumer and the producer engage in a service contract that guarantees a well performing
539 battery over the vehicle lifetime and, thus, the battery will be replaced based on warranty
540 periods or performance indicators. Close networks between EV producers, energy service
541 providers and battery recyclers are established, e.g. Nissan and energy service provider Eaton⁸¹
542 and Audi and recycler Umicore⁸² resulting in a 90% collection rate of ELV and LIB, whereby
543 10% of ELV remains export. In addition, EU battery production has increased to 70% of total

544 required production and all batteries are recycled inside the EU. In the final scenario, the policy
545 driven recycling scenario (PDR) the EU sets out a strong vision towards a circular economy
546 with a robust green industrial policy and comprehensive Extended Producer Responsibility
547 schemes to cover EVs and their batteries. A more stringent waste management policy increases
548 ELV and LIB collection rates in line with recent proposed changes the EU Batteries Directive
549 and End-of-Life Vehicles Directive⁸³. Key improvements to the ELV Directive include better
550 ELV tracking system and an improved registration and de-registration system to reduce
551 missing ELV problem⁸⁴. In this scenario, implications of the stringent ELV Directive adopted
552 is that by 2050, 90% of ELV are officially collected and only 10% are exported outside the
553 EU. An update of the Battery Directive is also assuming to lead to a 100% battery collection
554 rate.

555 **Data Availability**

556 All the data that were used for this study are available as supplementary tables in the
557 Supplementary Information file. Additional questions about the data can be directed to the
558 corresponding author.

559

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789 **Authors contributions**

790 JB initiated the study and conducted the research under guidance of TD, RB and OH. Data
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