Circular economy strategies for electric vehicle batteries reduce raw material reliance

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Abstract

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

Introduction

The global adoption of low-carbon sustainable energy technologies and infrastructures result in mineral resource challenges. These challenges are well illustrated in the case of Electric Vehicles (EVs), which are considered as one of the key technologies to climate change mitigation efforts in the transport sector. With a global record-breaking amount of EVs sales in 2019 and continuous policy and business support, this disruptive technology needs careful consideration in terms of natural resource challenges. International policy efforts to integrate Circular Economy Strategies (CES) may be a way forward to foster a sustainable use of global resources whilst meeting climate and Sustainable Development Goals. This study quantifies opportunities and limitations of CES for lithium-ion batteries (LIB) in EVs raw material supplies, with a focus on Cobalt (Co). Cobalt is an excellent case as its market is prone to three major supply risks[1].

First, Co is primarily mined as a by-product of nickel and copper (43% and 44% in 2015) and therefore relies on both markets for the expansion of new mines[2]. Second, the Co market has a high centralisation of mine production and reserves, located in the Democratic Republic of the Congo (DRC) as well as the increasing role of Chinese refining and mining ownership[3]. Figure 1 shows price peaks associated with events happening in the DRC and the recent market trends with prevailing DRC hegemony. Finally, substitution of Co whilst maintaining product performance is challenging and time consuming in applications such as hard facing materials, pigments, catalysts, supper-alloys and LIB[4]. For LIB, new chemistries partly substituting Co with Nickel (Ni) have been commercialized faster than expected[5]. However, the comparatively long path between lab scale innovations and commercialisation in the electro chemical energy industry[6] and the essential role of Co to provide high energy density and stable batteries, as well as the safety and performance improvement required by the automotive industry[7,8], makes it unlikely for Co to be entirely substituted from LIBs in the foreseeable future.

INSERT FIGURE 1

Figure 1. Annual cobalt price and production from 1950 until 2019. Price line reflects the annual real price of cobalt in dollar per tonne based on the 2019-dollar value. The dark blue shaded area represents global annual cobalt mine production and the light blue areas annual cobalt production of the DRC. The large price peak in 1979 was due to the insurgency in the cobalt mining province Katanga (DRC), the resulting concerns for supply availability and speculation on the cobalt market[9]. Production and price data compiled from USGS Yearbooks [10,11]

Governments and industry are increasingly aware of Co supply risks and formulate critical material strategies to mitigate risks, e.g. in the United States[12], Japan[13] and the European Union[14]. Most of these strategies point to the need of new sourcing avenues to ensure a stable supply of Co and address concerns over social scrutiny of mining practices, as evidenced through recent lawsuits filed against large tech companies over child labour[15]. Adopting CES has become popular in recent years to contribute to reducing primary extraction and to a more resilient and green supply chain for EV batteries. Based on the literature, we identified four relevant CES for LIBs in EVs. The first and second strategy focus on reducing or eliminating Co from current chemistries, e.g. through commercialisation of ground-breaking battery technologies[16] or a switch to high nickel (Ni) chemistry reducing the Co content. A third strategy aims to promote the re-use market for EV batteries in less demanding applications such as residential buildings[17] or communication base stations[18]. The fourth strategy is based on a closed loop battery recycling system, whereby waste batteries are a new source of secondary materials for new battery production. Although obstacles for such system still exist[19], the potential of recycling is promising[20-22] and has already an important impact for the battery material industry in countries with battery production at scale such as China and South Korea[23].

To underpin these strategies and overcome the lack of granularity of established datasets[24], we develop a detailed model of the current and future passenger vehicle fleet. We have incorporated novel data sources to allow for a more detailed understanding of the current and future Co demand and secondary supply. Due to the availability of such detailed data, the geographical scope of this study is limited to the European Union. The data of EVs was gathered and combined with company specific data on upstream battery production, Co refining, mining production and trade data to establish a static material flow analysis for 2017 (see the Supportive Information (SI) and Methodology for all details and data).

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

Results

EV Sales and the Flow of Cobalt in 2017

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

INSERT FIGURE 2

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

Future Cobalt Demand and Circular Economy Strategies

In the reference scenario, trends regarding future EV registration and new battery developments are taken into consideration. Secondary supply, however, is restricted to 2017 EU battery and vehicle collection and Co recovery rates. Future EVs registrations are based on new EU emissions regulations, whereby the annual EU passenger EV sales by 2050 are expected to be between 65% and 85% of the total vehicle sales[28]. We consider nine different passenger vehicle segments for which the battery characteristics are based on data from 2017 vehicles and trends around future battery chemistries and specific energy (Table 1). For future chemistries, we included a trend towards high Ni and low Co cathodes. The adaption of high Ni and low Co chemistries has been faster than expected[5], with the first mass produced EV using such cathode being delivered in 2019[7]. Despite the recent revival of the LFP chemistry, high Ni chemistries have the greatest potential to reach the desired range for most vehicle segments[8,29]. We also assumed the specific energy (Wh/kg^{-1}) will increase to 235 Wh/kg^{-1} on the pack level (the goal stated by US Department of Energy to make EVs commercially viable[30]), primarily driven by to the continuous evolvements of solid-state lithium metal batteries[31]. With the increase in specific energy as well as the higher market share of SUVs which require larger batteries, we estimate that the average BEV by 2030 has 86 kWh battery, up from 42 kWh in 2017. Despite the doubling in capacity, average Co content in BEVs is expected to only increase from 6.4 kg in 2017, to 10.3 kg in 2030 due to the shift in chemistry.

Table 1. Battery characteristics of the future vehicle fleet. Current and future battery characteristics for BEVs assuming battery weight and energy consumption remains the same as in 2017 and specific energy increased to 235 Wh/kg^{-1} for all segments based on US Department of Energy target[30]. Market share by segment are based on 2017 values[32]. Battery weight and energy consumption for 2017 is based on newly registered BEVs in the EU in 2017. All PHEV models are expected to have a future capacity of 15 kWh. Further data sources and 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

Based on expected EV demand and battery trends, total Co demand for EU EVs could reach 26.2 kt in 2030 and 57.4 kt in 2050, equal to 22% and 48% respectively of global Co mine production in 2017 (Figure 4). Estimates of total Co reserves of current mines and ongoing late stage exploration projects have identified a total Co reserves in Europe of 58 kt[33]. These reserves are in Finland and to a lesser extent in Sweden, Spain and Germany. Future supply projections based on cost of primary extraction and mine capacity estimate the future global annual mine supply capacity to be between 225-235 kt by 2025[34], and 190 kt with upper bounds between 237[33] and 311 kt[35] by 2030. All studies highlight that the dominant role of the DRC in future Co supply is likely to continue within the next decade, accounting for 60-75% of global mine production. In our reference scenario, secondary Co supply originating from batteries is limited to the 2017 vehicle collection and Co recovery rates. This results in a secondary Co supply of 5.9kt by 2040 and 17.4kt by 2050, assuming a 96% recovery rate. With the ongoing increase in EU battery production facilities (based on current production facilities and recent announcements, annual production capacity in the EU by 2030 would be 6.1 million EV batteries, enough to supply 40% of all vehicles registered in 2030 (including internal combustion engines) with a battery (Supplementary Table 20 for compiled data on current and future EU battery production), the recycling and material supply chain will have to scale up continuously within the next two decades to align with increased production capacity.

The impact of Circular Economy Strategies (CES)

Five parameters are considered to model potential improvements in reducing primary Co requirements in comparison to the reference scenario (Table 2). The first parameter, batteries replaced, indicates the percentage of batteries replaced after 8 years. OEMs typically provide an eight-year warranty on LIB. However, given the limited economic incentives for vehicle owners to replace batteries prior to the end-of-vehicle[36], and the often sufficient performance left beyond the warranty levels to meet travel needs for many drivers[37], it is unlikely that batteries will be replaced prior to the expected end-of-life of the vehicle (ELV). The second and third parameters refer to ELV and battery collection rates. Current ELV collection rate is low due to the large amount of ‘missing vehicles’ (39%) and exports (9.6%)[38]. Battery collection rate is set to 95% in the reference scenario, based on the European Commission Product Environmental Footprint Category Rules[39]. The fourth parameter refers to Co recovery rate from LIB recycling. In the reference scenario, this is based on current installed LIB recycling technologies in the EU. The final parameter, rate of adoption of new chemistries, estimates market penetration of new battery chemistries over time. “High” indicates a quick adoption of new chemistries with little to non-Co whereas “Low” indicates 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)

The Technology Driven Substitution (TDS) scenario aims to reduce the total amount of Co in EV batteries through new technological developments. Co content in batteries is substituted entirely due to new battery technology developments. As a result of the full commercialisation of chemistries without Co, such as sodium-ion batteries[16], lithium sulphur (Li/S)[40], lithium iron phosphate (LFP) or lithium nickel oxide (LNO)[41], total demand of primary Co could reach its peak by 2032 with total demand of 10.4kt and decline thereafter. This strategy is highly depended on the breakthrough of new technologies and full commercialisation of new chemistries. In the Technology Driven Reduction (TDR) scenario, Co content is reduced significantly due to the rapid adoption of low Co and high Ni chemistries containing less than 5% Co in the cathode. This strategy reduces total cumulative demand for primary Co between 2017 and 2050 by 54.6% compared to the reference scenario. However, Ni demand would increase significantly, reaching 172 kt in 2030 and 540 kt in 2050 (Figure 3).

INSERT FIGURE 3

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

In the Business model Driven Reuse (BDR) scenario, EV producers adopt a product-service-system business model. This means that they bundle of product and services to create customer utility, provide performance and generate value and ownership of materials remain with the manufacturer[42]. To increase the reuse of EV batteries, most vehicles require two batteries over their lifetime, resulting in a higher Co demand compared to the reference scenario. With only 8 years in the vehicle, some modules and cells originating from BEV battery packs will have enough capacity left to be directly reused in EV application for repair and remanufacturing purposes. From an energy systems perspective, a much larger amount of spent first life BEV batteries could be reused in Energy System Storage (ESS) applications where the decrease in capacity is less of an issue. Whilst the current energy storage market (excluding pumped hydro storage) in Europe is estimated to be 1.6 GWh[43], in the business model scenario an additional 175 GWh in 2040 alone would be available for ESS applications. Considering that the estimated amount of battery based ESS worldwide is expected to be 2,850 GWh by 2040[44] a large amount of this could be supplied by second life EV batteries. However, several safety, regulatory, economic and technical barriers exist to repurpose used EV batteries into ESS applications[45]. New batteries for specific ESS applications might, therefore, be a more viable alternative.

In the Policy Driven Recycling strategy (PDR), the EU adopts a more stringent waste management policy framework for priority waste streams. Secondary Co from EV batteries becomes an important source of supply (through increased recycling). Secondary Co only starts to flow back into the system from 2032 onwards after the first large volume of EVs reach their technical end of life and it is expected to stabilise primary Co from 2040 onwards. This requires a gradual expansion of the installed recycling capacity. Current global annual LIB recycling capacity is estimated to be over 300 kt of batteries[46], of which the EU has an annual processing capacity of around 30 kt for all batteries including mechanical processing of materials which is further refined abroad (for compiled data for the EU, see Supplementary Table 19). To process and recycle increasing end of life (EOL) EV batteries, European recycling capacity must increase five times the current size by 2035, and 45 times by 2050, to recycle all LIBs.

Discussion

Achieving circular economy strategies for batteries

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

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.

Following the analysis, the adoption of new chemistries reducing and eventually substituting Co from LIB looks compelling. The alternative chemistries such as sodium-ion cells prove to be cheaper, more abundant and less toxic than current technologies[16]. However, we consider the likelihood of these chemistries beyond current LIB being fully commercialised within the next decade rather small in light of several technological drawbacks for these new chemistries despite improved energy density and/or cost. For instance, Li-S has a lower technical cycle life and reduced performance[40]; sodium-ion suffers from low energy density[16] and there are continuous stability issues related to LNO batteries, despite two decades of intensive research. Our results show that substituting Co by Ni, currently the dominant strategy by OEMs, could see a 60 times increase in Ni demand for EU EVs compared to 2017 by 2030 and up to 190 times by 2050. Ni chemicals suitable for batteries are derived from Class 1 Ni products (containing more than 99.8% Ni) which are primarily produced from sulfide and to small extent (10% in 2011) limonite deposits [47]. In 2015, global Ni sulphide production was 593 kt[48] whilst the TDR scenario results illustrate a primary Ni demand for European EVs of 172kt by 2030. The Ni supply chain requires therefore further investigation to reflect on the implications of such large increase in demand.

The business model innovation strategy requires tighter demand management but provides higher resilience. It does not necessarily lead to lower Co demand due to the early replacement of batteries. A large amount of batteries, though, could be reused in less demanding applications such as ESS. EES could help to balance energy supply and increase required flexibility in increasingly decarbonised electricity systems. However, this may represent a suboptimal use of Co in the long run. For EV applications, batteries require a high energy density to reduce size and weight and enhance the range which is less of an issue for batteries in ESS application. Due to their longer lifetime with high cycle stability, the high safety standards and lower costs, LFP chemistries are increasingly favoured in ESS applications[49], although several large ESS vendors still using NCM. Additionally, a small share could be directly reused and/or remanufactured for EV applications. This is already happening at scale with most car makers having implemented either proprietary or third-party programs for remanufacturing.

In all scenarios, an efficient recycling system is a key requirement to reduce primary demand. Achieving CES for batteries will require improving the current recycling system. Historically a high number of LIBs has been lost at the end of life without becoming available for European recyclers. Most of these batteries are portable batteries which primarily are exported as part of their original devices such as mobile phones, tablets, and portable computers. Whilst research to investigate future trade with EV batteries at scale has yet to be undertaken, data suggests that vehicles might be exported for either, second hand markets or for the re-use of their components[50]. This could mean that EV batteries are lost in similar way as portable batteries and could potentially create concerns of inadequate handling and processing with associated environmental impacts[51]. In addition, material leakages also occur due to the poor vehicle traceability system in the EU, resulting in a high level of statistically missing vehicles (4.7 million vehicles in the EU in 2014)[50]. Clearly business viability of improved recycling will need to address unfavourable market conditions and economic uncertainties. Although our scenarios make reasonable assumptions based on detailed analysis, the volatility of the primary commodity markets, especially those on the Ni and Co market, have direct impacts on recycling. In addition, with Co being currently the main economic driver for battery recycling[52], the shift towards high Ni and low Co chemistries might impact the economic viability of recycling, which may then become more dependent on the price of Ni. In unfavourable market conditions, policy action might be required to incentivize recycling and ensure minimisation of negative environmental impacts or critical material depletion associated to inadequate end of life treatment of EVs batteries. Similar proposals have been made to enhance a circular flow of yttrium recovered from electronic waste[53] and could be expanded to EV batteries.

Outlook

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

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

Methods

Methodology overview and model structure

We used Material Flow Analysis (MFA) to analyse current and future stocks and flows of Co for EV batteries. The MFA approach applied in this study consists of a static MFA for Co flows in 2017 and a dynamic MFA of Co flows between 2017-2050[56]. The aim of the static MFA is to understand the global flows of Co (mine to production) and Co flows (consumption to EoL) for EVs registered in the EU in 2017. Data has been compiled from a wide variety of sources including secondary data sets from governmental statistics, company reports and primary data, collected through interviews and site visits to recyclers- see main manuscript and the SI. Based on the 2017 EV fleet characteristics and reference static MFA, a dynamic MFA model was established to project future EVs and Co stocks and flows. A reference business as usual scenario for 2017-2050 was then generated to project future trends and estimate future Co flows when little change in institutional conditions and end-of-life management from 2017 is expected but incorporating some technological changes (details in SI). Four circular economy scenarios were modelled modifying different parameters to compare potential resource savings from the reference scenario. The inputs to the 2017 base year and key features of the MFA model are described below. A more detailed on the model inputs can be found in the SI.

Calculating cobalt flows for 2017

The static MFA was developed by tracing the upstream flows of Co embedded in EU EVs in 2017. Flows were divided into seven processes including vehicle use, battery cell assembly, cathode production, Co consumption, refining, intermediate refining, and Co mine production (see Supplementary Figure 1 for the complete MFA system). Vehicle use: Due to the different chemistry types and varying sizes used for EVs, the Co content within batteries varies significantly. To include this heterogeneity of chemistries and size, vehicle specific details were considered. Vehicle registrations for all BEV and PHEV models in the EU in 2017 were derived from the CO_2 monitoring dataset by the European Environmental Agency[57]. All 28 EU member states are obliged to provide a wide variety of detailed information on each new passenger vehicle registration, including the manufacture name, vehicle type, model, CO_2 emissions, vehicle mass and other details. Due to the limitations of the dataset, several steps had to be taken to filter out both BEVs and PHEVs (see SI). For each individual model the battery capacity, weight, chemistry, specific energy, and battery producer were estimated based on a variety of sources. A full list of all vehicles and the battery details can be found in Supplementary Table 10 and 11. Co content per vehicle model was calculated based on the size of the battery (kWh) and material content for the considered chemistries derived primarily from the BatPaC model version 3.1 by the Argonne National Laboratory[58]. As most LMO chemistries are used with a blend of NCM[59], the LMO-NCM distribution was based on a teardown of a commonly used LMO cell[60]. Currently three major types of NCM chemistries are used, NCM 333, NCM 622, NCM 811, whereby the number indicates the content of Ni, manganese, and Co in the battery. Limited information is available describing which NCM type is used. As a higher Ni content increases the specific energy (Wh/kg^{-1})[8], the specific energy per vehicle, obtained from the US Environmental Production Agency – Clean Air Act certification summaries [61], was used to determine if the battery is a NCM 622/532 or 333 (NCM 811 was introduced for the first time in 2019[7]). Our data suggest that PHEVs have a lower specific energy than BEVs, which can be explained since battery cells for hybrid vehicles are optimised for high power requirements. The low specific energy in PHEVs makes it challenging to filter out the chemistry type. We therefore assumed that most PHEVs had an NCM 333 cathode if not reported differently in the literature.

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

– refined exports). Here we only included refined Co products that are used for batteries, including Co chemicals and powders[47] as well as broken cathodes, briquettes and ingots [62]. All data sources for refined production and trade flows can be found in the Supplementary Tables. Refining. Total refined Co production in 2017 of Co chemicals, powders and metals is based on data by Darton Commodities, provided by Bloomberg[63]. The refined Co metal data is further disaggregated into broken cathodes, briquettes and ingots based on company reports and trade brochures. Trade statistics were further used to determine the upstream flows of Co consumed by South Korea, Japan, USA and China. Trade flows are based on several Harmonised System trade codes using the UN Comtrade database, using different Co contents for each trade flow (see Supplementary Methods for more information on data extraction). Intermediate refining. Intermediate refining was estimated based on mass balance (mine production plus ore import minus ore export). Mine production. Mine specific data on global primary Co production in 2017 was compiled from company and governmental reports. This dataset was compared with geological survey data by the British Geological Survey (BGS) and the United States Geological Survey (USGS) to adjust for gaps were needed. See Supplementary Table 2 for the entire list of Co mines. Recycled Co is not taken into consideration due to the limited amount of available data. However, all European LIB recycling facilities are listed in Supplementary Table 19. Co losses during cell assembly, the cathode production, refining, and mining are also not considered in the analysis.

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

To forecast potential Co demand growth and end of life implications and solutions, a dynamic MFA scenario model was established. Central to the model is the mass balance principle and stock-flow relations[64]. An inflow-driven approach is adopted, with future vehicle inflows as the primary variable. We justify this approach based on the saturation of vehicle ownership in the EU[65], and no significant increase in ownership (vehicles per capita) is expected in the future. Annual vehicle inflows are therefore based upon the 2017 vehicle registration rate and population dynamics. The dynamic MFA system, including parameters, is illustrated in Supplementary Figure 2.

Calculating future cobalt demand

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

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

Future Co demand is driven by the expected annual sales of BEVs and PHEVs in the EU. Future EV registrations are expected to increase according the recent EC proposal for post-2020 CO_2 targets for cars[25]. The BEV and PHEV rates to achieve these targets are based on a study by Ricardo[28]. This study however only indicates the percentage BEVs and PHEVs of the entire passenger vehicle fleet required to meet the emissions targets. Future vehicle registrations are therefore calculated based upon historic car sales rate (annual sales of vehicles/population), assuming this remains the same until 2050 and including population projections of the EU28[66]. To account for the differences in battery size of BEVs, the future vehicle fleet model is categorised into different vehicle segments. The vehicle segmentation from the International Council for Clean Transport (ICCT) is used, which include 9 categories: mini, small, lower medium, medium, upper medium, luxury, sport, Van and SUV. All 2017 BEV models were categorised into these segments to include the battery size, weight, specific energy and range for each vehicle segment (see Supplementary Table 15). In the model it is expected that specific energy of all vehicle segments will gradually increase to 235 Wh/kg^{-1} (pack level) by 2030 as set by the Electrochemical Energy Storage Technical Team Roadmap by the US Department of Energy[30]. It is assumed that the increase in energy density is primarily driven by the use of a lithium metal anode and solid-state electrolyte[29,31].

Battery and vehicle weight per segment are assumed to remain the same as in 2017. As a result, battery capacity will increase whilst the energy efficiency of the vehicle (km/kWh) is assumed to remain the same for all vehicle segments as in 2017. With an increase in specific energy, most vehicles would provide a range of 480 km or more, acceptable to 60 to 90% of consumers according to market studies[67]. It is assumed that by 2030, EVs will be cost competitive with ICE and BEV market shares of the different vehicle segment will be the same as all vehicles in 2017 in the EU as provided by ICCT[32]. Due the limited variety in battery capacity of PHEVs in 2017 and range being less of an issue, future battery capacity for all PHEV models increases to 15 kWh as used by the IEA[68]. Future market share of different chemistries where included based on different sources and technology roadmaps. Supplementary Table 16 illustrates the assumed future market share for each chemistry. Co and Ni content of batteries are calculated the same as in the static MFA except for the NCA chemistry. It is assumed that new NCA chemistries will be solely based on the low Co NCA technology (referred to as NCA-II in the SI) based on Wentker, et al.[69]. Material content (kg/kWh) per chemistry can be found in Supplementary Table S14.

Calculating future secondary supply

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

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

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

Outflow. Two different battery end of life routes for BEVs and one for PHEVs are included. In the first route for BEVs, batteries retire simultaneously with the vehicle, the second route assumes that batteries are replaced prior to the end of vehicle life. Due to the lack of real-life battery degradation data, lifetime distributions for batteries and EVs are not available. A static vehicle and battery lifetime were therefore included. Vehicle lifetime was set to 15 years based on an European study on vehicle lifetime distance travelled and vehicle mass[70]. Some BEV batteries will be replaced after 8 years, a proxy for current calendar life warranty periods[71]. PHEV batteries are assumed to remain in the vehicle due to the limited incentive for replacement and thus have a lifetime of 15 year. Despite the lack of certainty around second life LIB aging[72], the lifespan of indirect reused LIB is assumed to be 10 years[36]

PHEV batteries are assumed to be directly recycled due their high degradation as a result of the long lifetime (batteries are not replaced) and high cycling rate (charge and discharge). Batteries from end-of-life BEVs are either reused directly in EV applications, reused indirectly in ESS or recycled in closed-loop and open loop systems. The state of health (SOH), the remaining capacity of the battery after its first life, determines the end-of-life (EOL) route of BEVs. To estimate the SOH, annual capacity fade of batteries is based upon calendric aging and total charging cycles. Due to the missing long-term experiences of EV battery calendar aging and uncertainties in battery aging models[73], a simplified approach regarding calendar age is taken based on Schmidt, et al.[74]. All battery chemistries are expected to reach 80% of their initial capacity within 12 years, a capacity loss of 1.67% per year. Cycling degradation is defined for each vehicle segment and chemistry based on annual charging cycles and depth of discharge. Average cycling lifetime per chemistry, defined as amount of cycles until the battery reaches a SOH of 80%, is based on the consolidation of a wide range of scientific and industry data sources on lithium-ion batteries provided by Peters, et al.[73]. Annual charging cycles are based on the depth of discharge, vehicle range and annual km driven. DoD for all BEV segments are assumed to be 40% based on a European average[75]. Annual KM driven for each segment is based upon the correlation between vehicle mass and KMs driven[70]. The calculations and sources used can be found in the SI. Batteries with a SOH below 80% are directly recycled and those between 85% and 80% are reused in less-demanding energy system storage (ESS). Batteries with a SOH larger than 85% might still be fit to be reused in smaller EV batteries, where range is less of an issue or used to replace damaged cells[76]. However, as individual cells under equal conditions age differently[77,78], not all cells can be reused. BEV battery packs with a SOH above 85% are assumed to be dismantled to cell level and further tested for reuse as currently done with EOL Nissan Leaf batteries[79]. A dataset on cycling degradation of 24 LIB cells[77] is used to determine the percentage of individual cells in a battery pack with a SOH >85% can be directly reused.

An overview of the circular economy strategies (CES)

We model four future scenarios to understand the potential of the four CES to reduce and replace primary Co for EVs. Five parameters are altered to change the outcome of the model in the four scenarios. These include battery chemistry, end-of-vehicle life and battery collection rates, Co recovery rates and batteries replaced prior to vehicle end of life. In the reference scenario (REF) EV adoption will continue to increase and lower Co, higher Ni chemistries will be adopted based estimates from the IEA[80], reflecting the higher than previously expected adoption of high Ni cathodes[5]. Secondary Co from recycled batteries in this scenario is constrained by current limited collection and recovery rates in the EU. In this scenario, all batteries are assumed to reach end of life simultaneously with the vehicle given the limited economic incentives for vehicle owners to replace batteries before that[36]. The goal of this scenario is to define the business as usual conditions against which to simulate savings associated with more circular flow of materials.

In the technology driven substitution (TDS) scenario, novel battery technologies substituting Co entirely are adopted, following the compilation of technology roadmaps by the IEA[68]. By 2030, it is assumed that chemistries with less than 5% Co in the cathode (NCA-II or NCM9.5.5) will be the dominant technology. Beyond 2030, it is expected that new chemistries without Co such as Li-Sulphur and Li-Air are commercialised and used in passenger EVs. In the technology driven reduction (TDR) scenario, Co content is rapidly reduced but not entirely substituted. Here low Co and high Ni (NCA-II/NCM9.5.5) chemistries are the dominant technology by 2050.

In the business model driven reuse scenario (BDR), EV producers adopt a product service system business model, whereby a bundle of product and service aim to create customer utility and generate value[42]. It is assumed that 95% of all EV batteries are now leased to consumers, whereby the battery ownership remains with the car manufacturer or a third party. The consumer and the producer engage in a service contract that guarantees a well performing battery over the vehicle lifetime and, thus, the battery will be replaced based on warranty periods or performance indicators. Close networks between EV producers, energy service providers and battery recyclers are established, e.g. Nissan and energy service provider Eaton[81] and Audi and recycler Umicore[82] resulting in a 90% collection rate of ELV and LIB, whereby 10% of ELV remains export. In addition, EU battery production has increased to 70% of total required production and all batteries are recycled inside the EU. In the final scenario, the policy driven recycling scenario (PDR) the EU sets out a strong vision towards a circular economy with a robust green industrial policy and comprehensive Extended Producer Responsibility schemes to cover EVs and their batteries. A more stringent waste management policy increases ELV and LIB collection rates in line with recent proposed changes the EU Batteries Directive and End-of-Life Vehicles Directive[83]. Key improvements to the ELV Directive include better ELV tracking system and an improved registration and de-registration system to reduce missing ELV problem[84]. In this scenario, implications of the stringent ELV Directive adopted is that by 2050, 90% of ELV are officially collected and only 10% are exported outside the EU. An update of the Battery Directive is also assuming to lead to a 100% battery collection rate.

Data Availability

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

References

1 Campbell, G. A. The cobalt market revisited. *Mineral Economics*, doi:10.1007/s13563-019-00173-8 (2019).

2 Shedd, K. B., McCullough, E. A. & Bleiwas, D. I. Global trends affecting the supply security of cobalt. *Mining Engineering Magazine* **69**, 37-42 (2017).

3 Gulley, A. L., McCullough, E. A. & Shedd, K. B. China's domestic and foreign influence in the global cobalt supply chain. *Resources Policy* **62**, 317-323, doi:10.1016/j.resourpol.2019.03.015 (2019).

4 Petavrazi, E., Gunn, G. & Kresse, C. *Commodity Review: Cobalt.* (British Geological Survey, 2019).

5 *Electric Vehicle Outlook 2020* (Bloomberg New Energy Finance, 2020).

6 Whittingham, M. S. History, Evolution, and Future Status of Energy Storage. *Proceedings of the IEEE* **100**, 1518-1534, doi:10.1109/JPROC.2012.2190170 (2012).

7 Li, W., Erickson, E. M. & Manthiram, A. High-nickel layered oxide cathodes for lithium-based automotive batteries. *Nature Energy* **5**, 26-34, doi:10.1038/s41560-019-0513-0 (2020).

8 Schmuch, R., Wagner, R., Hörpel, G., Placke, T. & Winter, M. Performance and cost of materials for lithium-based rechargeable automotive batteries. *Nature Energy* **3**, 267-278, doi:10.1038/s41560-018-0107-2 (2018).

9 Alonso, E., Gregory, J., Field, F. & Kirchain, R. Material Availability and the Supply Chain: Risks, Effects, and Responses. *Environmental Science & Technology* **41**, 6649-6656, doi:10.1021/es070159c (2007).

10 *Mineral commodity summaries 2019* (US Geological Survey, 2019).

11 *Historical statistics for mineral and material commodities in the United States: US Geological Survey Data Series, 140* (US Geological Survey, 2017).

12 *Final List of Critical Minerals 2018* (US Department of the Interior, 2018).

13 *Australia's Critical Minerals Strategy 2019* (Commonwealth of Australia, 2019).

14 *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: on the 2017 list of Critical Raw Materials for the EU.* (European Commision, 2017).

15 Lavietes, M. Tesla, Apple among firms accused of aiding child labor in Congo. *Reuters*. (16 December 2019).

16 Vaalma, C., Buchholz, D., Weil, M. & Passerini, S. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials* **3**, 18013, doi:10.1038/natrevmats.2018.13 (2018).

17 Cusenza, M. A., Guarino, F., Longo, S., Ferraro, M. & Cellura, M. Energy and environmental benefits of circular economy strategies: The case study of reusing used batteries from electric vehicles. *Journal of Energy Storage* **25**, doi:10.1016/j.est.2019.100845 (2019).

18 Yang, J., Gu, F. & Guo, J. Environmental feasibility of secondary use of electric vehicle lithium-ion batteries in communication base stations. *Resources, Conservation and Recycling* **156**, doi:10.1016/j.resconrec.2020.104713 (2020).

19 Harper, G. *et al.* Recycling lithium-ion batteries from electric vehicles. *Nature* **575**, 75-86, doi:10.1038/s41586-019-1682-5 (2019).

20 Ziemann, S., Müller, D. B., Schebek, L. & Weil, M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resources, Conservation and Recycling* **133**, 76-85, doi:10.1016/j.resconrec.2018.01.031 (2018).

21 Harvey, L. D. D. Resource implications of alternative strategies for achieving zero

greenhouse gas emissions from light-duty vehicles by 2060. *Applied Energy* **212**, 663-679, doi:10.1016/j.apenergy.2017.11.074 (2018).

22 Miedema, J. H. & Moll, H. C. Lithium availability in the EU27 for battery-driven vehicles: The impact of recycling and substitution on the confrontation between supply and demand until2050. *Resources Policy* **38**, 204-211, doi:https://doi.org/10.1016/j.resourpol.2013.01.001 (2013).

23 Melin, H. E. *State-of-the-art in reuse and recycling of lithium-ion batteries - A research review* (Circular Energy Storage, 2019).

24 Nguyen, R. T., Fishman, T., Zhao, F., Imholte, D. D. & Graedel, T. E. Analyzing critical material demand: A revised approach. *Sci Total Environ* **630**, 1143-1148, doi:10.1016/j.scitotenv.2018.02.283 (2018).

25 *Regulation (EU) 2019/631 of the European Parliament and the Council of 17 april 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011* (European Union, 2019).

26 Hill, G., Heidrich, O., Creutzig, F. & Blythe, P. The role of electric vehicles in near-term mitigation pathways and achieving the UK's carbon budget. *Applied Energy* **251**, 113111 (2019).

27 Godoy León, M. F., Blengini, G. A. & Dewulf, J. Cobalt in end-of-life products in the EU, where does it end up? - The MaTrace approach. Resources, Conservation and Recycling 158, doi:10.1016/j.resconrec.2020.104842 (2020).

28 *Europe's Clean Mobility Outlook: Scenarios for the EU light-duty vehicle fleet, associated energy needs and emissions, 2020-2050* (Ricardo, 2018).

29 Berg, H. & Zackrisson, M. Perspectives on environmental and cost assessment of lithium metal negative electrodes in electric vehicle traction batteries. *Journal of Power Sources* **415**, 83-90, doi:10.1016/j.jpowsour.2019.01.047 (2019).

30 *US DRIVE -Electrochemical Energy Storage Technical Team Roadmap* (US Department of Energy, 2017).

31 Lee, Y.-G. *et al.* High-energy long-cycling all-solid-state lithium metal batteries enabled by silver–carbon composite anodes. *Nature Energy*, doi:10.1038/s41560-020-0575-z (2020).

32 *European Vehicle Market Statistics - Pocketbook 2017/18* (ICCT, 2017).

33 Dias, A. P., Blagoeva, D. T., Pavel, C. & Arvanitidis, N. *Cobalt: demand-supply balances in the transition to electric mobility* (European Commission, Joint Research Centre, 2018).

34 *Lithium and cobalt - a tale of two commodities* (McKinsey, 2018).

35 Fu, X. *et al.* Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand. *Environmental Science & Technology*, doi:10.1021/acs.est.9b04975 (2020).

36 Neubauer, J. S., Smith, K., Wood, E. & Pesaran, A. *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries* (National Renewable Energy Laboratory, 2015).

37 Saxena, S., Le Floch, C., MacDonald, J. & Moura, S. Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models. *Journal of Power Sources* **282**, 265-276, doi:10.1016/j.jpowsour.2015.01.072 (2015).

38 *Assessment of the implementation of Directive 2000/53/EU on end-of-life vehicles (the ELV Directive) with emphasis on the end of life vehicles of unknown whereabouts* (European Commission, 2018).

39 *PEFCR—Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications* (Recharge Association, 2018).

40 Placke, T., Kloepsch, R., Dühnen, S. & Winter, M. Lithium ion, lithium metal, and

alternative rechargeable battery technologies: the odyssey for high energy density. *Journal of Solid State Electrochemistry* **21**, 1939-1964, doi:10.1007/s10008-017-3610-7 (2017).

41 Bianchini, M., Roca-Ayats, M., Hartmann, P., Brezesinski, T. & Janek, J. There and Back Again-The Journey of LiNiO2 as a Cathode Active Material. *Angew Chem Int Ed Engl* **58**, 10434-10458, doi:10.1002/anie.201812472 (2019).

42 Boehm, M. & Thomas, O. Looking beyond the rim of one's teacup: a multidisciplinary literature review of Product-Service Systems in Information Systems, Business Management, and Engineering & Design. *Journal of Cleaner Production* **51**, 245-260, doi:https://doi.org/10.1016/j.jclepro.2013.01.019 (2013).

43 AESE & Delta-EE. European Electrical Storage Market Grows by 49% in 2017 to 589 MWh. *Delta Energy & Environment* (2 July 2018).

44 Henze, V. Energy Storage Investments Boom As Battery Costs Halve in the Next Decade. *Bloomberg New Energy Finance* (31-July 2019).

45 Hill, N., Clarke, D., Blair, L. & Menadue, H. *Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles, Final Project Report.* (Ricardo, 2019).

46 *Circular Energy Storage Online* (Circular Energy Storage, 2020).

47 Schmidt, T., Buchert, M. & Schebek, L. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. *Resources, Conservation and Recycling* **112**, 107-122, doi:10.1016/j.resconrec.2016.04.017 (2016).

48 *Cobalt [advanced release] - 2015 Minerals Yearbook* (US Geological Survey 2019).

49 Müller, M. *et al.* Evaluation of grid-level adaptability for stationary battery energy storage system applications in Europe. *Journal of Energy Storage* **9**, 1-11, doi:10.1016/j.est.2016.11.005 (2017).

50 Stahl, H. *et al. Evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators*. (Trinomics, 2018).

51 Tagliaferri, C. *et al.* Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chemical Engineering Research and Design* **112**, 298-309, doi:10.1016/j.cherd.2016.07.003 (2016).

52 Wang, X., Gaustad, G., Babbitt, C. W. & Richa, K. Economies of scale for future lithium-ion battery recycling infrastructure. *Resources, Conservation and Recycling* **83**, 53-62, doi:10.1016/j.resconrec.2013.11.009 (2014).

53 Favot, M. & Massarutto, A. Rare-earth elements in the circular economy: The case of yttrium. *J Environ Manage* **240**, 504-510, doi:10.1016/j.jenvman.2019.04.002 (2019).

54 Laner, D. & Rechberger, H. in *Special Types of Life Cycle Assessment* (ed Matthias Finkbeiner) 293-332 (Springer Netherlands, 2016).

55 Hoogmartens, R., Eyckmans, J. & Van Passel, S. A Hotelling model for the circular economy including recycling, substitution and waste accumulation. *Resources, Conservation and Recycling* **128**, 98-109, doi:10.1016/j.resconrec.2017.09.015 (2018).

56 Müller, E., Hilty, L. M., Widmer, R., Schluep, M. & Faulstich, M. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. *Environ Sci Technol* **48**, 2102-2113, doi:10.1021/es403506a (2014).

57 *Monitoring of CO2 emissions from passenger cars - Data 2017* (European Environmental Agency, 2020)

58 Nelson, P. A., Gallagher, K. G., Bloom, I. & Dees, D. W. *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles* (Argonne National Laboratory, 2012).

59 Pillot, C. *Lithium ion battery raw material Supply & demand 2016-2025* (Avicenne Energy 2017).

60 Cusenza, M. A., Bobba, S., Ardente, F., Cellura, M. & Di Persio, F. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *Journal of Cleaner Production*, doi:10.1016/j.jclepro.2019.01.056 (2019).

61 *EPA's Transportation and Air Quality Document Index System (DIS)* (Environmental Protection Agency, 2019).

62 Heppel, G. Cobalt shifts from metal to chemical markets. *CRU* (8 September 2017).

63 Farchy, J. & Warren, H. China has a secret weapon in the race to dominate electric cars. *Bloomberg* (2 December 2018).

64 Brunner, P. H. & Rechberger, H. *Handbook of material flow analysis : for environmental, resource, and waste engineers*. Second Edition. edn, (CRC Press, Taylor & Francis Group, 2016).

65 Wu, T., Zhao, H. & Ou, X. Vehicle Ownership Analysis Based on GDP per Capita in China: 1963–2050. *Sustainability* **6**, 4877-4899, doi:10.3390/su6084877 (2014).

66 *Population on 1st January by age, sex and type of projection - (proj_15npms)* (Eurostat, 2018).

67 Nykvist, B., Sprei, F. & Nilsson, M. Assessing the progress toward lower priced long range battery electric vehicles. *Energy Policy* **124**, 144-155, doi:10.1016/j.enpol.2018.09.035 (2019).

68 *Global EV Outlook 2018 - Towards cross-modal electrification* (International Energy Agency, 2018).

69 Wentker, M., Greenwood, M. & Leker, J. A Bottom-Up Approach to Lithium-Ion Battery Cost Modeling with a Focus on Cathode Active Materials. *Energies* **12**, doi:10.3390/en12030504 (2019).

70 Dun, G., Pridmore, A., Gibson, G., Kollamthodi, S. & Skinner, I. *Data gathering and analysis to assess the impact of mileage on the cost effectiveness of the LDV CO2 Regulation* (Ricardo, 2014).

71 Zubi, G., Dufo-López, R., Carvalho, M. & Pasaoglu, G. The lithium-ion battery: State of the art and future perspectives. *Renewable and Sustainable Energy Reviews* **89**, 292-308, doi:10.1016/j.rser.2018.03.002 (2018).

72 Martinez-Laserna, E. *et al.* Technical Viability of Battery Second Life: A Study From the Ageing Perspective. *IEEE Transactions on Industry Applications* **54**, 2703-2713, doi:10.1109/tia.2018.2801262 (2018).

73 Peters, J. F., Baumann, M., Zimmermann, B., Braun, J. & Weil, M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. *Renewable and Sustainable Energy Reviews* **67**, 491-506, doi:10.1016/j.rser.2016.08.039 (2017).

74 Schmidt, T. S. *et al.* Additional Emissions and Cost from Storing Electricity in Stationary Battery Systems. *Environ Sci Technol*, doi:10.1021/acs.est.8b05313 (2019).

75 Corchero, C., Gonzalez-Villafranca, S. & Sanmarti, M. in *2014 IEEE International Electric Vehicle Conference (IEVC).* 1-6 (IEEE).

76 Canals Casals, L., Amante García, B. & Cremades, L. V. Electric vehicle battery reuse: Preparing for a second life. *Journal of Industrial Engineering and Management* **10**, doi:10.3926/jiem.2009 (2017).

77 Harris, S. J., Harris, D. J. & Li, C. Failure statistics for commercial lithium ion batteries: A study of 24 pouch cells. *Journal of Power Sources* **342**, 589-597, doi:10.1016/j.jpowsour.2016.12.083 (2017).

78 Baumhöfer, T., Brühl, M., Rothgang, S. & Sauer, D. U. Production caused variation in capacity aging trend and correlation to initial cell performance. *Journal of Power Sources* **247**, 332-338, doi:10.1016/j.jpowsour.2013.08.108 (2014).
79 Nissan, Sumitomo Corp. and 4R set up plant to recycle electric-car batteries (Nissan, 28 March 2018).
80 *Global EV Outlook 2019* (International Energy Agency, 2019).
81 xStorage Home - Eaton Nissan Home energy storage. *Nissan and Eaton* (June 2017).
82 New power from old cells: Audi and Umicore develop closed loop battery recycling. *Umicore* (26 October 2018).
83 Bourguignon. *Circular economy package - Four legislative proposals on waste* (European Parliamentary Research Service, 2018).
84 Hatzi-Hull, A. *The ELV Directive What comes next?* (EuRIC Annual Conference, 2018).

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Authors contributions

JB initiated the study and conducted the research under guidance of TD, RB and OH. Data was collected by JB and analysed by JB, TD, OH and HEM. The first draft was written by JB under guidance of OH. Additional background information was provided by HEM. The manuscript was edited by TD, OH, HEM, and RB. The writing and publication process, correspondence between authors, editors, revision and publication was led by OH. All authors are responsible for the contributions to the manuscript from the research, data, code and materials presented in the manuscript, Supportive information (SI) and Methodology.