Lithium-ion batteries and the transition to electric vehicles: environmental challenges and opportunities from a life cycle perspective

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2 Future material demand for automotive lithium-based batteries[a]

Abstract

The world is shifting to electric vehicles to mitigate climate change. Here, we quantify the future demand for key battery materials, considering potential EV fleet and battery chemistry developments as well as second-use and recycling of EV batteries. We find that in a lithium nickel cobalt manganese oxide dominated battery scenario, demand is estimated to increase by factors of 18-20 for Lithium, 17-19 for Cobalt, 28-31 for Nickel, and 15-20 for most other materials from 2020 to 2050, requiring a drastic expansion of Lithium, Cobalt, and Nickel supply chains and likely additional resource discovery. However, uncertainties are large. Key factors are the development of the electric vehicles fleet and battery capacity requirements per vehicle. If other battery chemistries were used at a large scale, *e.g.*, lithium iron phosphate or novel Lithium-Sulphur or Lithium-Air batteries, the demand for Cobalt and Nickel would be substantially smaller. Closed-loop recycling plays a minor, but increasingly important role in reducing primary material demand until 2050, however, advances in recycling are necessary to economically recover battery-grade materials from end-of-life batteries. Second-use of electric vehicle batteries further delays recycling potentials.

2.1 Introduction

Electric vehicles (EVs) generally have a reduced climate impact compared to internal combustion engine vehicles[52]. Together with technological progress and governmental subsidies, this advantage led to a massive increase in the demand for EVs[62]. The global fleet of light-duty EVs grew from a few thousand just a decade ago to 7.5 million vehicles in 2019[63]. Yet, the global average market penetration of EVs is still just around 1.5% in 2019 and future growth is expected to dwarf past growth in absolute numbers[63].

Lithium-ion batteries (LIBs) are currently the dominant technology for EVs[62]. Typical automotive LIBs contain lithium (Li), cobalt (Co), and nickel (Ni) in the cathode, graphite

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in the anode, as well as aluminum and copper in other cell and pack components. Commonly used LIB cathode chemistries are lithium nickel cobalt manganese oxide (NCM), lithium nickel cobalt aluminum oxide (NCA), or lithium iron phosphate (LFP), although battery technology is currently evolving fast and new and improved chemistries can be expected in the future[62,64].

Due to the fast growth of the EV market, concerns over the sustainable supply of battery materials have been voiced. These include supply risks due to high geopolitical concentrations of cobalt[65,66] and social and environmental impacts associated with mining[67,68], as well as the availability of cobalt and lithium reserves[36] and the required rapid upscaling of supply chains to meet expected demand[65].

Understanding the magnitude of future demand for EV battery raw materials is essential to guide strategic decisions in policy and industry and to assess potential supply risks as well as social and environmental impacts. Several studies have quantified the future demand for EV battery materials for specific world regions such as Europe[30], the United States[31,32], and China[22], or for specific battery materials only[33-35]. Weil et al.[36] assess the material demand for EV batteries at the global level and find that shortages for key materials, such as Li and Co, can be expected. However, their model does not investigate the influence of battery chemistry developments (*e.g.*, improved NCM chemistries or novel Lithium-Sulphur (Li-S) and Lithium-Air batteries (Li-Air)) as well as alternative fleet and different recycling scenarios.

Here, we go beyond previous studies by developing comprehensive global scenarios for the development of the EV fleet, battery technology (including potentially game-changing chemistries such as Li-S and Li-Air) as well as recycling and second-use of EV batteries. We assess the global material demand for light duty EV batteries for Li, Ni, and Co, as well as (for model see Supplementary Fig. 2.1) for manganese (Mn), aluminum (Al), copper (Cu), graphite and silicon (Si). We also relate material demands to current production capacities and known reserves and discuss key factors for reducing material requirements. The results presented are intended to inform the ongoing discussion on the transition to electric vehicles by providing a better understanding of future battery material demand and the key factors driving it.

2.2 Methods

Model overview. We develop a dynamic material flow analysis (MFA) model, which is a frequently used approach to analyze material stocks and flows[69]. Our stock-driven MFA model estimates the future material demand for EV batteries as well as EoL materials available for recycling. It consists of an EV layer, a battery layer, and a material layer, and considers key technical and socio-economic parameters in three layers (Supplementary Fig. 2.1). The EV layer models the future EV stock (fleet) development until 2050 as well as required battery capacity. The EV stock then determines the battery stock, which in turn determines the battery inflows and, considering their lifespan distributions (Supplementary Fig. 2.2), the outflow of EoL batteries. The battery layer considers future battery chemistry developments and market shares. The material layer models material compositions of battery chemistries using the BatPaC model[70]. The fate of EoL batteries is modelled considering three recycling scenarios and a second-use scenario and these determine the material availability for closed-loop recycling. The model layers and parameters are described in the following.

EV fleet scenarios and required battery capacity. Projections for the development of the EV fleet vary, but most studies project a substantial penetration of EVs in the light duty vehicle (LDV) market in the future (Supplementary Fig. 2.3). We use two EV fleet development scenarios of the IEA until 2030: the stated policies (STEP) scenario and the sustainable development (SD) scenario[63] (and estimate the annual EV stock based on the equivalent IEA 2019 scenarios[71], see Supplementary Fig. 2.4). We then extrapolate the EV fleet penetration until 2050 using a logistic model (see Supplementary Fig. 2.5) based on a target penetration of EVs in the LDV market in 2050 of 25% in the STEP scenario and 50% in the SD scenario (which is in line with other EV forecasts, as shown in Supplementary Fig. 2.3). To estimate future EV fleet until 2050, we further assume a linear growth for global LDV stock from 503 million vehicles in 2019 to 3.9 billion vehicles in 2050, which is in line with projection by Fuel Freedom Foundation[72]. Global predictions of the future development of BEV and PHEV shares were not available. To estimate future shares of BEVs and PHEVs in the EV stock, we assumed that the global share of BEVs increases in the same way as the US BEV share projected by the US Energy Information Administration[73], but starting from the 2030 levels of the STEP and SD scenarios (*i.e.*, from 66% in 2030 to 71% in 2050 in STEP scenario and 70% in 2030 to 75% in 2050 in SD scenario, see Supplementary Fig. 2.6).

We classify EVs models into 3 market segments (small, mid-size, and large cars for both BEVs and PHEVs) based on vehicle size classes used in the Fuel Economy Guide by EPA (see Supplementary Table 2.1)[74], and collect global sales of each EV model from the Marklines database[75] . We use the distribution of cumulative sales until 2019 to represent EV sales market shares among small, mid-size, and large segments (Supplementary Fig. 2.7 and Supplementary Fig. 2.8). As a result, we obtained 19%, 48%, and 34% for small, mid-size, and large cars for BEVs, and 23%, 45% and 32% for PHEVs. We assume EV sales market share remains constant, however, a sensitivity analysis is conducted to obtain the upper and lower bounds for material requirements if all vehicles were large BEV or small PHEV (see sensitivity analysis).

We collect range, fuel economy, and motor power of each EV model from Advanced Fuels Data Center of US DOE[76], and calculate sales-weighted average range, fuel economy, and motor power for 3 market segments for both BEVs and PHEVs[77] (Supplementary Table 2.2 and Supplementary Table 2.3). By assuming 85% available battery capacity for driving EVs based on BatPaC model[70], we obtain 33 kWh, 66 kWh, and 100 kWh for small, mid-size, and large BEVs (see Supplementary Table 2.3 for PHEV).

Passenger car lifespans have been found to vary from 9 to 23 years among countries with an average lifespan of around 15 years[78]. EV lifespan depends on consumer behavior, technical lifespan (see next section), and other factors. Here we use a Weibull distribution[79] to model the EV lifespan assuming the minimum, maximum, and most likely lifespans of EVs to be 1, 20, and 15 years respectively (see Supplementary Fig. 2.2). We do not consider battery remanufacture and reuse from one EV to another EV due to performance degradation, technical compatibility and consumer acceptance.

Battery chemistry scenarios and market shares. Although various EV battery chemistries have been developed for EVs to decrease cost and improve performance, current major battery roadmaps in US[80], EU[81], Germany[82], and China[83] focus on cathode material development considering high-energy NCM (transition to low cobalt and high nickel content) and NCA based chemistries to be the likely next generation of LIBs for EVs in next decade, as well as anode material development considering adding Si to graphite anode. This is also reflected in commercial activities by battery producers (*e.g.*, LG Chem or CATL)[84] and market share projections until 2030 by Avicenne Energy85, which we use in this study. We assume that NCM batteries continue to decrease cobalt content and increase nickel content after 2030 and compile the NCX scenario (where X represents either Al or Mn) until 2050 (including 8 chemistries, see Supplementary

Table 2.4. In the NCX scenario, we assume that NCM955 (90% nickel, 5% cobalt, 5% manganese) are introduced in 203086, and gradually replace other previous chemistries proportionally to reach a market share of one third by 2050 (*i.e.*, market shares of NCM111, NCM523, NCM622, NCM622-Graphite (Si), NCM811-Graphite (Si), NCA, and LFP batteries are assumed to decrease proportionally after 2030, see Fig. 2.2b).

Future battery chemistry developments after 2030 are uncertain, but conceivable battery chemistries, in addition to NCM and NCA batteries, include already existing LFP batteries[87,88], as well high-capacity Li-metal solid-state batteries, such as Li-S and Li-Air[81,89]. Therefore, we include two additional what-if scenarios next to the NCX scenario: an LFP scenario and a Li-S/Air scenario. In the LFP scenario, the market share of LFP chemistry is assumed to increase linearly from around 30% in 2019 to 60% by 2030 and remain at this level until 2050 (*i.e.*, other batteries lost market share proportionally compared to the NCX scenario, see Fig. 2.2b). In the Li-S/Li-Air scenario, we assume Li-S and Li-Air batteries to be commercially available in 2030 based on commercial plans of Li-S by OXIS Energy[90] and Li-Air by Samsung Electronics[91] and then they obtain linearly increasing market share to 30% each (totally 60%) by 2040, and maintain this share until 2050 (NCA and NCM batteries supply the rest of the market by historical proportions, see Fig. 2.2b).

The real-world lifespan of batteries is influenced by additional factors not modelled here, such as ambient temperature, depth, rates of charge and discharge, and driving cycles[92]. We use the technical lifespan of batteries. Before 2020, we assume that batteries are likely to last 8 years (based on the battery warranty of EV manufactures)[93], which is shorter than EV lifespan (Supplementary Table 2.5 and Supplementary Table 2.6). We assume a 50% battery replacement rate for EVs (*i.e.*, one EV requires 1.5 battery packs on average). Battery research agendas in the US[80], EU[81], and China[83] include targets to increase the lifespan of batteries, which is why we assume that after 2020 batteries will have the same lifespan distributions as EVs and no replacement of batteries is required. Note that we assume higher lifespans for LFP batteries (20 years on average) (Supplementary Fig. 2.2), which leads to a higher second-use potential than for the other battery types.

Battery material compositions. The battery material compositions are calculated by using the BatPaC model version 3.1[70] as a function of the 2 EV types (BEVs or PHEVs), the 3 EV market segments (small, mid-size, and large cars), and the 8 battery chemistries (LFP, NCA, NCM11, NCM523, NCM622, NCM622-Graphite (Si), NCM811-Graphite (Si), NCM955-Graphite (Si)), which yields 48 unique battery chemistries. The input parameters include the EV range, fuel economy, and motor power, which determine the required capacity of each EV type and market segment (Supplementary Table 2.2 and Supplementary Table 2.3), and battery chemistry and other parameters (like the design of battery modules and cell components) for which we use the default values in the BatPaC model. To calculate the material compositions of battery chemistries that do not exist in BatPaC (*i.e.*, NCM523, NCM622-Graphite (Si), NCM811-Graphite (Si), NCM955-Graphite (Si)), we use the closest matching battery chemistry in BatPaC as a basis and then adapt technical parameters, such as Ni, Co, Mn contents in the positive active material and Si and graphite contents in the negative active material, by stoichiometry, as well as active material capacities and open circuit voltage (see Supplementary Table 2.7 and Supplementary Note 2.1). For Li-S and Li-Air chemistries, we performed a literature review on the specific energy and material compositions of Li-S and Li-Air cells (Supplementary Table 2.8 and Supplementary Table 2.9), and then scale these linearly to meet required battery capacities for each EV type and market segment. The pack components of Li-S and Li-Air are assumed to be based on the pack configurations of NCA chemistry (*i.e.*, the same weight ratio between cell components and pack components). Supplementary Table 2.10 shows the material compositions used in this paper.

Recycling scenarios. Recycling of EoL batteries provides a secondary supply of materials. Here we assume 100% collection rates and explore the effects of recycling efficiencies of three recycling scenarios (see Supplementary Table 2.11) on primary material demand, including recovered quantities and some discussion of recycled material qualities. The primary material demand when there is no collection and recycling of EoL batteries is captured by the "without recycling" scenario (Fig. 2.4). Currently commercialized recycling technologies include pyrometallurgical (pyro) and hydrometallurgical (hydro) recycling. Direct recycling is under development for cathode-to-cathode recycling. For NCX and LFP batteries, pyro, hydro, and direct recycling are assumed in the three recycling scenarios, respectively, while mechanical recycling is assumed for Li-S and Li-Air batteries in all three scenarios. Recycling technologies differ in recycled materials, chemical forms, recovery efficiencies, and economic prospects[17,94,95] (Fig. 2.5).

The pyrometallurgical recycling scenario we consider is in fact a hybrid pyro and hydro process. After feeding disassembled battery modules and/or cells to the smelter, graphite is burnt off, aluminum and lithium end up in the slag, and nickel, cobalt, and copper end up in a matte. After leaching of the matte, copper ion is recovered as copper metal through electrowinning, while the nickel and cobalt ions are recovered as battery-grade nickel and cobalt compounds through solvent extraction or precipitation. The lithium in the slag can be refined to produce battery-grade lithium compounds, but it is only economical when lithium price is high and recycling at scale. Technically, aluminum in the slag can also be recovered, but it is not economical and not considered by pyro recycling companies (the slag may be used, *e.g.*, as aggregate in construction material).

The hydrometallurgical recycling scenario starts with shredding disassembled modules and/or cells. The shred then goes through a series of physical separation steps to sort the materials into cathode powder, anode powder, and mixed aluminum and copper scraps. Depending on the scrap metal prices, the mixed aluminum and copper scraps may be further sorted into aluminum scraps and copper scraps. The copper scraps can be incorporated back into the battery supply chain with minimal processing (*i.e.*, remelting). The closed-loop recycling of aluminum is more challenging as the recovered aluminum scraps are a mixture of different aluminum alloys (*e.g.*, from current collector and casing) and Al is, therefore, typically downcycled. Closed-loop recycling of aluminum would require separating the aluminum alloy before or during the recycling process, which may or may not be economical[96]. The cathode powder is subsequently leached with acid, where nickel, cobalt, and manganese leach out as ions, and recovered as battery-grade compounds after solvent extraction and precipitation. Lithium ends up in solid waste which can also be used as construction materials. Similar to pyro recycling, lithium in the solid waste can be recovered as battery-grade compounds, but the economic viability depends on the lithium price. The anode powder recovered through hydro, which can be a blend of graphite and silicon, is not battery-grade. Although they can be refined to battery-grade, at present the economic viability is unclear.

The direct recycling scenario is the same as hydro except for cathode powder recycling.

In the direct process, the cathode powder is recovered and then regenerated by reacting with a lithium source (re-lithiation and upgrading). Lithium, nickel, cobalt, and manganese are therefore recovered as one battery-grade compound. Since lithium refining is not needed here as with pyro and hydro, lithium recovery in direct process is economical at least from a lab-scale perspective.

The material recovery efficiencies for pyro, hydro, and direct are taken from the EverBatt[94] model developed at Argonne National Laboratory (Supplementary Table 2.11). As for mechanical recycling of Li-S and Li-Air batteries, we assume that only metallic lithium is recovered from the process. The material recovery efficiency of metallic lithium is assumed to be 90%, and the recovery is considered economical due to the relatively simple process and high value of recovered lithium metal.

Second-use/use scenarios. EoL EV batteries may experience a second-use for less demanding applications (non-automotive), such as stationary energy storage, as they often have remaining capacities of around 70-80% of their original capacity[97,98]. Technical barriers exist (*e.g.*, the performance of repurposed batteries) and economic uncertainty (the cost of repurposing including disassembly, testing, and repackaging) that depend on the battery chemistry, state-of-health, and the intended second-use application[98-100]. Here we distinguish the second-use rates of LFP and other chemistries due to the long cycle life[101] and the reduced chance of cascading failure of LFP[102]. LFP batteries are assumed to have a 100% second-use rate. For the rest of the battery chemistries, we assume a 50% second-use rate before 2020, rising to 75% during 2020-2050 because of improved technical lifespan of EV batteries (Supplementary Table 2.12). The second-use applications vary from home use to electricity system integration, resulting in the second-use lifespan varying from 6 to 30 years[103]. We assume a typical 10-year second-use lifespan[98] to explore the effects of second-use on the availability of materials for recycling. Note here the second-use assumes 100% reuse of battery modules, while pack components enter recycling directly.

Sensitivity analysis. The effect of important factors such as EV fleet size and battery chemistry are investigated in dedicated scenarios. In addition, we perform sensitivity analysis for a) battery lifespan, b) required battery capacity per vehicle, c) the market penetration of Co- and Ni-free battery chemistries, and d) the future specific energies of Li-S and Li-Air chemistries (for which conservative numbers were assumed).

(a) Battery lifespan has an important effect on the number of batteries required for EVs. We perform a sensitivity analysis of the effect of lower battery lifespans on battery material demand by assuming that also after 2020 one EV needs 1.5 batteries on average (results in Supplementary Fig. 2.9).

(b) Future market shares of BEVs and PHEVs and EV battery capacity are also key for determining the quantity of required materials. While battery capacity is driven by many factors like EV range, fuel economy, and powertrain configurations, we perform a sensitivity analysis on two extreme situations, 100% BEV with 110 kWh capacity (large SUVs such as Tesla Model S Long Range Plus[104], see Supplementary Table 2.13 for material compositions) and 100% PHEV with 10 kWh capacity, to explore the bounds of future material demand (see Supplementary Table 2.14 for material compositions, and annual results in Supplementary Fig. 2.10).

(c) Similarly, we also explore the effects of 100% market share of LFP in the LFP scenario and 100% market share of Li-S and Li-Air in the Li-S/Air scenario (see Supplementary Fig. 2.11 and associated material requirements in Supplementary Fig. 2.12 and Supplementary Fig. 2.13 respectively).

(d) The improvement of material performance of battery chemistry, especially specific energy (stored energy per weight), may reduce material demand dramatically. Here we chose Li-S and Li-Air chemistries in the Li-S/Air scenario to perform a sensitivity analysis of the potential specific energy improvement from 400 Wh/kg to 600 Wh/kg for Li-S and from 500 Wh/kg to 1000 Wh/kg for Li-Air (values based on review of industrial and lab-scale achievements, see Supplementary Table 2.10 for material compositions and associated material requirements in Supplementary Fig. 2.14).

2.3 Results

2.3.1 EV fleet growth

Fig. 2.1 shows the projected EV fleet development. We base our scenarios on two scenarios of the International Energy Agency (IEA) until 2030: the Stated Policies (STEP) scenario, which incorporates existing government policies and the Sustainable Development (SD) scenario, which is compatible with the climate goals of the Paris agreement and includes also the target of reaching a 30% global sales share for EVs by 2030[63]. According to these scenarios, EVs will make up 8-14% of the total light duty vehicle fleet by 2030, of which 89-166 million are battery electric vehicles (BEVs) and 46-71 million are plug-in hybrid electric vehicles (PHEVs)[71]. We extend these scenarios until 2050 assuming logistic growth curves where the global fleet penetration of EVs in 2050 will be 25% in the STEP scenario and 50% in the SD scenario. This is in line with other projections, see Supplementary Fig. 2.3. In the STEP scenario, the EV stock will increase by a factor of 72 from 2020-2050 to nearly 1 billion vehicles and annual EV sales will rise to 109 million vehicles (Supplementary Fig. 2.15). In the SD scenario, the EV stock will increase by a factor of 102 from 2020-2050 to 2 billion vehicles and annual EV sales will rise to 211 million vehicles (Supplementary Fig. 2.15).

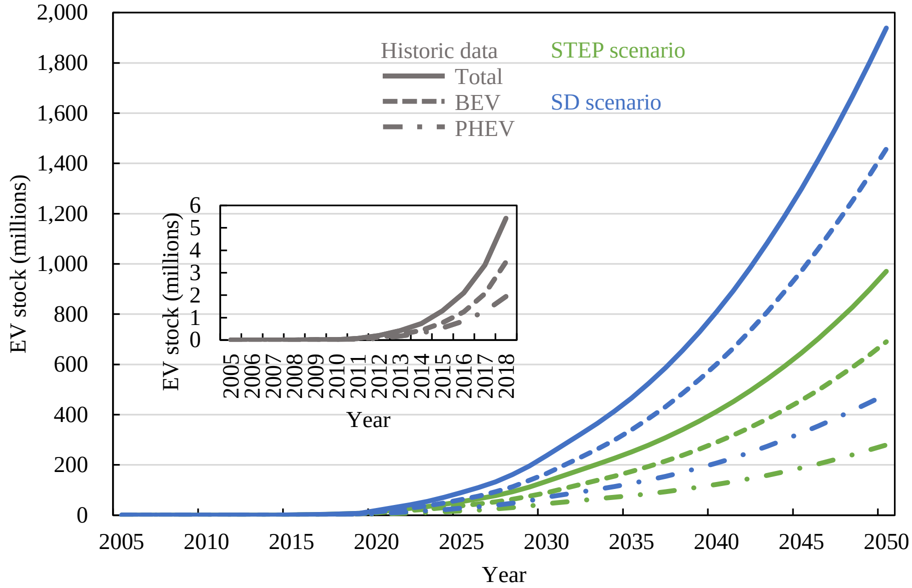


Fig. 2.1: Global EV stock development projected until 2050. BEV = battery electric vehicle. PHEV = plug-in hybrid electric vehicle. STEP scenario = the Stated Policies scenario. SD scenario = Sustainable Development scenario.

2.3.2 Battery capacity and market shares

Fig. 2.2 shows that in the STEP scenario approximately 6 TWh of battery capacity will be required annually by 2050 (and 12 TWh in the SD scenario, see Supplementary Fig. 2.16). The required future battery capacity depends on the development of the EV fleet as well as the required battery capacity per vehicle (we assume 66 kWh and 12 kWh as average capacity for BEVs and PHEVs, respectively, see Supplementary Table 2.2 and Supplementary Table 2.3 for details) and the battery lifespans (see Supplementary Table 2.6 and Supplementary Fig. 2.2). The material requirements depend on the choice of battery chemistries used. Three battery chemistry scenarios are considered (see Fig. 2.2 and detailed description in methods).

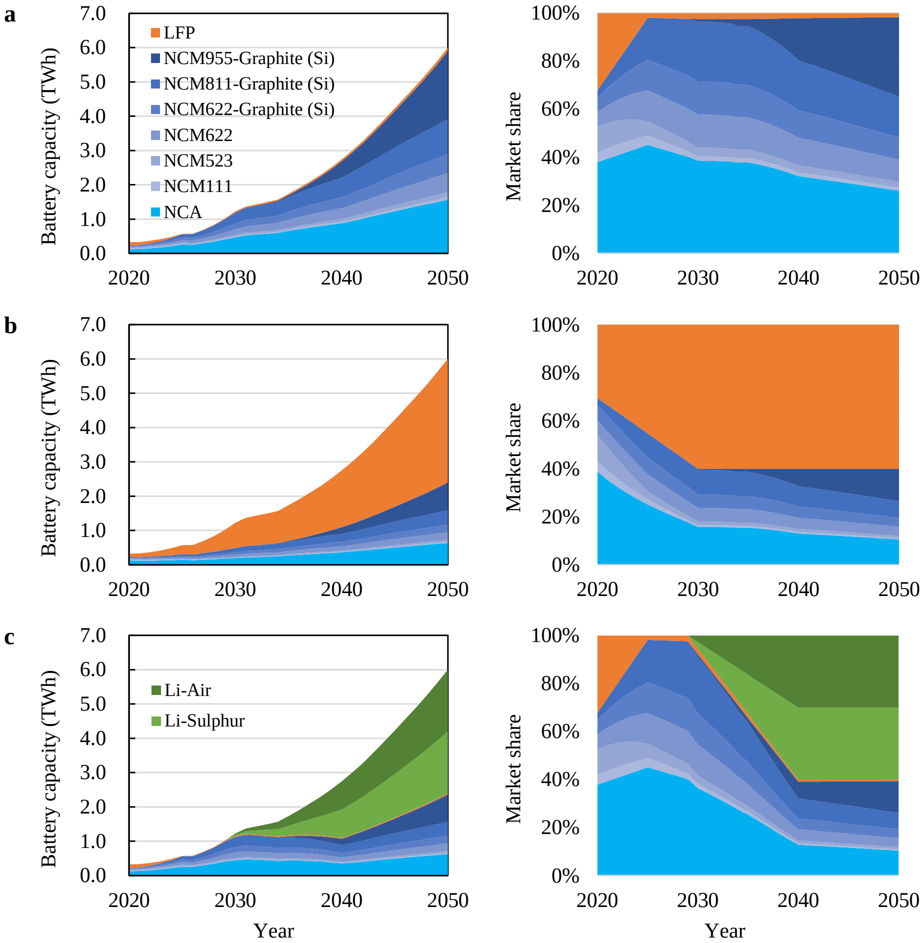


Fig. 2.2: Battery market shares and yearly EV battery sales until 2050 for the fleet development of the STEP scenario. a NCX scenario. **b** LFP scenario. **c** Li-S/Air scenario. See Supplementary Fig. 2.16 for the Sustainable Development scenario. See Supplementary Fig. 2.17 for battery sales in units.

The most likely NCX scenario follows the current trend of widespread use of lithium nickel cobalt aluminum (NCA) and lithium nickel cobalt manganese (NCM) batteries (henceforth called the NCX scenario with X representing either Al or Mn)[85]. Battery producers are seeking to replace costly cobalt with nickel, which has led to an evolution from NCM111 to NCM523, NCM622, and NCM811 batteries (numbers denote ratios of nickel, cobalt, and manganese)[85] and NCM955 (90% nickel, 5% cobalt, 5% manganese) are expected to be available by 2030[86]. Specific energies at the pack level assumed here range from 160 Wh/kg for NCM111 to 202 Wh/kg for NCM955-Graphite (Si) battery for typical mid-size BEVs (Supplementary Table 2.15), and lifespans are assumed to increase to an average of 15 years to match vehicle lifespans (Supplementary Fig. 2.2)[105].

The LFP scenario considers the possibility that LFP ($LiFePO_4$) batteries will be increasingly used for EVs in the future. The principle drawback of LFPs is their lower specific energy compared to NCA and NCM chemistries, which negatively impacts fuel economy and range of EVs. Advantages of LFPs are lower production costs due to the abundance of precursor materials, safety due to better thermal stability, and longer cycle life[101]. While LFP batteries have seen their main application in commercial vehicles, such as buses, there are prospects of a more widespread use of LFPs in light-duty EVs (*e.g.*, Tesla has recently announced to equip the Chinese version of its Model 3 with LFP batteries[87]). In this scenario, we assume that LFP batteries (with a specific energy of 129 Wh/kg at pack level for typical mid-size BEVs and on average lifespan of 20 years[106]) will have a market share of 60% from 2030-2050, while the rest of the market follows the trends in the NCX scenario.

In the Li-S/Air scenario, we consider the possibility of breakthroughs in Li-metal solid-state battery chemistries, specifically, Li-S and Li-Air batteries, which are seen as potential successors of LIBs[89,107]. Although Li-S and Li-Air batteries are still in early development and considerable challenges remain to be solved before commercialization, *e.g.*, low cycle life and safety issues[62,64], Li-S batteries could reach 2 times and Li-Air batteries up to 3 times the specific energy of current LIBs, which would likely lead to cost reductions and improved EV ranges[89]. Although it is highly uncertain if and when such batteries could reach market readiness, we assume that Li-S and Li-Air batteries (with specific energies of 308 and 383 Wh/kg, respectively, at pack level for typical mid-size BEVs and lifespans equal to NCM batteries) enter the market in

2030[81] and reach a market share of 60% by 2040, while the rest of the market follows the trends in the NCX scenario.

2.3.3 Battery material demand

Fig. 2.3a shows the global demand for Li, Co, and Ni for EV batteries (Mn, Al, Cu, graphite, and Si are shown in Supplementary Fig. 2.18a). It can be observed that higher EV deployments in the SD scenario lead to 1.7-2 times higher annual material demand than in the STEP scenario. The demand for Li is only slightly influenced by the battery chemistry scenario (although the Li-S/Air scenario requires slightly more Li due to the Li-metal anodes in Li-S and Li-Air batteries). The demand for Ni and Co is strongly influenced by the battery chemistry scenario and substantially smaller in the LFP and Li-S/Air scenarios due to the lower market shares of NCX batteries. From 2020 to 2050 in the more conservative STEP scenario, Li demand would rise by a factor of 17-21 (from 0.036 Mt to 0.62-0.77 Mt), Co by a factor of 7-17 (from 0.035 Mt to 0.25-0.62 Mt), and Ni demand by a factor of 11-28 (from 0.13 Mt to 1.5-3.7 Mt) (Supplementary Fig. 2.19, Supplementary Fig. 2.20, and Supplementary Fig. 2.21). Note that the demand increase for Co is smaller than for Ni due to the assumed partial replacement of Co by Ni in future NCM batteries. Mn and Si follow the same trend as Ni and Co in the three battery scenarios as they are also not used in LFP, Li-S, and Li-Air batteries. The demand for Al, Cu, and graphite in the LFP scenario is slightly higher than in the NCX scenario due to specific energy differences, and lower in the Li-S/ Air scenario, since Li-S and Li-Air batteries use less Al and Cu on a per kWh basis and typically do not contain graphite.

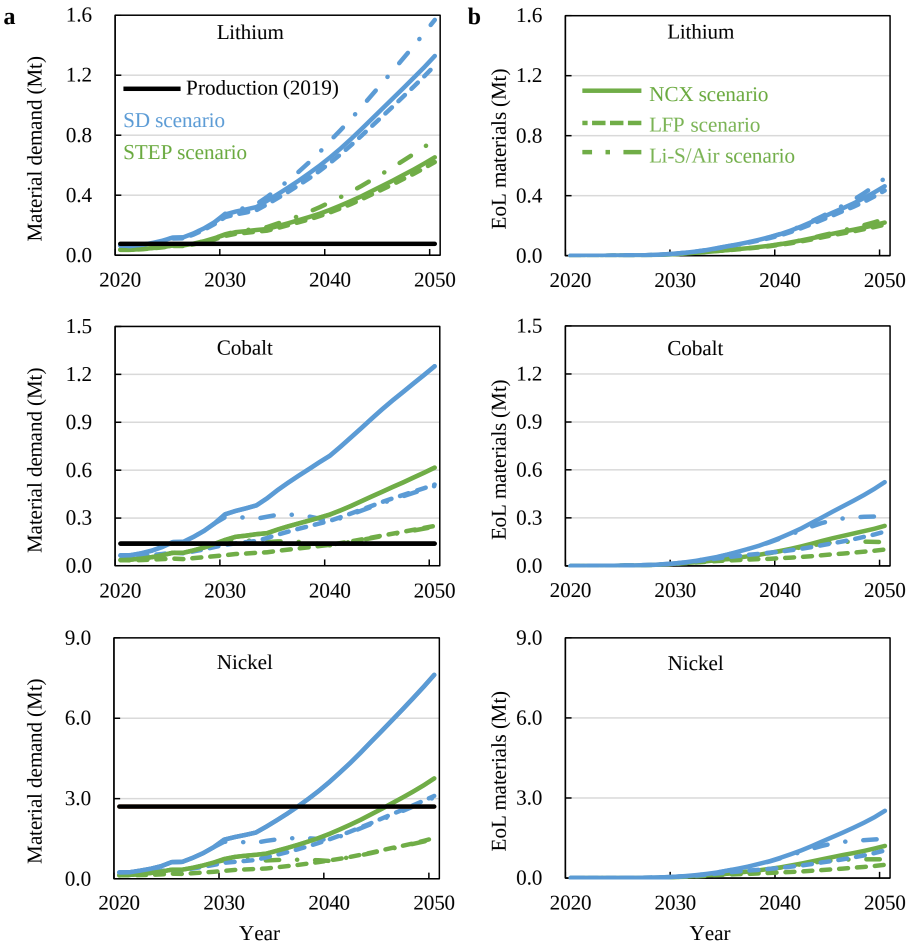


Fig. 2.3: Battery material flows from 2020 to 2050 for lithium, nickel, and cobalt in the NCX, LFP and Li-S/Air battery scenarios. a Primary material demand. **b** materials in end-of-life batteries. STEP scenario = the Stated Policies scenario. SD scenario = Sustainable Development scenario. See Supplementary Fig. 2.18 for other materials. Mt = million tons.

Fig. 2.4 shows the cumulative demand from 2020-2050. It ranges from 7.3-18.3 Mt for Li, 3.5-16.8 Mt for Co, and 18.1-88.9 Mt for Ni across fleet and battery chemistry scenarios (numbers for all materials are reported in Supplementary Table 2.16). The cumulative demand is twice as high in the SD scenario, and 2-2.5 times higher for Ni and Co in the NCX compared to the LFP and Li-S/Air scenarios. Consequently, there is a factor of 4-5 between the cumulative Ni and Co demands in the SD-NCX and the

STEP-LFP or STEP-Li-S/Air scenarios.

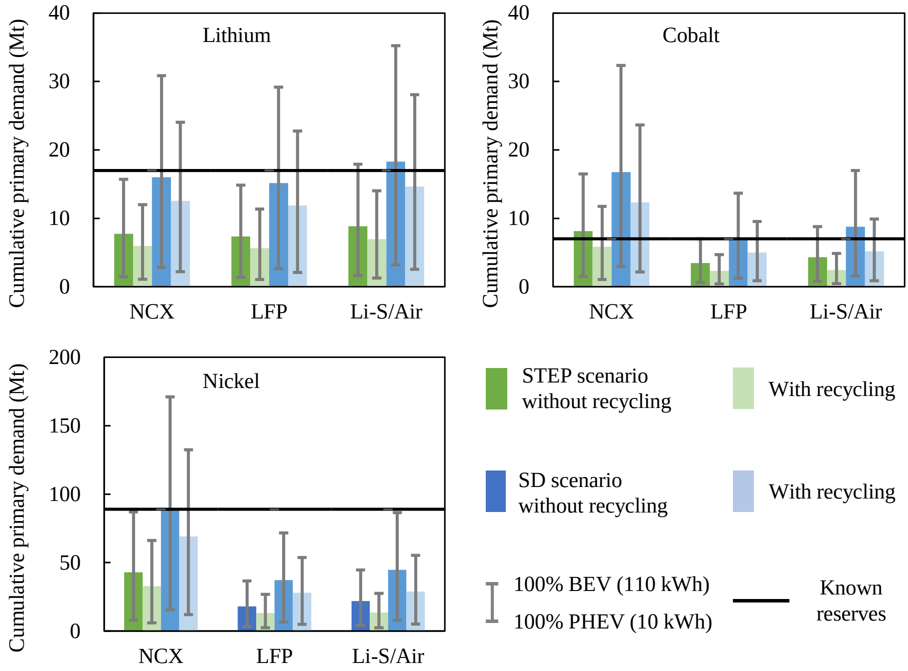


Fig. 2.4: Cumulative primary material demand in 2020-2050 without recycling and with hydrometallurgical recycling. STEP scenario = the Stated Policies scenario. SD scenario = Sustainable Development scenario. Grey error bars represent a sensitivity analysis for battery capacity considering two extreme cases (if all EVs were PHEVs with small 10 kWh batteries or if all EVs were large SUVs with 110 kWh batteries, *e.g.*, Tesla's Model S Long Range Plus[104], see annual results in Supplementary Fig. 2.10). The black line represents known reserves[108]. See Supplementary Fig. 2.22 for other materials.

2.3.4 Recycling potentials

Fig. 2.3b shows the materials contained in end-of-life (EoL) batteries over time (0.21-0.52 Mt of Li, 0.10-0.52Mt of Co, and 0.49-2.52Mt of Ni in 9-27 Mt EoL batteries, see Supplementary Fig. 2.23 for EoL battery weight, and Supplementary Fig. 2.24 and Supplementary Fig. 2.25 for other materials in EoL batteries). The recovery of these materials could help to reduce primary material production[33,109]. Current commercial recycling technologies for EV batteries include pyrometallurgical and hydrometallurgical processing[110]. Pyrometallurgical recycling involves smelting entire batteries or, after pretreatment, battery components. Hydrometallurgical processing involves acid leaching and subsequent recovery of battery materials, *e.g.*, through solvent extraction and precipitation. In closed-loop recycling, pyrometallurgical processing is followed by hydrometallurgical processing to convert the alloy into metal salts, as illustrated in Fig. 2.5. Direct recycling aims at recovering cathode materials while maintaining their chemical structures, which could be economically and environmentally advantageous[49], however, it is currently still in early development stages[17]. In order to quantify recycling potentials, we consider three potential recycling scenarios: pyrometallurgical, hydrometallurgical, and direct recycling for NCX and LFP batteries as well as mechanical recycling for Li-S and Li-Air batteries. They differ in recovered materials and associated chemical forms (see methods and summary in Fig. 2.5).

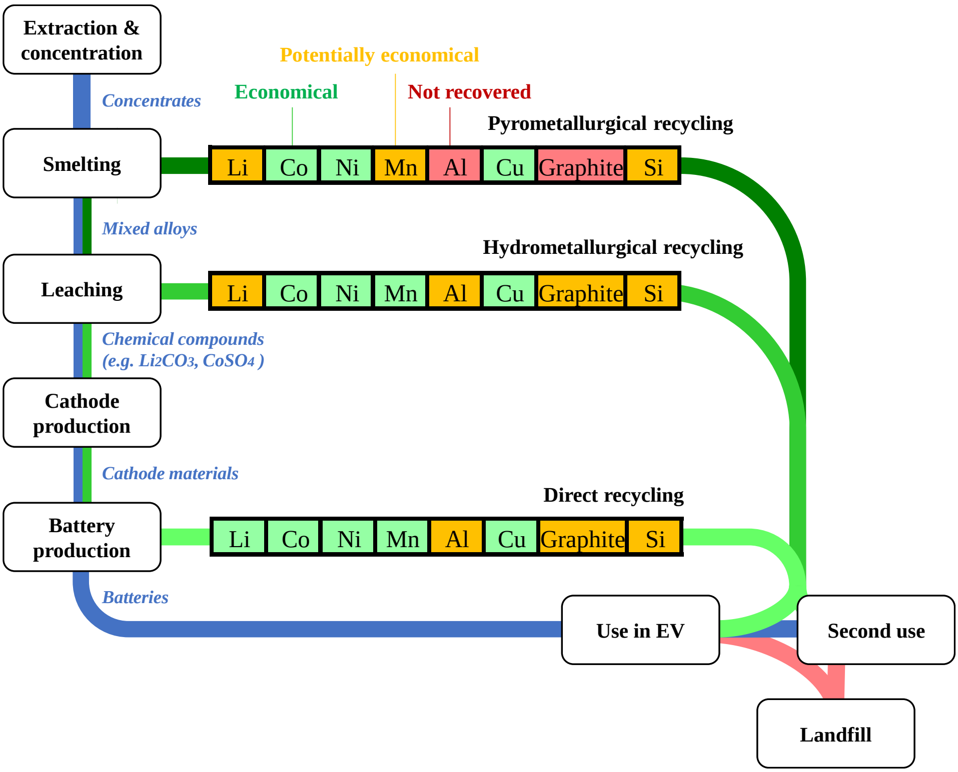


Fig. 2.5: Conceptual schematic showing how the three considered recycling scenarios close battery material loops and which materials are recovered. In reality not all materials go through all processing steps. For example, pyrometallurgical recycling (smelting) still requires hydrometallurgical

processing (leaching) before cathode materials can be produced, while direct recycling is designed to recover cathode materials directly. In pyro- and hydrometallurgical recycling the recovery of Li may not be economical and in pyrometallurgical recycling graphite is incinerated and Al not recovered from the slag (see also methods).

We also consider the potential second-use of EoL EV batteries. The exact second-use application, the battery state-of-health, battery chemistry, and other factors determine, if and for how long second-use is possible. For the sake of simplicity and to illustrate the effect of second-use, we assume that 50% of NCX, Li-S and Li-Air batteries before 2020 (increasing to 75% after 2020), and 100% of LFP batteries, due to their higher cycle life, experience a 10-year second-use in stationary energy storage, which is likely to be economically and environmentally beneficial[111], before finally entering recycling (Supplementary Table 2.12)

Fig. 2.4 shows the cumulative battery material demand from 2020-2050 for both fleet scenarios without recycling (representing the maximum primary material demand), and with hydrometallurgical recycling of NCX and LFP batteries and mechanical recycling of Li-S and Li-Air batteries without second-use (representing the minimum primary material demand) (Supplementary Fig. 2.26 shows the development over time for all materials). Considering additional material losses, *e.g.*, during collection and recycling, or material recovery delays due to second-use, would yield figures in between these bounds. This shows that battery recycling has, at best, the potential to reduce 20-23% of the cumulative material demand for Li until 2050 (8% for Li metal), 26-44% for Co, and 22-38% for Ni (see Supplementary Table 2.17 for other materials). The most important reason for this is the fast growth of the EV market and the time lag between the need for materials and the availability of EoL material. It should be noted that in a steady-state system, *i.e.*, once the battery stock of a saturated EV market has been built up, secondary material shares could, theoretically, be as high as recycling efficiencies, *i.e.*, above 90%. Supplementary Table 2.18 shows the increasing potential of recycling to mitigate primary material demand over time.

Fig. 2.6 shows the temporal evolution of the closed-loop recycling potential (CLRP), *i.e.*, the percentage of battery material demand that can be met with secondary material from battery recycling, for the next three decades. While the CLRP is small for the current decade (below 10%) it may reach as much as 20-71% during 2040-2050. The CLRP for Co and Ni are higher in the LFP and Li-S/Air scenarios, since LFP, Li-S, and Li-

Air battery chemistries do not require these materials and the total quantity of required materials for NCX batteries is growing much slower or even stagnating for some time (see Fig. 2.3). Note that CLRP of Li and Ni does not exceed 31% in the NCX and LFP scenario due to the continued growth of NCX chemistries, while it surpasses 50% in the Li-S/Air scenario (71% for Co) in 2040-2050 due to the higher stock of NCX batteries built up until 2030 when Li-S/Air chemistries are introduced (see Fig. 2.2). In the Li-S/Air scenario, lithium compounds (*e.g.*, Li_2CO_3 or LiOH) used for cathode production of LIBs need to be distinguished from lithium metal used for Li-S and Li-Air battery anodes (see demand for each in Supplementary Fig. 2.14), since existing recycling technologies recover lithium as compounds, and further processing of these compounds would be necessary to produce lithium metal. Although this is technically feasible, it is unlikely to be cost-competitive with primary lithium metal production from brine, which does not require the intermediate compounds production step and may work with lower-purity feedstock[112]. In the Li-S/Air scenario, the CLRP of lithium compounds surpasses 50% from 2040-2050. On the other hand, the CLRP for Li metal barely reaches 10% during 2040-2050 due to the fast growth of the Li-S and Li-Air batteries and the small historical stock (see also Supplementary Table 2.18).

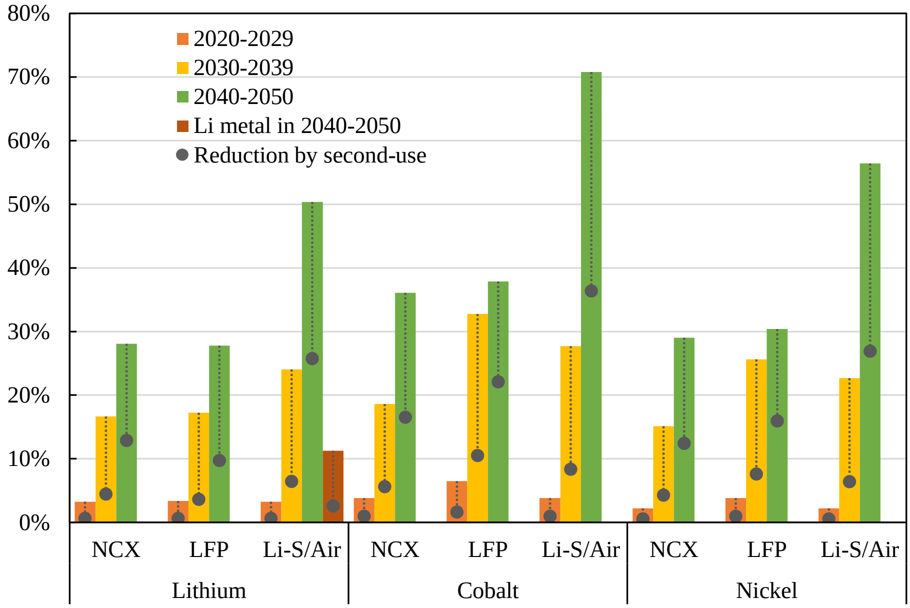


Fig. 2.6: Closed-loop recycling potential of battery materials in periods of 2020-2029, 2030-2039, 2040-2050 in the STEP scenario. Hydrometallurgical recycling is used for NCX and LFP batteries and mechanical recovery of Li-metal for Li-S and Li-Air batteries. Grey dot displays the reduction of closed-loop recycling potential as second-use delays the availability of end-of-life materials. See Supplementary Table 2.18 for other materials.

If a significant share of batteries experiences a second-use, the recovery of that material will be delayed in time and thus the CLRP will be substantially lower for the decades to come (shown by the dashed lines in Fig. 2.6). The CLRP of other materials follow similar patterns (see Supplementary Table 2.18).

2.4 Discussion

Given the magnitude of the battery material demand growth across all scenarios, global production capacity for Li, Co, and Ni (black lines in Fig. 2.3) will have to increase drastically (see Supplementary Table 2.19 and Supplementary Table 2.20). For Li and Co, demand could outgrow current production capacities even before 2025. For Ni, the situation appears to be less dramatic, although by 2040 EV batteries alone could consume as much as the global primary Ni production in 2019. Other battery materials could be supplied without exceeding existing production capacities (Supplementary

Table 2.20), although supplies may still have to increase to meet demands from other sectors[36,65]. The known reserves for Li, Ni, and Co (black lines in Fig. 2.4) could be depleted before 2050 in the SD scenario and for Co also in the STEP scenario. For all other materials known reserves exceed demand from EV batteries until 2050 (Supplementary Table 2.16). In 2019 around 64% of natural graphite and 64% of Si are produced in China[108], which could create vulnerabilities to supply reliability[113]. However, synthetic graphite has begun to dominate the LIB graphite anode market (56% market share in 2018) due to its superior performance and decreasing cost over natural graphite[85]. Thus, among EV battery materials Co and Li, and to a lesser extent Ni and graphite, can be considered to be most critical concerning the up-scaling of production capacities (see Supplementary Table 2.19), reserves and other supply risks, which confirms previous findings[30,36,65,113,114] even without taking into consideration the potential additional demand from heavy-duty vehicles[34] and other sectors[35]. In contrast to Li and Ni, Co reserves are also geographically more concentrated and partly in conflict areas[115], thus increasing potential supply risks[65]. Battery manufacturers are already seeking to decrease their reliance on cobalt, *e.g.*, by lowering the Co content of NCM batteries, however, as shown in Fig. 2.3, absolute decoupling is unlikely to occur in the coming decades. Shortages could also occur at a regional level, such as the access to Li and Ni for Europe[30]. Obviously, it is possible that the outlined supply risks change, *e.g.*, with the discovery of new reserves[116].

According to our model, lithium demand for EV batteries in 2050 (0.6-1.5 Mt) could be significantly lower than projected by Weil et al.[36] (1.1-1.7 Mt) and likely higher than projected by Hao et al.[34] (0.65 Mt), Deetman et al.[35] (0.05-0.8 Mt), and Ziemann et al.[33] (0.37-1.43 Mt). For cobalt, our estimations (0.25-1.25 Mt) are in line with the predictions by Weil et al.[36] (0.3-1.1 Mt) despite important differences in underlying scenarios and likely considerably higher than Deetman et al.[35] (0.06-0.62 Mt). For nickel our estimations (1.5-7.6 Mt) partly overlap but are generally higher than those by Weil et al.[36] (0.6-2.6). There are thus notable uncertainties concerning the primary material demand for EV materials related to several key factors that could be strategically addressed to mitigate supply risks. Probably the most important factor is the future required battery capacity. A sensitivity analysis is shown in Fig. 2.4 for two extreme battery capacity cases, *i.e.*, if all EVs were PHEVs with small 10 kWh batteries or if all EVs were large SUVs with 110 kWh batteries, such as Tesla Model S Long Range Plus[104].

While it is unlikely that the global average EV battery capacity will be close to either end of this range, this analysis illustrates the high importance of this factor. The demand for battery capacity depends on technical factors, such as vehicle design, vehicle weight, and fuel efficiency[117], and perhaps even more importantly, on socio-economic factors, such as the future EV fleet size (see also Fig. 2.4), consumer choices concerning the size and ranges of EVs, the cost of EV batteries and raw materials, the development of alternative transportation means and technologies (*e.g.*, fuel cell EVs[118]), and policy.

Opportunities lie in the development of battery technology. As shown here, Li-S and Li-Air batteries would reduce the dependency on Co, and Ni, while offering higher energy densities. Our analysis assumes conservative, *i.e.*, technically proven values, but if higher specific energies were to be achieved, *e.g.*, 600 instead of 400 Wh/kg for Li-S and 1000 instead of 500 Wh/kg for Li-Air (Supplementary Table 2.10 and Supplementary Table 2.21), the cumulative lithium demand in the Li-S/Air scenario could be reduced by 20% and the Li-metal demand by 40% (Supplementary Fig. 2.14). High market shares of Li-S/Air or LFP batteries or breakthroughs in post-Li batteries based on abundant elements such as sodium, magnesium, or calcium[64] could lead to an absolute decoupling from lithium, cobalt, and nickel (see Supplementary Fig. 2.11, Supplementary Fig. 2.12, and Supplementary Fig. 2.13).

It is also uncertain whether the lifespans assumed here will be reached in practice, especially for Li-S and Li-Air batteries[62]. Lower battery lifespans could require additional battery replacements and thus lead to considerably higher material demand (Supplementary Fig. 2.9 and Supplementary Table 2.22). On the other hand, batteries in a state-of-health that would typically be considered to mark their EoL (*i.e.*, 70-80%) may still be used by consumers who prefer to accept a shorter range over the expense of a battery replacement[34] (EVs with 80% residual battery capacity could still meet daily travel requirements in 85% of cases in the US[119] and widespread charging infrastructure could further support this[120]).

Truly circular EV batteries will not be available anytime soon. Over the next decades, we first need to produce the EV battery stock for a large fleet, mostly from primary materials. Closed-loop recycling will gain importance, depending on EV fleet and battery chemistry developments, second-use, and other factors, such as standardization[121], legislation, business models[122], eco-design or design for recycling[123], collection systems, and recycling technology[17,109]. The difference between the recycling technologies is not so much in the recycling efficiency for individual materials, but whether materials are recovered and in what chemical form and purity[17,36]. All recovered battery materials can, in principle, be refined to battery-grade. For example, in the pyrometallurgical process, lithium ends up in the slag, while in the hydrometallurgical process, lithium ends up in the solid waste from the leaching step. Both slag and solid waste could be refined to produce battery-grade lithium carbonate, however, lithium has hardly been recovered so far as the lithium price did not enable a cost-effective recovery[36,124]. The most economically and environmentally promising technology for closed-loop recycling, although currently largely unproven outside of the lab, is direct recycling, which could recover cathode material "as is" without intermediate smelting or leaching step (Fig. 2.5). Challenges for direct recycling include the development of sorting processes that can separate cathode powder from different battery chemistries, re-lithiation and upgrading processes for cathode chemistries that have become obsolete and further standardization of batteries to support effective recycling[95].

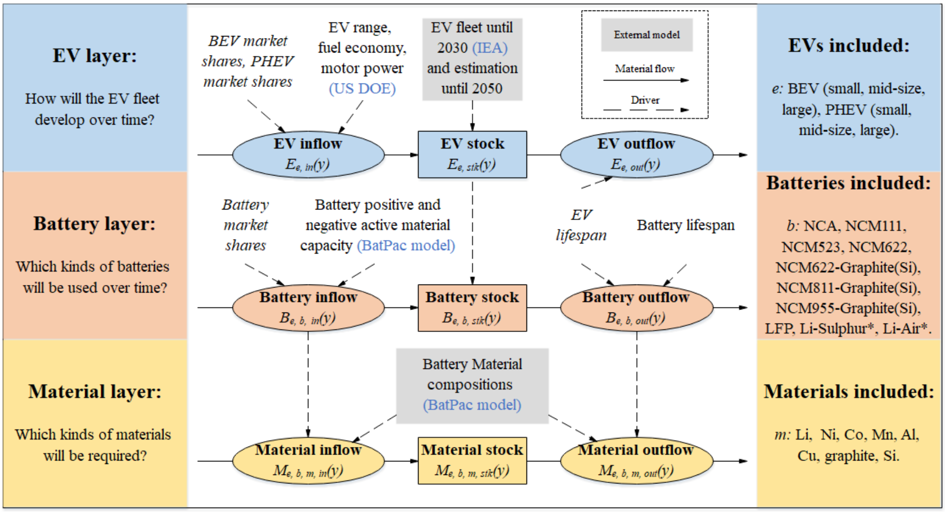
The success of the transition to electric vehicles will depend partly on whether the material supply can keep up with the growth of the sector in a sustainable way and without damaging the reputation of EVs. Science-based sustainability assessments should guide the selection of alternative battery chemistries and raw materials to avoid unfavorable burden-shifts. The global demand scenarios presented here also provide a basis to assess the global economic, environmental, and social impacts related to EVs and batteries from a lifecycle perspective.

2.5 Data availability

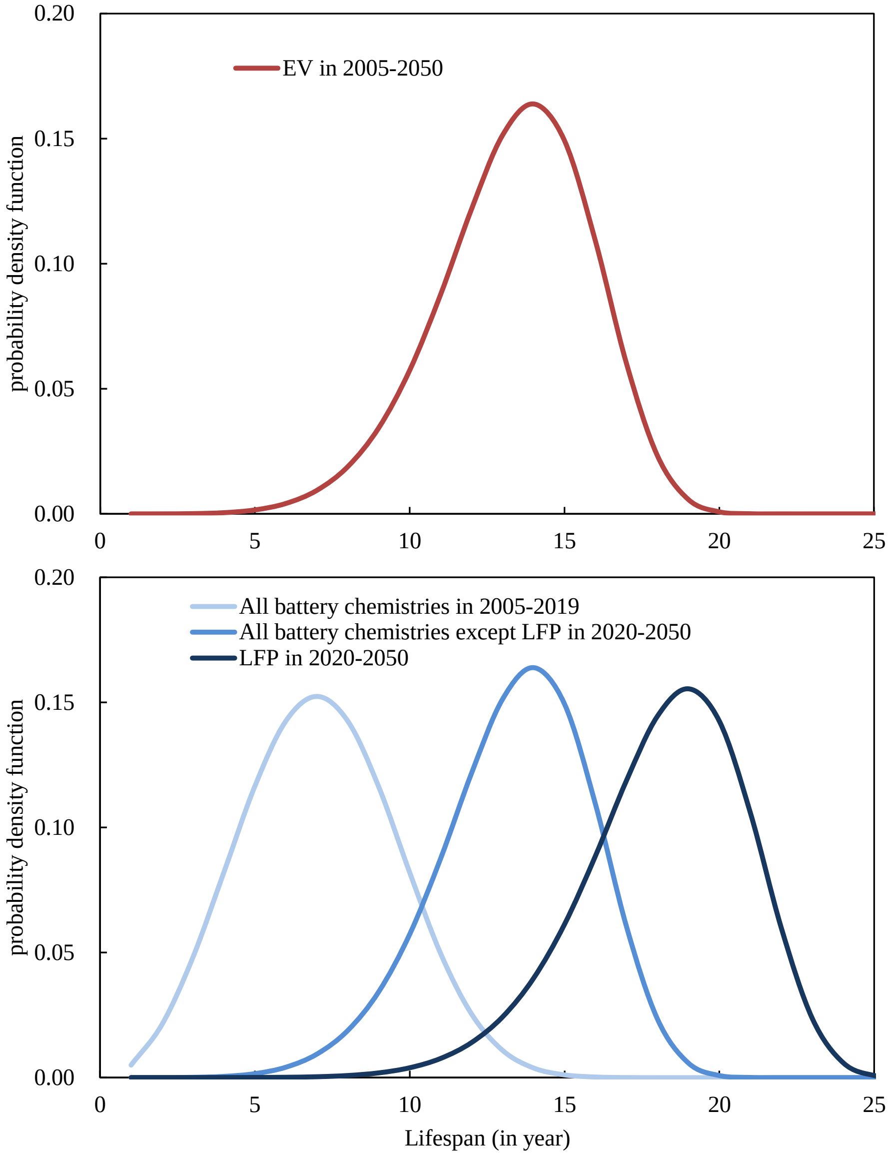
The authors declare that the data used as model inputs supporting the findings of this study are available within the paper and its Supplementary Information files. Data and model are also provided as Excel files to facilitate further research (10.6084/m9.figshare.13042001).

2.6 Supplementary information

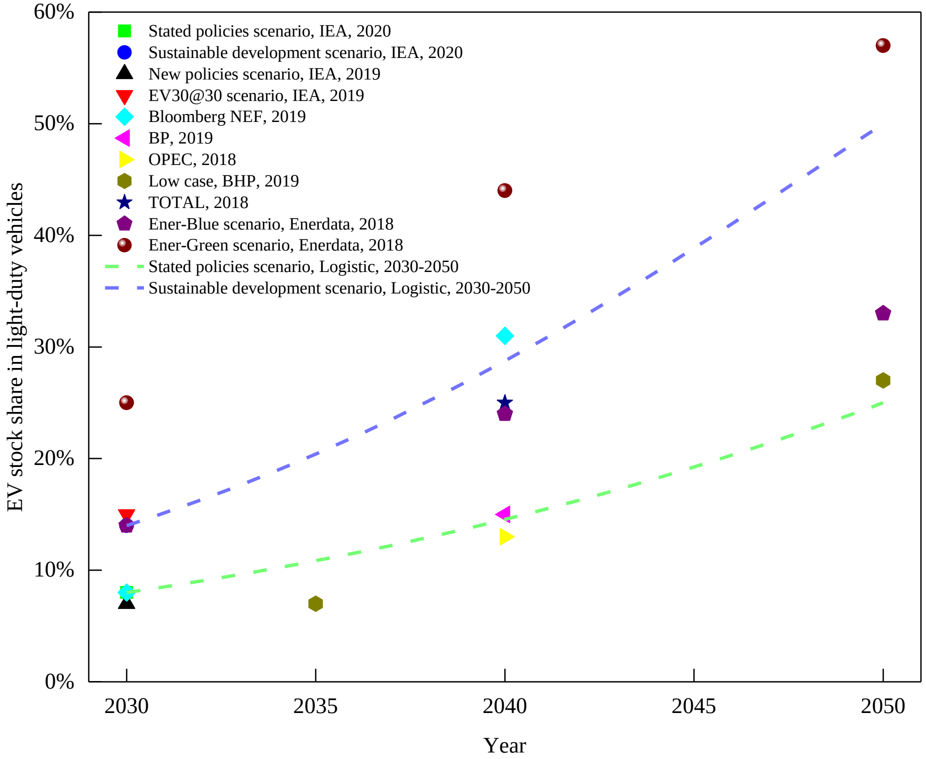
2.6.1 Supplementary Figures



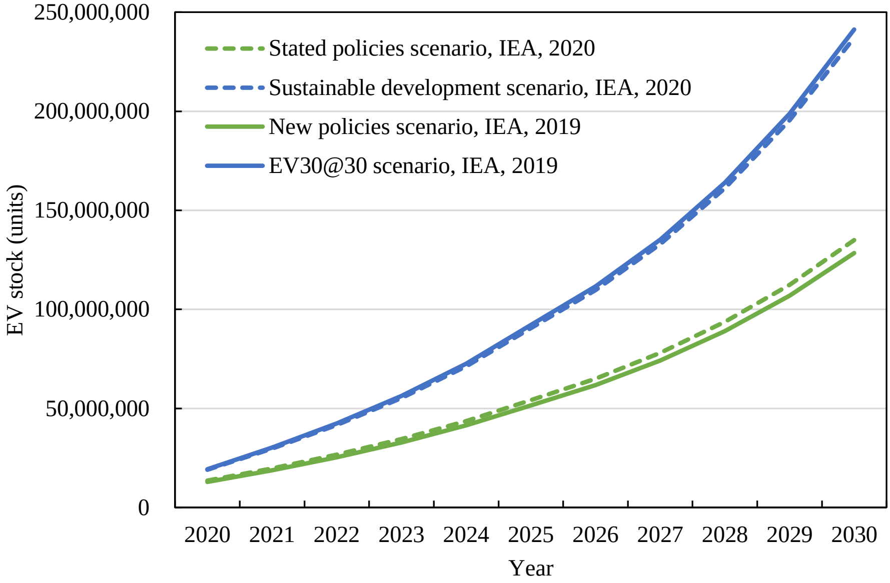
Supplementary Fig. 2.1: Stock dynamics model on the EV, battery, and material layers: research questions (left), model structure (middle), and included categories (right). Driving factors are classified into predominantly technical and socio-economic (in italic) drivers. We use two EC fleet development scenarios until 2030 from International Energy Agency (IEA)[57]. The EV range, fuel economy, and motor power of various EV models are collected from the US DOE (US Department of Energy)[125]. The material compositions for various battery chemistries are calculated by using the BatPaC (Battery Performance and Cost) model from Argonne National Laboratory[70], expected for Li-Sulphur and Li-Air chemistries (marked with * as they are associated with uncertainty for EV applications[81]). Abbreviations: E, B, and M = EV, battery, and material; e, b, and m = categories of EV, battery, and material; In, stk, and out = inflow, stock, and outflow; y = year. See the section on battery replacement and reuse for calculation equations.



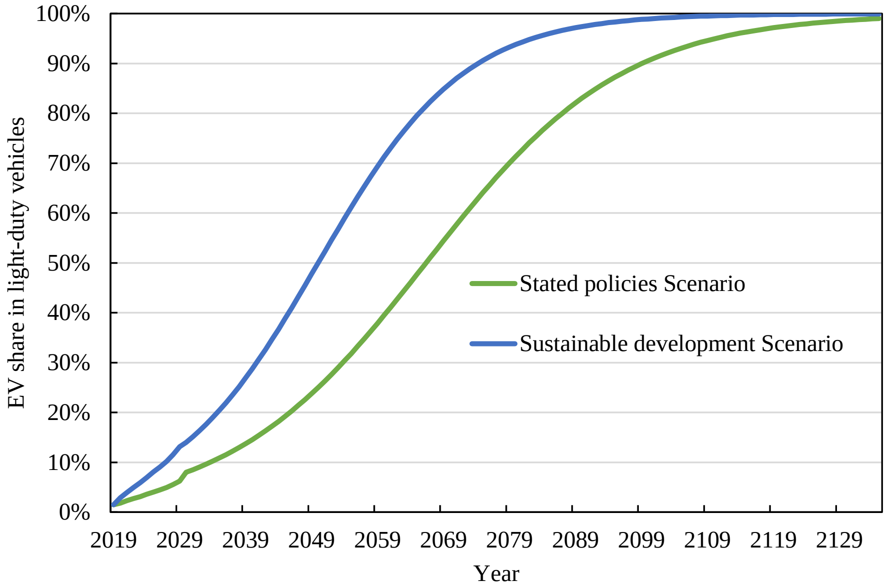
Supplementary Fig. 2.2: Weibull lifespan distributions of EVs and batteries.



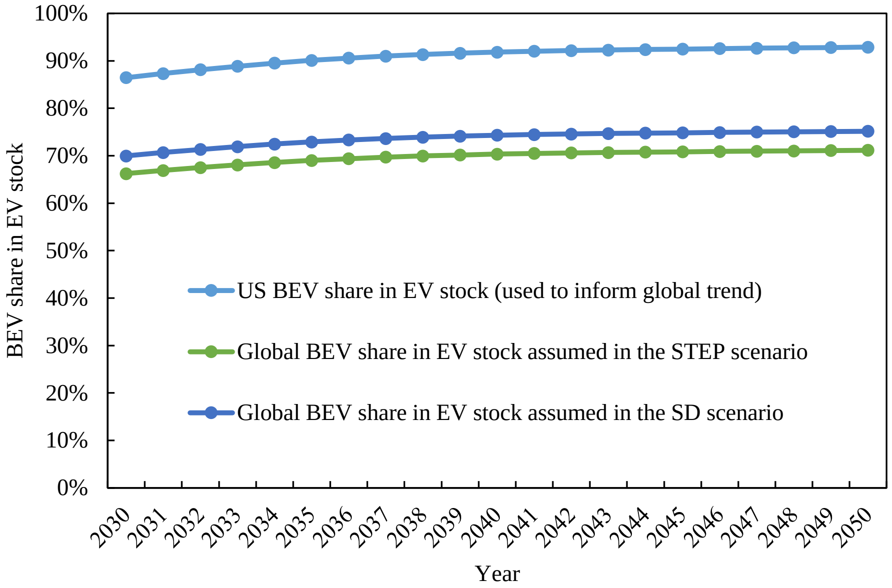
Supplementary Fig. 2.3: Projections of EV stock share in light-duty vehicles from 2030 to 2050[57,126-132]. TOTAL projects 20%-30% of EV fleet share in 2040[130], which is shown as an average number of 25% in the figure. Green and blue dashed lines represent own estimations for the EV fleet share in the stated policies scenario and the sustainable development scenario of IEA[57] until 2050 by logistic model[133] respectively, which is comparable to other studies.



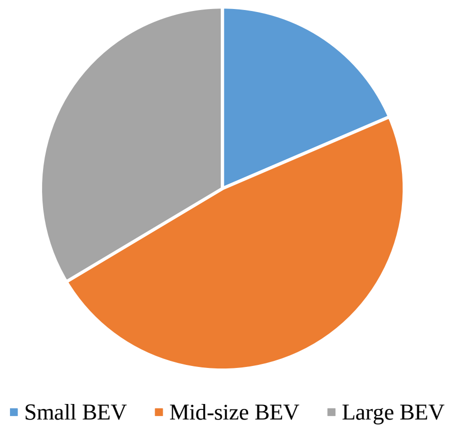
Supplementary Fig. 2.4: EV stock estimations of stated policies scenario and sustainable development scenario from 2020-2030 of IEA global EV outlook 2020[57], in proportion with new policies scenario and EV30@30 scenario of IEA global EV outlook 2019[132], respectively.



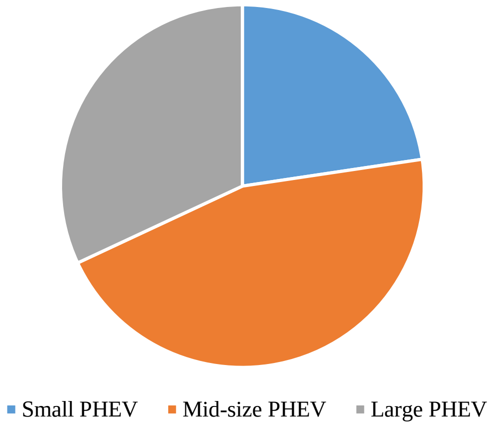
Supplementary Fig. 2.5: Estimation of EV fleet penetration in stated policies scenario and sustainable development scenario of IEA (reach 100% until the year 2135). The EV fleet penetration until 2030 is based on the stated policies scenario and the sustainable development scenario of IEA[57], and we model the EV fleet penetration after 2030 by logistic model[133]. Here the figure shows the process of full transition to EVs in light-duty passenger vehicle market, and the time point when EV fleet share reaches 100% in the stated policies scenario and the sustainable development scenario, if our estimations of 25%-50% of EV fleet share in 2050 are realized.



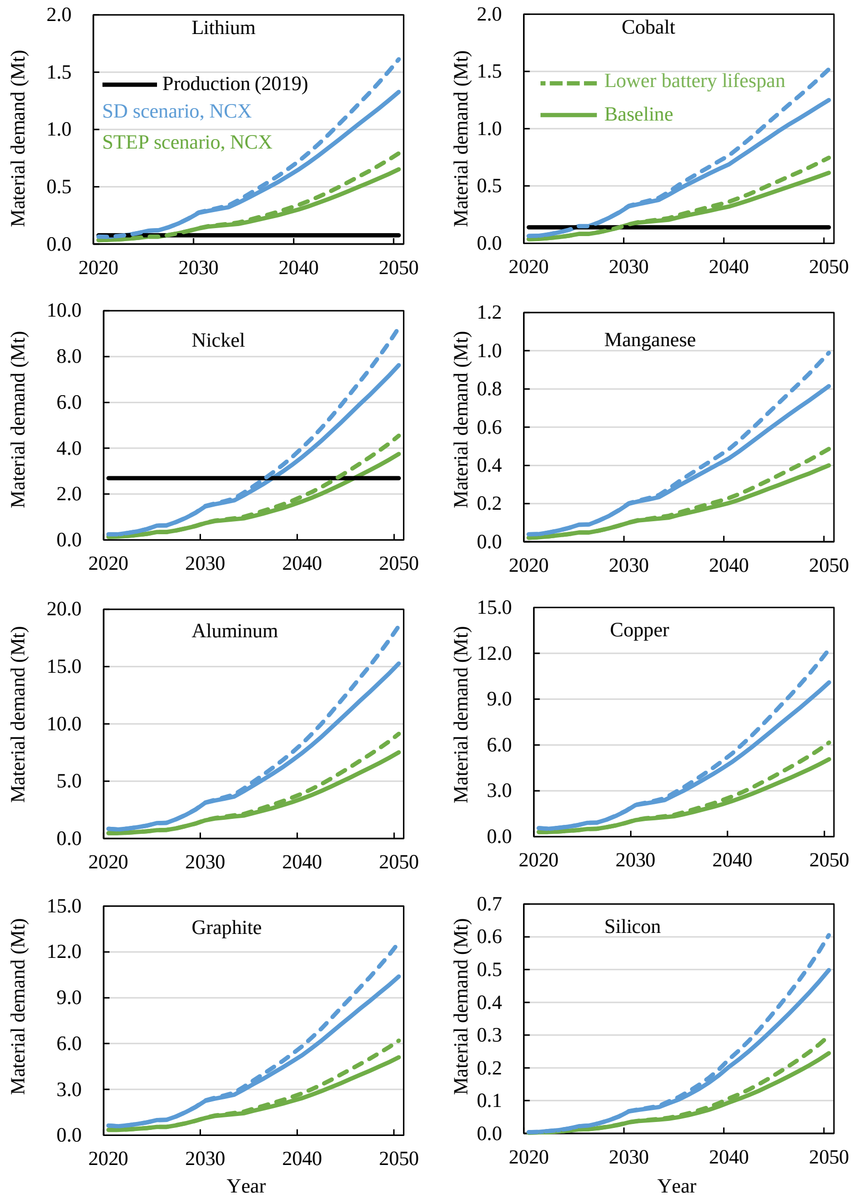
Supplementary Fig. 2.6: Global BEV share in total EV stock in 2030-2050, in proportion with US BEV stock share projection by US Energy Information Administration[134].



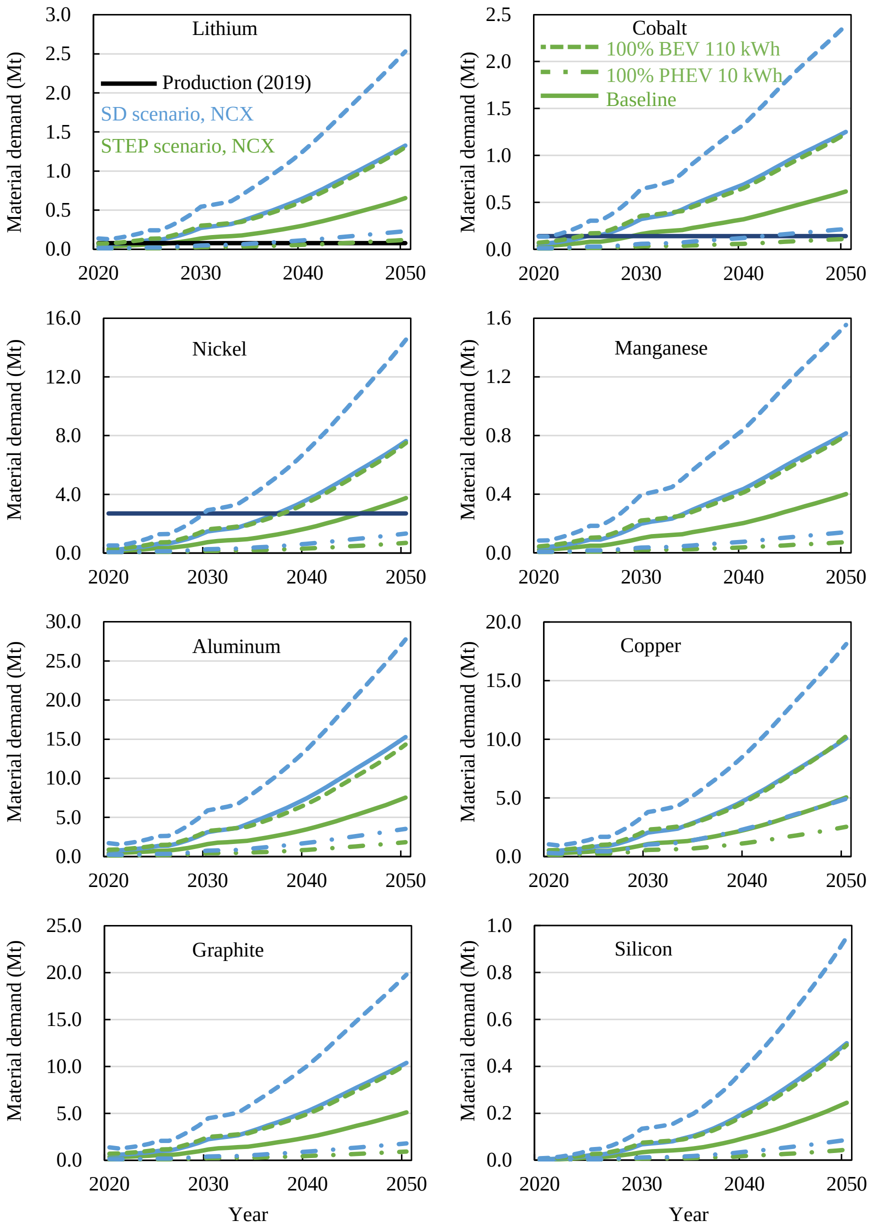
Supplementary Fig. 2.7: BEV sales market shares among small/mid-size/large segments. The market shares are based on cumulative sales until 2019 of each BEV model included in each BEV market segment. BEV sales market shares are assumed stable in 2020-2050, while sensitivity analysis is conducted.



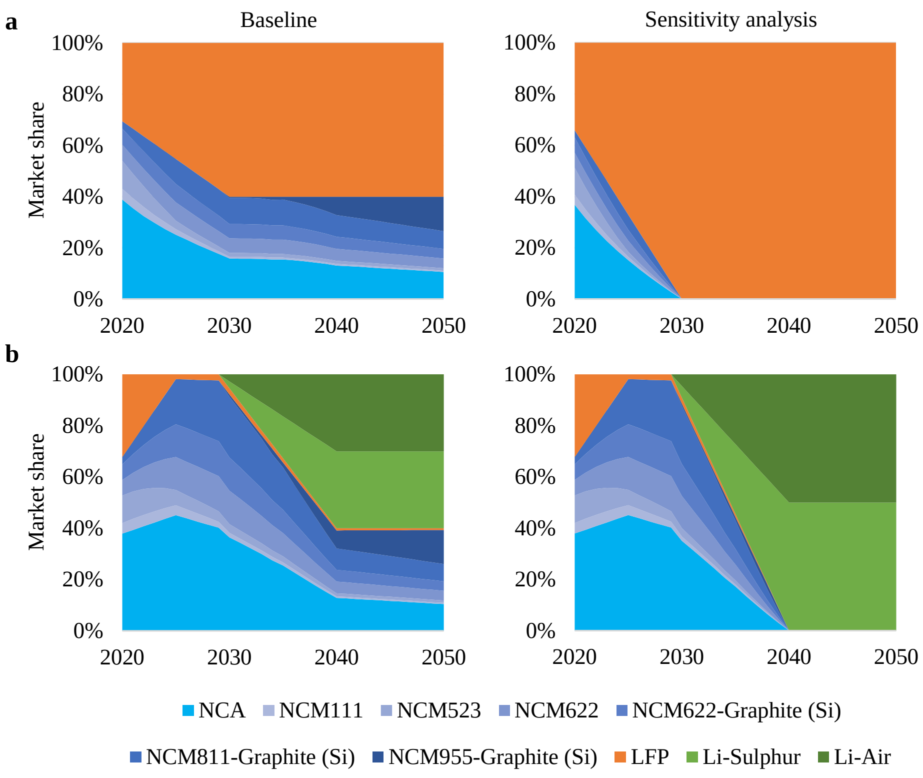
Supplementary Fig. 2.8: PHEV sales market shares among small/mid-size/large segments. The market shares are based on cumulative sales until 2019 of each PHEV model included in each PHEV market segment. PHEV sales market shares are assumed stable in 2020-2050, while sensitivity analysis is conducted.



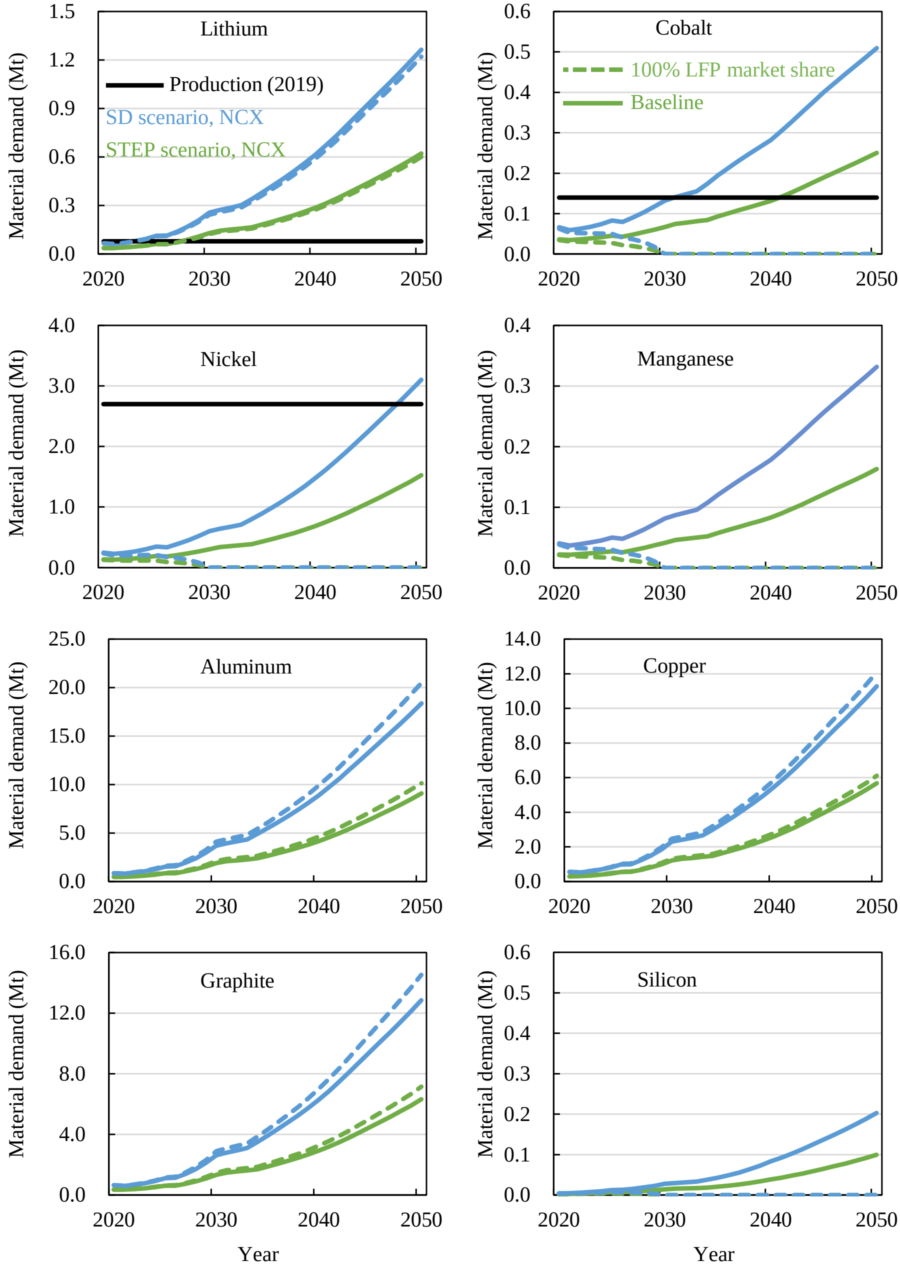
Supplementary Fig. 2.9: Result of sensitivity analysis of lower battery lifespan (*i.e.*, one EV will use 1.5 battery packs on average after 2020, while in the baseline scenario one EV will use 1 battery pack after 2020) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.



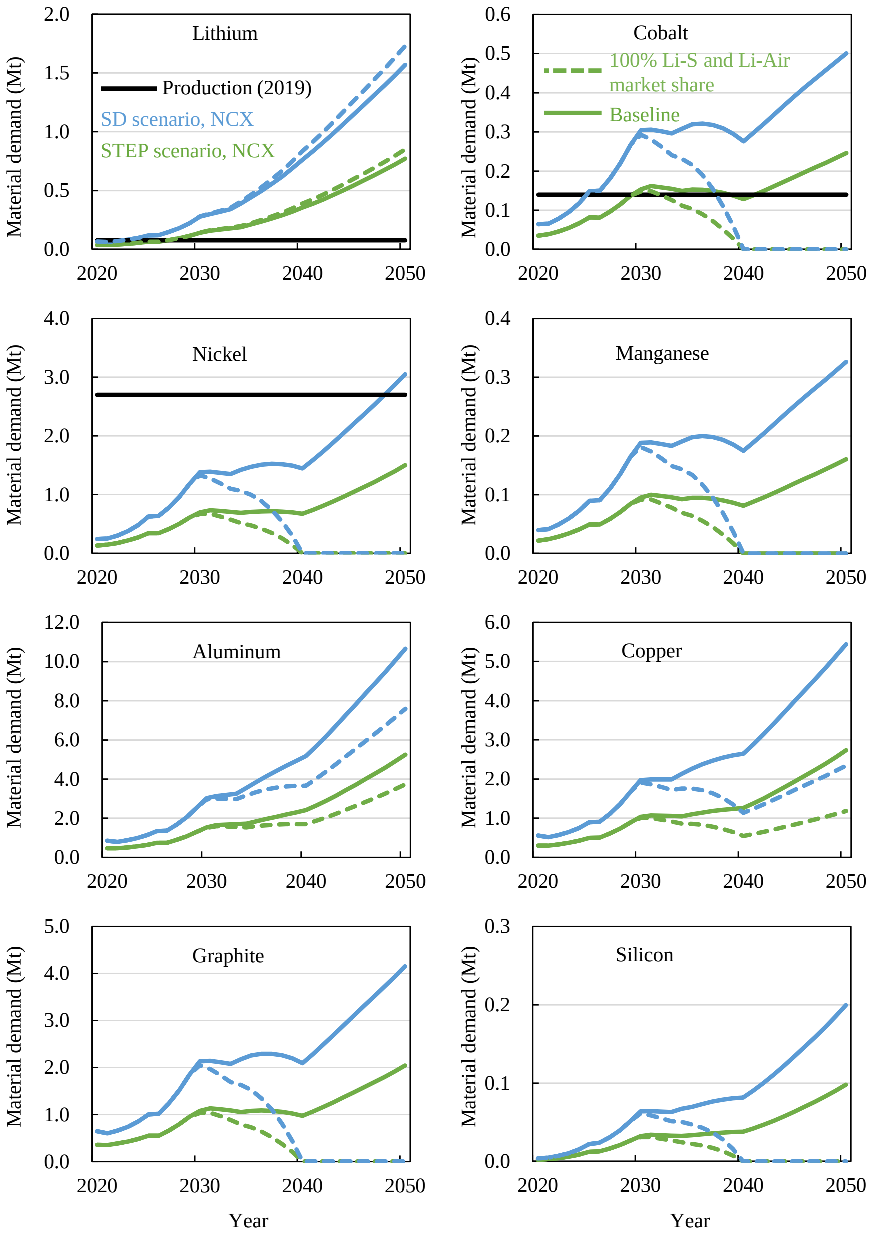
Supplementary Fig. 2.10: Result of sensitivity analysis of required battery capacity (*i.e.*, 100% BEV with 110 kWh and 100% PHEV with 10 kWh) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.



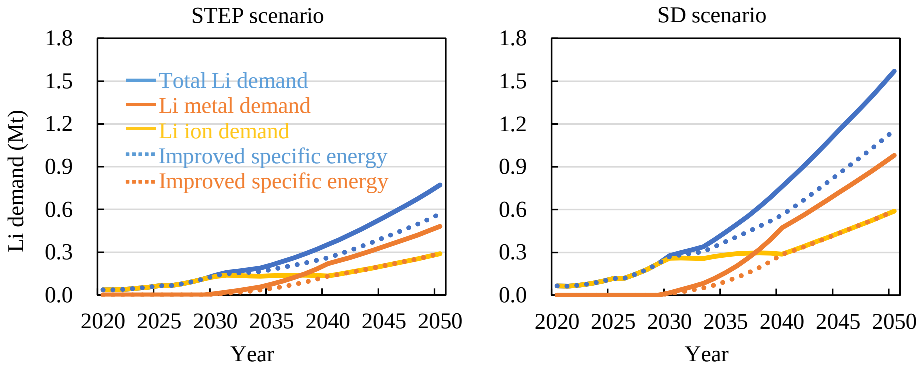
Supplementary Fig. 2.11: Input of sensitivity analysis of LFP market share in the LFP scenario (a) and Li-S and Li-Air market shares in the Li-S/Air scenario (b).



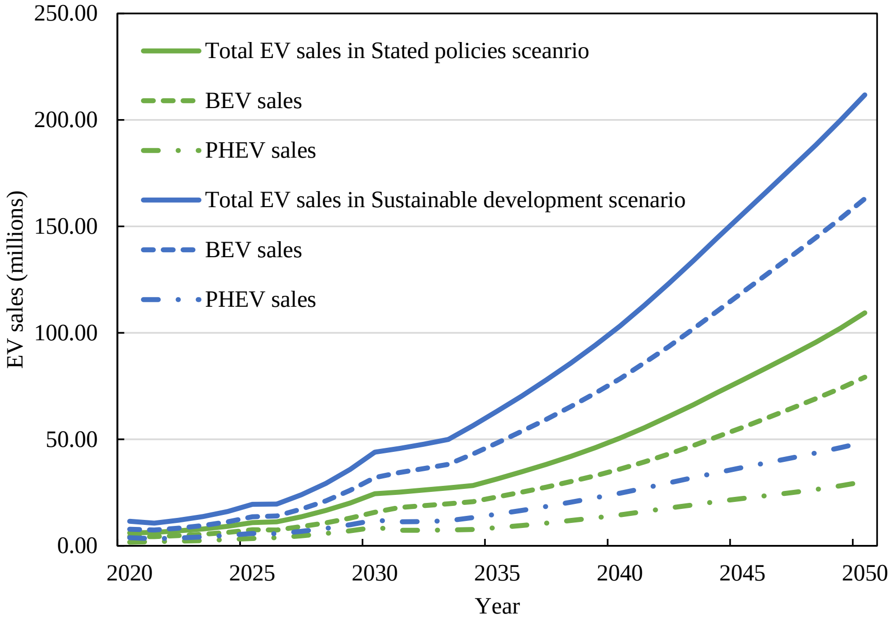
Supplementary Fig. 2.12: Result of sensitivity analysis of 100% LFP market share (by 2030) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.



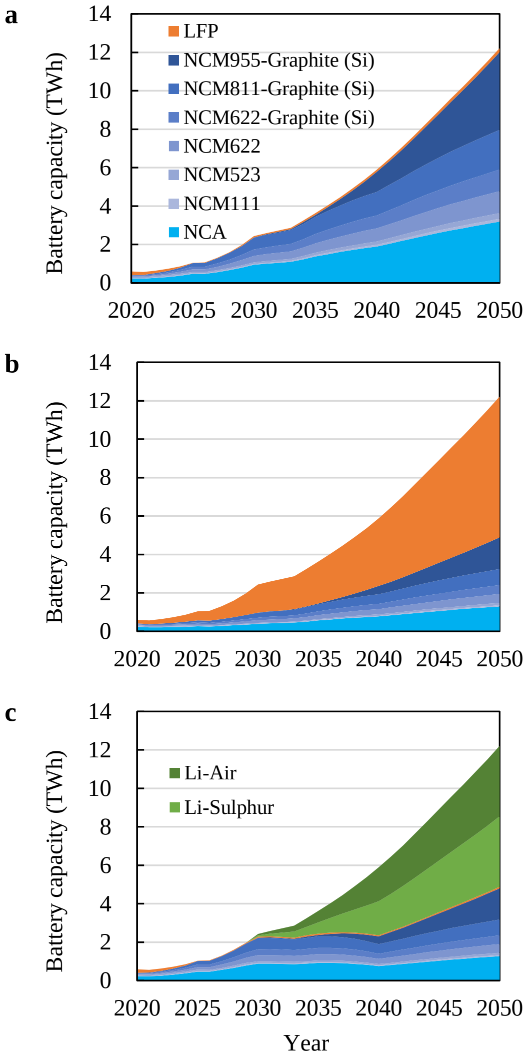
Supplementary Fig. 2.13: Result of sensitivity analysis of 100% Li-S and Li-Air market share (by 2040) on annual demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling.



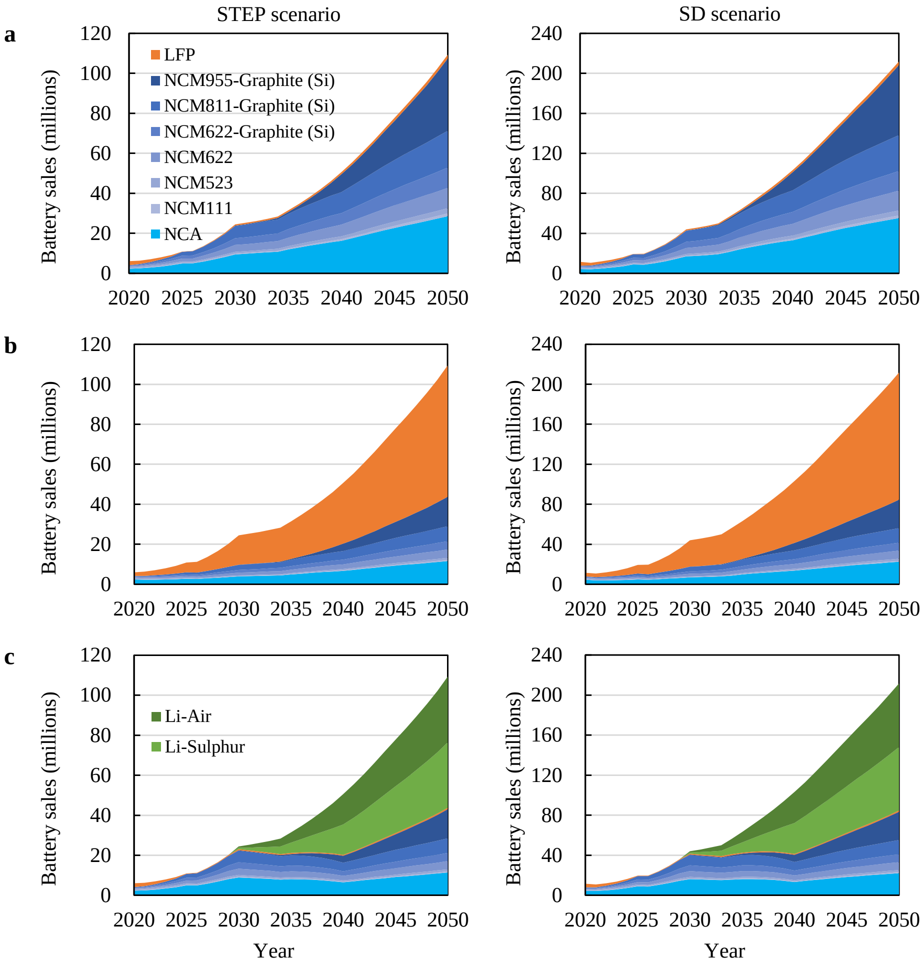
Supplementary Fig. 2.14: Lithium demand split by Li ion (in the form of chemicals like Li_2CO_3, LiOH, *etc*.) and Li metal (in Li anode of Li-S and Li-Air chemistries) in the Li-S/Air scenario, including a sensitivity analysis for improved specific energy of Li-S and Li-Air chemistries. Based on a review of the specific energy of Li-S and Li-Air cells from lab and commercial scales (see Supplementary Table 2.22 and Supplementary Table 2.1), the specific energy of Li-S cells is improved from 400 Wh/kg to 600 Wh/kg, and the specific energy of Li-Air cells from 500 Wh/kg to 1000 Wh/kg. Specific energy improvements of Li-S and Li-Air cells can make total Li demand in the Li-S/Air scenario lower than LFP and NCX scenarios.



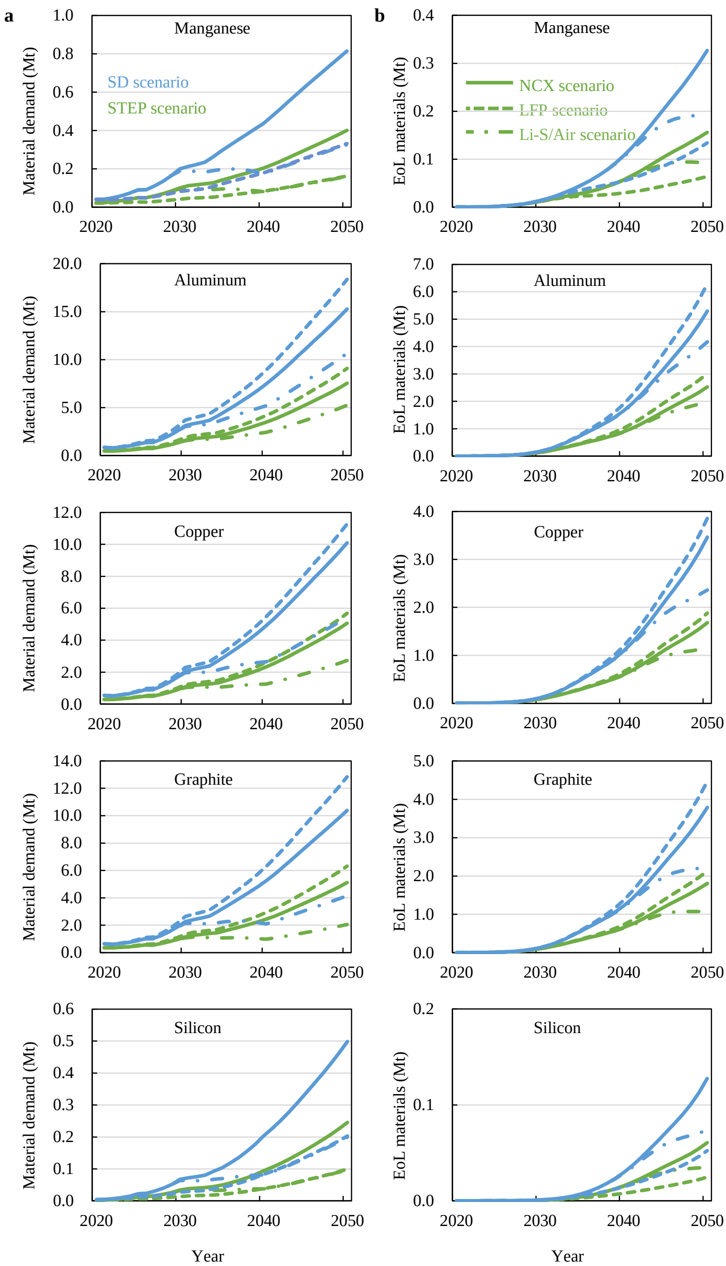
Supplementary Fig. 2.15: Projections of global EV sales in the stated policies scenario and the sustainable development scenario in 2020-2050. EV sales are in rapid growth phase until 2050, based on the projections of EV stock share in light-duty passenger vehicles.



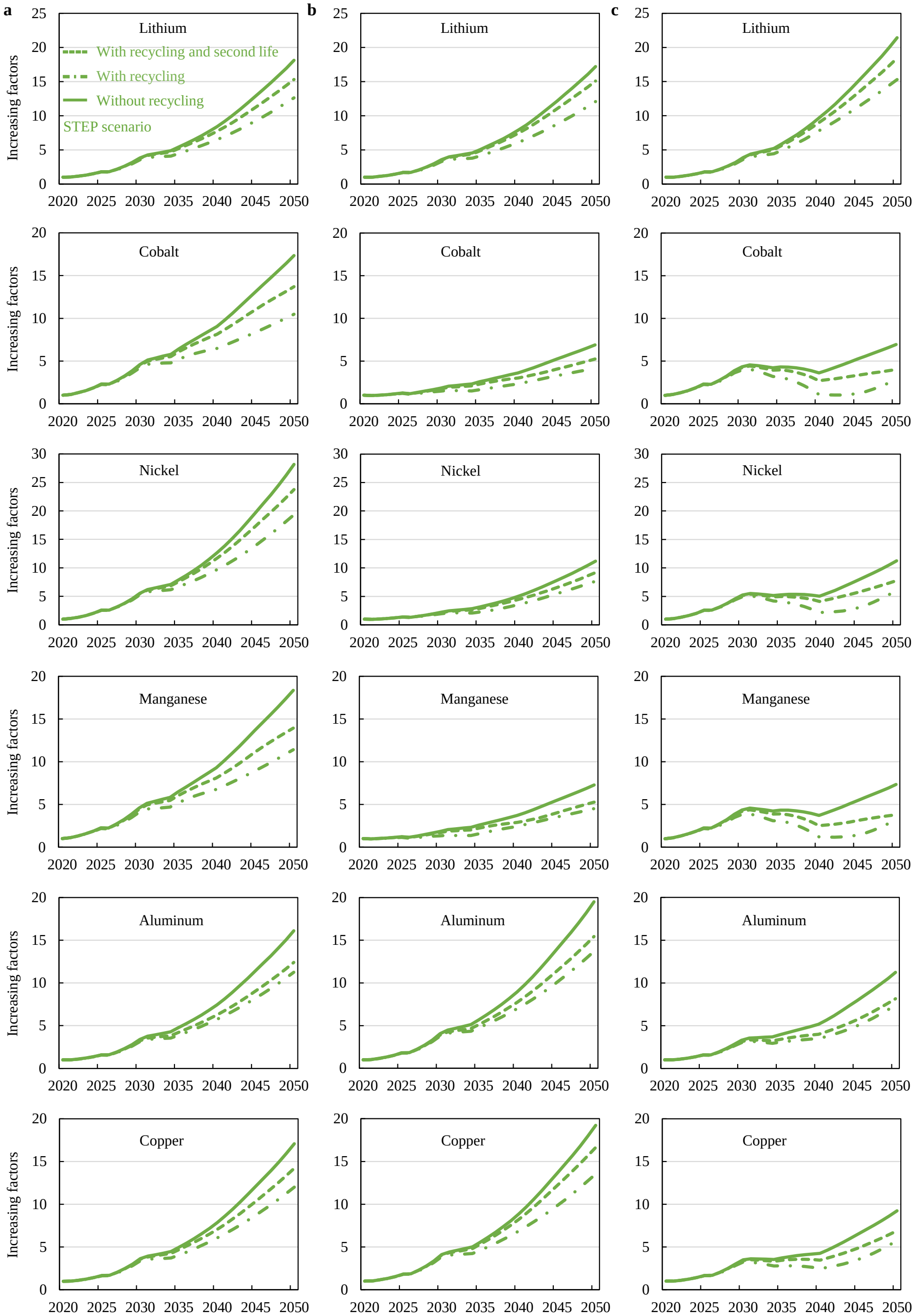
Supplementary Fig. 2.16: EV battery sales by year in the NCX (a), LFP (b) and Li-S/Air (c) scenarios until 2050 for the fleet development of the SD scenario (unit: 1 TWh = 10^3 GWh = 10^6 MWh = 10^9 kWh).



Supplementary Fig. 2.17: EV battery sales by year in the NCX (a), LFP (b) and Li-S/Air (c) scenarios until 2050 for the fleet development of the STEP scenario and the SD scenario (unit: millions).



Supplementary Fig. 2.18: Primary material demand (a) and materials in EoL batteries (b) from 2020 to 2050 for Mn, Al, Cu, graphite, and Si in the NCX, LFP and Li-S/Air battery scenarios.


a
b
c
Lithium
With recycling and second life
With recycling
Without recycling
STEP scenario
Cobalt
Nickel
Manganese
Aluminum
Copper
Increasing factors
0
5
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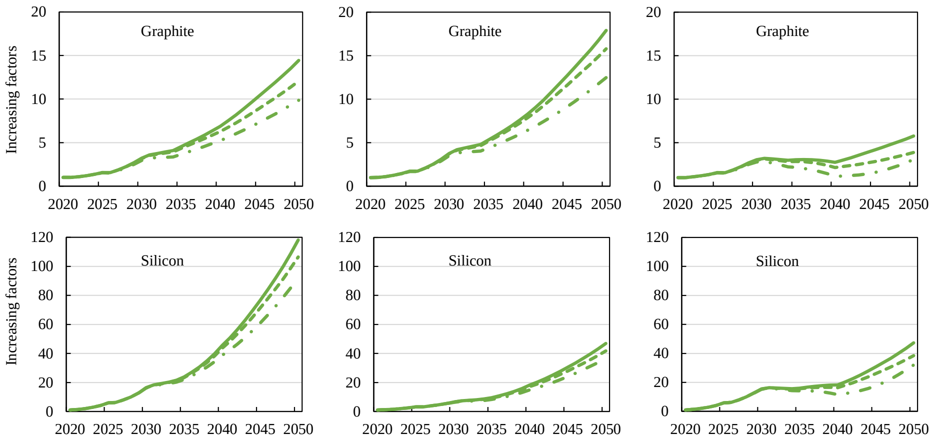
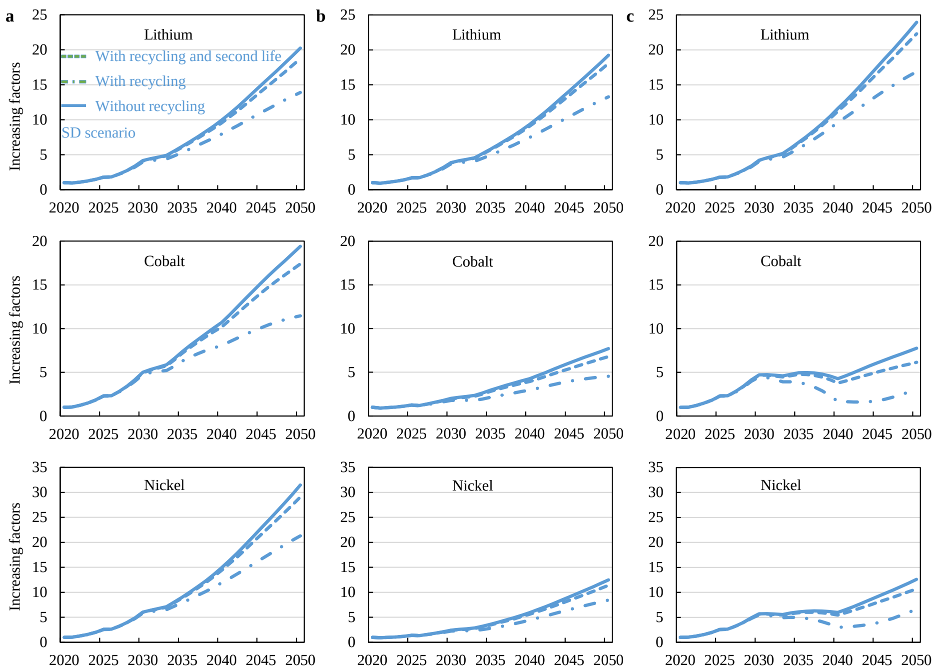
2020 2025 2030 2035 2040 2045 2050

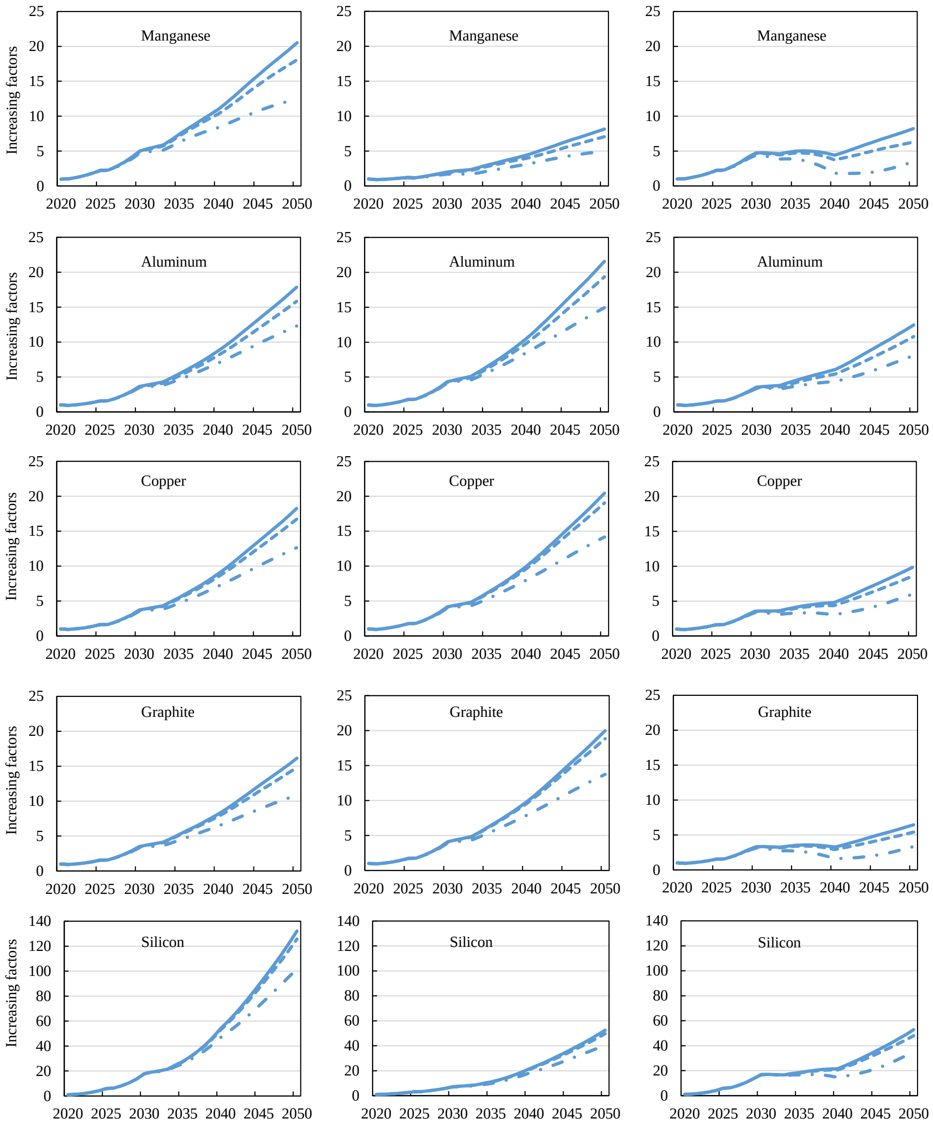
Supplementary Figure 2.19 (Continued).



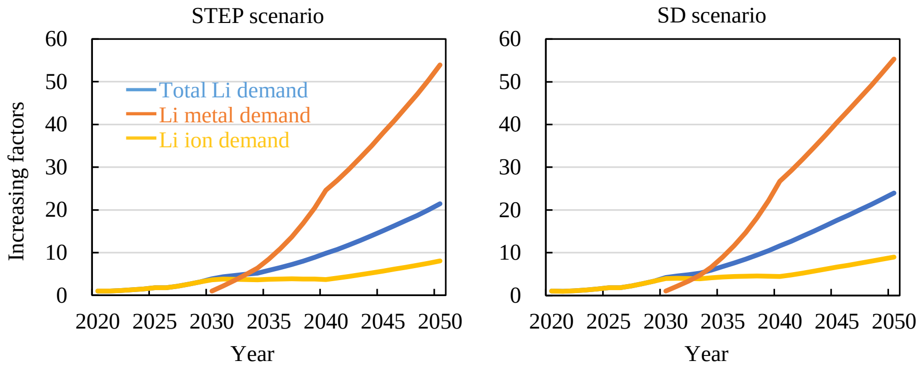
Supplementary Fig. 2.19: Increasing factors for the primary demand for Li, Ni, Co, Mn, Al, Cu, graphite, and Si from 2020 to 2050 in the STEP scenario in the NCX (a), LFP (b) and Li-S/Air (c) scenarios. Here recycling refers to hydrometallurgical recycling as an example.



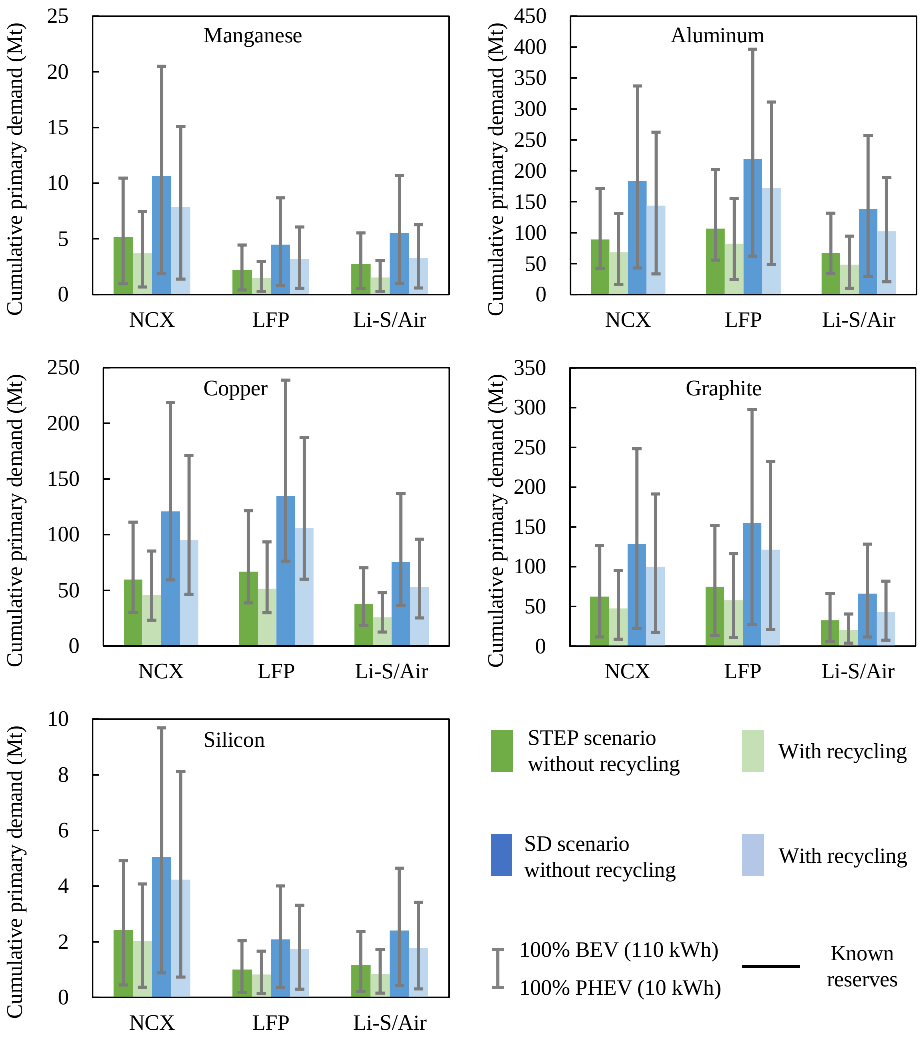
Supplementary Figure 2.20 (Continued).



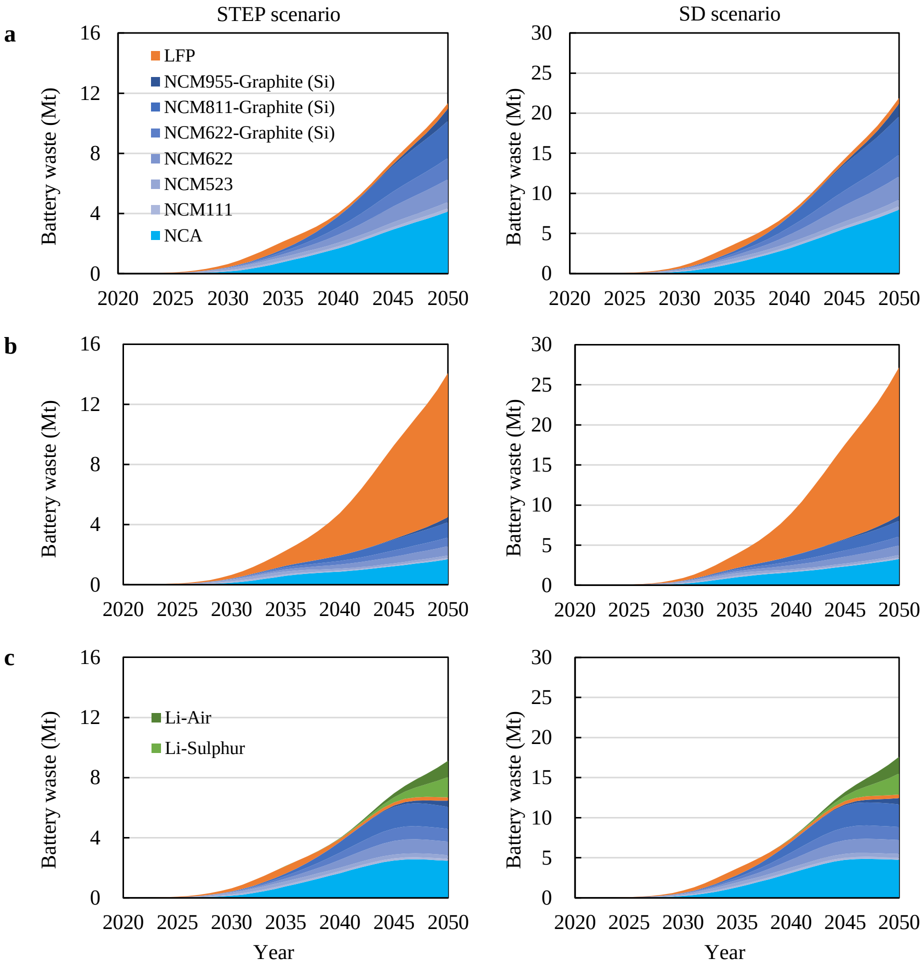
Supplementary Fig. 2.20: Increasing factors for the primary demand of Li, Ni, Co, Mn, Al, Cu, graphite, and Si from 2020 to 2050 in the SD scenario in the NCX (a), LFP (b) and Li-S/Air (c) scenarios. Here recycling refers to hydrometallurgical recycling as an example.



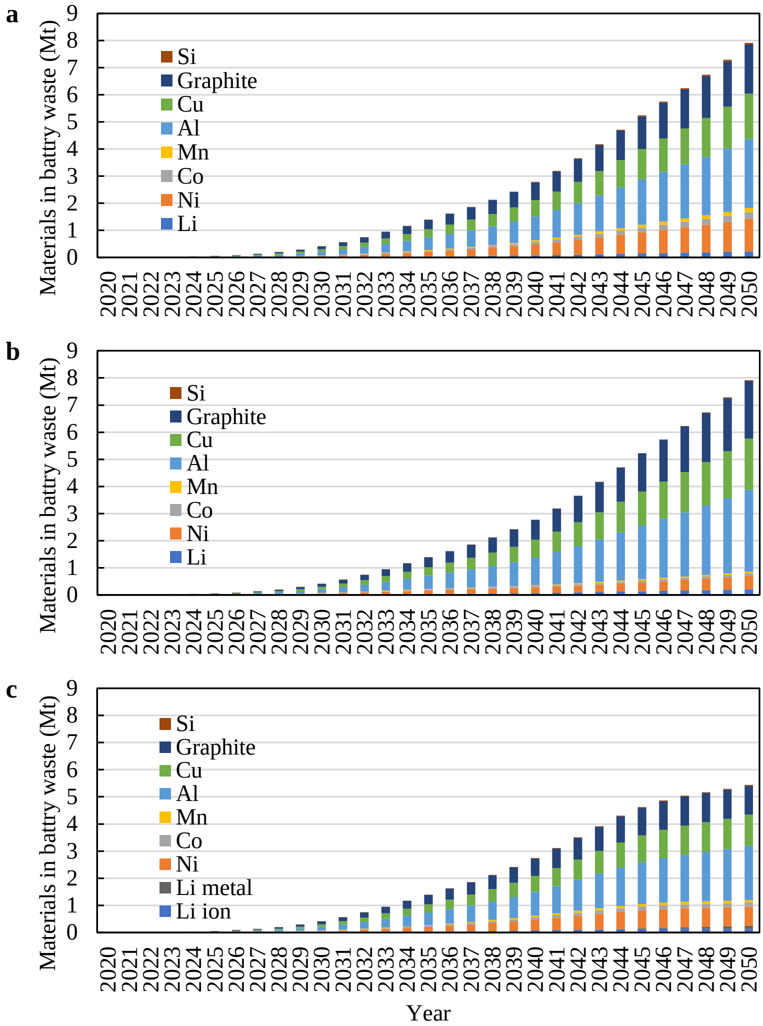
Supplementary Fig. 2.21: Increasing factors for lithium demand split by Li ion (in the form of chemicals like Li2CO3, LiOH, *etc*.) and Li metal (in Li anode of Li-S and Li-Air chemistries) demand in the Li-S/Air scenario.



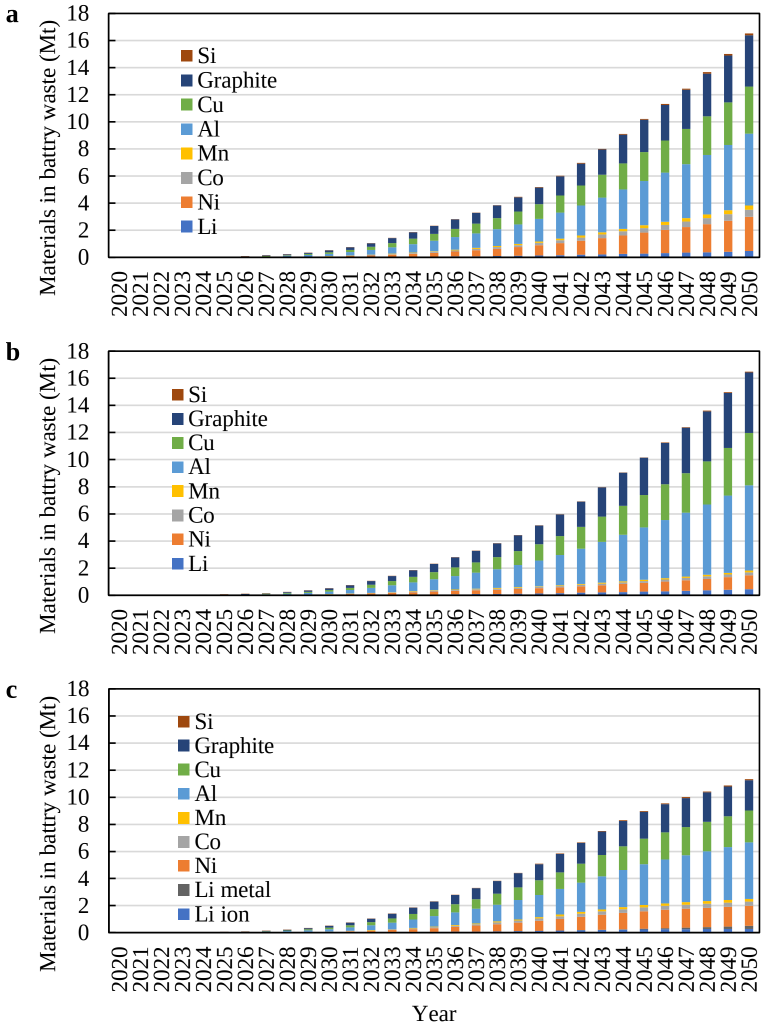
Supplementary Fig. 2.22: Cumulative primary demand for Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling or with hydrometallurgical recycling. Grey error bars represent a sensitivity analysis for battery capacity considering two extreme cases (if all EVs were PHEVs with small 10 kWh batteries or if all EVs were large SUVs with 110 kWh batteries, *e.g.*, Tesla's Model S Long Range Plus[104]). The global known reserves in 2019 for Mn, Al, Cu, graphite, and Si are shown in Supplementary Table 2.2, which are much higher than cumulative primary material demand from EV batteries only.



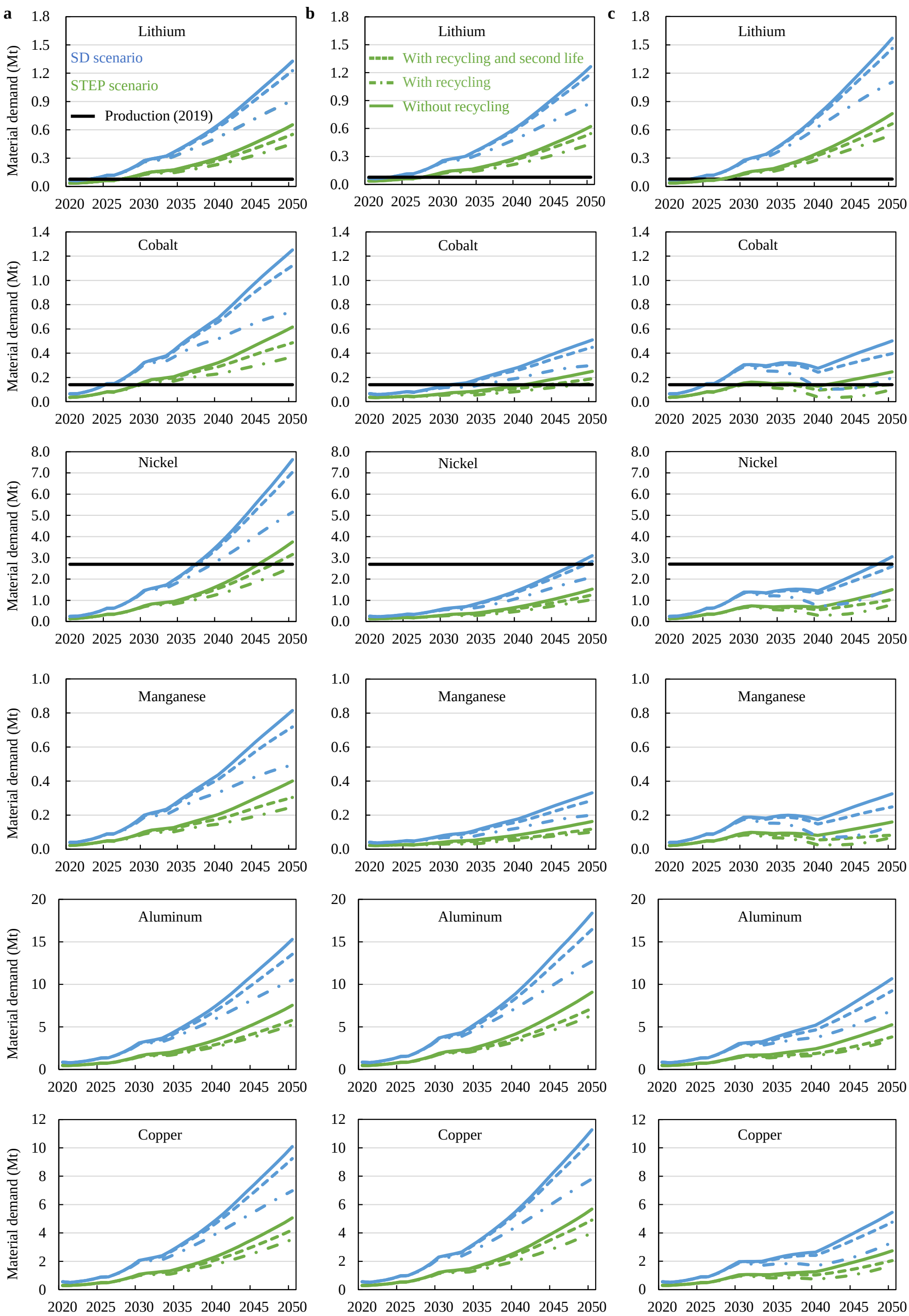
Supplementary Fig. 2.23: Future battery waste stream by chemistry in the NCX (a), LFP (b) and Li-S/Air (c) scenarios until 2050 (unit: Mt = million tons). Under the STEP scenario, the EV battery waste stream reaches around 11 Mt in 2050 if NCX scenario is realized, which is lower than the LFP scenario (14 Mt) and higher than the Li-S/Air scenario (9 Mt). The differences among three battery chemistry scenarios are associated with the relatively lower specific energy of LFP chemistry and higher specific energy of Li-S and Li-Air chemistries compared to NCA and NCM series chemistries. Driven by higher EV fleet deployments, the weight of EV battery waste stream reaches around 2 times in the SD scenario than the STEP scenario.



Supplementary Fig. 2.24: Materials in future EV battery waste steam potentially available for recycling without second life use until 2050 in the STEP scenario in the NCX (a), LFP (b) and Li-S/Air (c) scenarios (unit: Mt = million tons). The total weight of eight EoL materials in 2050 in the NCX scenario is almost equal to the LFP scenario, but with different material shares, especially for the EoL Ni weight in the NCX scenario is much higher than the LFP scenario. The total weight of eight EoL materials in the Li-S/Air scenario (Li includes Li ion in lithium chemical compounds and Li metal) is much lower than the other two battery scenarios, however, EoL Li weight is slightly higher.

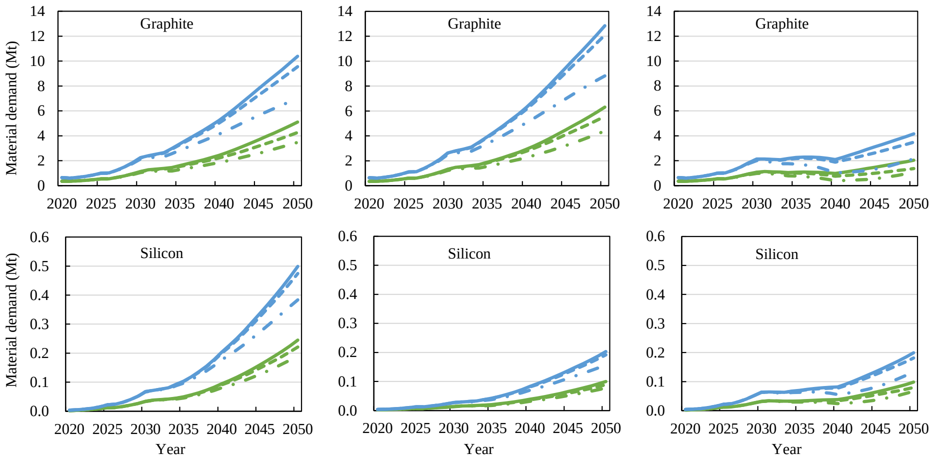


Supplementary Fig. 2.25: Materials in future EV battery waste steam potentially available for recycling without second life use until 2050 in the SD scenario in the NCX (a), LFP (b) and Li-S/Air (c) scenarios (unit: Mt = million tons). We can see the same pattern for EoL materials in the SD scenario as in the STEP scenario. However, the weight of EoL materials available for recycling in the SD scenario is around 2 times than STEP scenario.



a
b
c
Lithium
Cobalt
Nickel
Manganese
Aluminum
Copper
SD scenario
STEP scenario
Production (2019)
With recycling and second life
With recycling
Without recycling
Material demand (Mt)
2020 2025 2030 2035 2040 2045 2050

Supplementary Figure 2.26 (Continued).



Supplementary Fig. 2.26: Primary battery material demand in the NCX (a), LFP (b) and Li-S/Air (c) scenarios from 2020 to 2050 without recycling, with recycling, and with recycling and second life. Here recycling refers to hydrometallurgical recycling as an example.

2.6.2 Supplementary Tables

Supplementary Table 2.1: Compiled EPA car size class[74] used in this study. Note here small cars include two-Seaters, minicompact sedans, subcompact sedans, and compact sedans by the EPA car size class. Large cars include large sedans, small station wagons, SUVs, and vans by the EPA car size class.

Class	Passenger & Cargo Volume (Cu. Ft.)
Small	< 110
Mid-size	110 to 119
Large	> 119

Supplementary Table 2.2: Sales-weighted average BEV range, fuel economy, and motor power. We collect sales of each BEV model including in small/mid-size/large car segments until 2019[75], and calculate the distribution of cumulative sales until 2019 of three car segments (to represent BEV market shares among small/mid-size/large car segments). The range, fuel economy, and motor power of each BEV segment are calculated by cumulative sales-weighted average method. The required battery capacity = EV range * fuel economy / 0.85, where 0.85 is the ratio of available battery capacity for driving EVs based on the assumption in the BatPaC model when calculating battery material compositions[70]. Average required battery capacity for BEVs reaches around 66 kWh.

BEVs	Range (miles)	Fuel economy (Wh/mile)	Electric motor power (kW)	Required capacity (kWh)
Small BEVs	96	291	101	33
Mid-size BEVs	194	291	169	66
Large BEVs	241	353	295	100

Supplementary Table 2.3: Sales-weighted average PHEV range, fuel economy, and motor power. Average required battery capacity for PHEVs reaches around 12 kWh.

PHEVs	Range (miles)	Fuel economy (Wh/mile)	Electric motor power (kW)	Required capacity (kWh)
Small PHEVs	44	336	123	17
Mid-size PHEVs	22	303	55	8
Large PHEVs	22	470	61	12

Supplementary Table 2.4: Summary of capacity of the cathode and anode of battery chemistry as input to the BatPaC model. The majority of cathode and anode capacity are kept as defaults in the BatPaC model[70], unless otherwise based on Supplementary Table 2.28, Supplementary Table 2.15, Supplementary Table 2.13, or references. We use composite graphite anode with 9 wt% Si to represent Graphite (Si) anode in this table, and its capacity is from[135].

Battery chemistry	Cathode	Cathode capacity (mAh/g)	Anode	Anode capacity (mAh/g)
LFP	$LiFePO_4$	150	Graphite	360
NCA	$LiNi_{0.8}0Co_{0.15}Al_{0.05}O_2$	200	Graphite	360
NCM111	$Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$	155	Graphite	360
NCM523	$Li_{1.05}(Ni_{0.5}Mn_{0.3}Co_{0.2})_{0.95}O_2$	158	Graphite	360
NCM622	$Li_{1.05}(Ni_{0.6}Mn_{0.2}Co_{0.2})_{0.95}O_2$	180	Graphite	360
NCM622-Graphite (Si)	$Li_{1.05}(Ni_{0.6}Mn_{0.2}Co_{0.2})_{0.95}O_2$	180	Graphite (Si)	517[135]
NCM811-Graphite (Si)	$Li_{1.05}(Ni_{0.8}Mn_{0.1}Co_{0.1})_{0.95}O_2$	191	Graphite (Si)	517[135]
NCM955-Graphite (Si)	$Li_{1.05}(Ni_{0.9}Mn_{0.05}Co_{0.05})_{0.95}O_2$	211	Graphite (Si)	517[135]

Supplementary Table 2.5: The minimum, most likely, and maximum lifespans of EVs from 2005 to 2050 as input to the calculation of shape and scale parameters of Weibull lifespan distribution of EVs (unit: year, expect for shape and scale parameters).

Period	Minimum lifespan, a	Most likely lifespan, d	Maximum lifespan, c	Shape parameter, α	Scale parameter, β
2005-2050	1	15	20	6.3	14.4

Supplementary Table 2.6: The minimum, most likely, and maximum lifespans of EV batteries from 2005 to 2050 as input to the calculation of shape and scale parameters of Weibull lifespan distribution of batteries (unit: year, except for shape and scale parameters). Other chemistries refer to all battery chemistries except LFP.

Period	Chemistries	Minimum lifespan, a	Most likely lifespan, d	Maximum lifespan, c	Shape parameter, α	Scale parameter, β
2005-2019	All chemistries	1	8	15	3.1	7.9
2020-2050	Other chemistries	1	15	20	6.3	14.4
2020-2050	LFP	1	20	25	8.1	19.3

Supplementary Table 2.7: Reference chemistry and changing parameters as input to the BatPaC model for the calculation of the material compositions of the non-existing battery chemistries in the BatPaC model. Here we assume a linear growth for open circuit voltage (OCV) at different levels of battery state of charge (SOC) from NCM523, to NCM622-Graphite (Si), to NCM811-Graphite (Si), to NCM955-Graphite (Si). The OCV of NCM523 = the average of OCV (NCM111) and OCV (NCM622) in the BatPaC model. The OCV of NCM622-Graphite (Si) = OCV (NCM622) – 0.076 (see Supplementary Note 2.1 for the assuming average voltage difference between graphite (Si) anode and graphite anode). Cathode capacity and Li, Ni, Co, and Mn content are from Supplementary Table 2.14.

Battery chemistry	NCM523	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)
Reference chemistry	NCM111	NCM622	NCM622	NCM622
Cathode capacity (mAh/g)	158	180	191	211
Anode capacity (mAh/g)	360	517	517	517
OCV at 20% SOC (V)	3.5405	3.489	3.5135	3.538
OCV at 50% SOC (V)	3.7105	3.674	3.7135	3.753
OCV at 80% SOC (V)	3.95	3.924	3.974	4.024
OCV at 100% SOC (V)	4.15	4.124	4.174	4.224
Li (g/g active material)	0.07751513	0.077221916	0.076949595	0.076813626
Ni (g/g active material)	0.296520724	0.354478904	0.470971788	0.528915777
Co (g/g active material)	0.119093288	0.118642798	0.059112203	0.031060614
Mn (g/g active material)	0.166530137	0.11060014	0.055105055	0.027508722

Supplementary Table 2.8: Review of the specific energy of Li-S chemistry on cell level (unit: Wh/kg).

References	Battery shape	Specific energy	Technology readiness
Ref1[136]		400	
Ref2[137]		370	
Ref3[138]		300-620	R&D
Ref4[90]	Pouch	300-400	
Ref4[90]	Pouch	500-600	R&D
Ref5[139]		400-620	
Ref6[136]	Pouch	350-400	Commercial
Ref7[140]	Pouch	300	Lab

Supplementary Table 2.9: Review of the specific energy of Li-Air chemistry on cell level (unit: Wh/kg).

References	Battery shape	Specific energy	Technology readiness
Ref1[136]		1700	
Ref2[137]		1700	
Ref3[138]		500-900	
Ref4[141]	Pouch	362	R&D
Ref5[91]		520	
Ref6[142]	Coin	1000	
Ref7[143]	Folded structure	1214	
Ref8[139]		500-1000	

Supplementary Table 2.10: Modelled material compositions of a Li-S (600 Wh/kg) and a Li-Air (1000 Wh/kg) pack used for sensitivity analysis. (unit: kg per battery pack)

EV types	Materials	Li-Sulphur	Li-Air
Small BEVs	Li ion	0.19	0.12
	Li metal	3.62	1.69
	Al	16.42	9.92
	Cu	6.44	0.27
	Al in modules	6.86	4.18
	Cu in modules	6.14	0.10
Mid-size BEVs	Li ion	0.39	0.24
	Li metal	7.30	3.40
	Al	30.20	18.25
	Cu	13.33	0.77
	Al in modules	13.72	8.36
	Cu in modules	12.53	0.29
Large BEVs	Li ion	0.59	0.36
	Li metal	11.03	5.13
	Al	45.64	27.58
	Cu	21.75	2.12
	Al in modules	20.63	12.58
	Cu in modules	20.52	1.39
Small PHEVs	Li ion	0.10	0.06
	Li metal	1.91	0.89
	Al	7.26	4.39
	Cu	7.52	2.62
	Al in modules	3.53	2.15
	Cu in modules	4.37	2.62

Supplementary Table 2.10 (continued).

EV types	Materials	Li-Sulphur	Li-Air
Mid-size PHEVs	Li ion	0.05	0.03
	Li metal	0.88	0.41
	Al	3.97	2.40
	Cu	4.51	1.84
	Al in modules	1.70	1.04
	Cu in modules	3.06	1.84
Large PHEVs	Li ion	0.07	0.04
	Li metal	1.32	0.61
	Al	5.48	3.31
	Cu	7.26	3.05
	Al in modules	2.49	1.52
	Cu in modules	5.08	3.05

Supplementary Table 2.11: Comparisons of three EV battery recycling technologies by recycled material type, recycling efficiency, and the quality of recovered materials, where mechanical recycling is especially for the recovery of Li metal (a different form compared to Li ion in chemicals), Al, and Cu form Li-S and Li-Air chemistry. Numbers in the table show the material recycling efficiencies. The different colors show the feasibility of recovered materials being reused in new battery production (*i.e.*, closed-loop recycling). Yellow color indicates the economic feasibility of closed-loop recycling is in question, but maybe become potentially economical with future technology development and price fluctuance of recovered materials. Pyro and hydro recycling are already commercially available, while direct recycling and mechanical recycling marked with star (*) are in still lab-scale development.

Technology	Li	Ni	Co	Mn	Al	Cu	Graphite	Si
Pyro	90%	98%	98%	90%	0%	90%	0%	0%
Hydro	90%	98%	98%	98%	90%	90%	90%	90%
Direct*	90%	90%	90%	90%	90%	90%	90%	90%
Mechanical*	90%				90%	90%		

	Not present
	Lost
	Potentially economical
	Eonomical

Supplementary Table 2.12: Assumptions of second-use rate of batteries distinguished by LFP and other chemistries, based on the assumptions of EV and battery lifespan distribution (Supplementary Table 2.19 and Supplementary Table 2.20).

Periods	Battery chemistry	Second-use rate
2005-2019	LFP	100%
	Others	50%
2020-2050	LFP	100%
	Others	75%

Supplementary Table 2.13: Material compositions of a BEV battery with 110 kWh capacity used for sensitivity analysis. (unit: kg per battery pack)

EV types	Materials	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
BEV with 110 kWh capacity	Li ion	10.98	11.35	15.63	15.16	13.16	13.36	12.42	11.13	0.96	0.78
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.15	11.26
	Ni	0.00	73.36	38.42	55.88	58.02	59.22	73.36	73.79	0.00	0.00
	Co	0.00	13.81	38.58	22.45	19.42	19.82	9.21	4.33	0.00	0.00
	Mn	0.00	0.00	35.97	31.39	18.10	18.48	8.58	3.84	0.00	0.00
	Al	172.79	135.08	141.95	140.31	136.19	130.17	127.98	124.94	75.12	60.53
	Cu	99.58	86.46	87.62	86.66	85.42	86.01	85.07	84.02	35.80	4.66
	Graphite	130.80	117.71	120.79	119.27	116.56	78.64	77.26	75.60	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	7.78	7.64	7.48	0.00	0.00
	Al in modules	85.70	66.31	69.31	68.54	66.54	64.01	62.84	61.37	33.96	27.60
	Cu in modules	95.86	83.15	84.30	83.38	82.18	82.70	81.80	80.78	33.78	3.04

Supplementary Table 2.14: Material compositions of a PHEV battery with 10 kWh capacity used for sensitivity analysis. (unit: kg per battery pack)

EV types	Materials	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
PHEV with 10 kWh capacity	Li ion	1.01	1.04	1.42	1.38	1.20	1.22	1.13	1.02	0.09	0.07
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.65	1.02
	Ni	0.00	6.66	3.49	5.07	5.27	5.37	6.66	6.70	0.00	0.00
	Co	0.00	1.25	3.50	2.04	1.76	1.80	0.84	0.39	0.00	0.00
	Mn	0.00	0.00	3.26	2.85	1.64	1.68	0.78	0.35	0.00	0.00
	Al	29.81	16.90	17.27	17.13	16.86	16.45	16.29	16.14	6.28	5.07
	Cu	34.74	23.03	22.70	22.67	22.74	23.23	23.22	23.30	6.50	3.02
	Graphite	11.83	10.71	10.99	10.86	10.61	7.16	7.03	6.88	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	0.71	0.70	0.68	0.00	0.00
	Al in modules	15.69	8.75	8.83	8.72	8.63	8.57	8.49	8.46	3.05	2.48
	Cu in modules	22.07	11.57	11.19	11.08	11.20	11.65	11.65	11.80	3.78	3.02

Supplementary Table 2.15: Specific energy of EV battery pack (unit: Wh/kg).

EV types	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
Small BEVs	122	169	151	153	164	176	183	192	295	365
Mid-size BEVs	129	178	160	163	174	186	193	202	308	383
Large BEVs	128	176	159	162	172	185	191	201	308	384
Small PHEVs	101	151	132	134	147	155	161	169	265	327
Mid-size PHEVs	74	109	103	104	109	116	118	121	224	272
Large PHEVs	75	115	106	108	114	119	121	124	234	287

Supplementary Table 2.16: Cumulative demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling, compared to global known reserves in 2019 (unit: Mt). Note Li demand includes Li ion demand (in the form of chemicals like Li_2CO_3) and Li metal demand in the Li-S/Air battery scenario, for example, 9.1 (4.8) for Li demand under the STEP and Li-S/Air scenario is shown in the form of total Li demand (Li metal demand). * Yearend production capacity for Al reserve. ‡ Si reserves are not available, but ample for use. Known reserves in 2019 are referred from USGS[144].

Materials	STEP scenario, NCX	STEP scenario, LFP	STEP scenario, Li-S/Air	SD scenario, NCX	SD scenario, LFP	SD scenario, Li-S/Air	Known reserves in 2019
Li	7.8	7.3	8.8 (4.6)	16.0	15.1	18.3 (9.6)	17
Co	8.1	3.5	4.3	16.8	7.1	8.8	7
Ni	43.0	18.1	21.9	88.9	37.2	44.7	89
Mn	5.2	2.2	2.7	10.6	4.5	5.5	810
Al	89.3	106.5	67.4	183.8	218.7	138.1	77.9*
Cu	59.8	66.8	37.6	121.0	134.6	75.4	870
Graphite	62.4	74.8	32.6	128.8	154.4	66.2	300
Si	2.4	1.0	1.2	5.0	2.1	2.4	Ample‡

Supplementary Table 2.17: Effects of recycling on cumulative demand for Li, Ni, Co, Mn, Al, Cu, graphite, and Si in 2020-2050. Numbers in the table represent reduction percentages by recycling compared to primary cumulative demand. Note Li demand includes Li ion demand (in the form of lithium chemicals) and Li metal demand in the Li-S/Air battery scenario. For example, 20.2% (8.0%) under the STEP scenario is shown in the form of the reduction percentage of total Li demand (reduction percentage of Li metal demand). The reduction percentage of total Li demand is more than 2 times the reduction percentage of Li metal demand. From this table, we can see the reduction of cumulative material demand through 2050 could reach around 20%-30% by recycling in the NCX and LFP scenarios, while it is raised to around 30%-40% in the Li-S/Air scenario due to the quick shift of battery chemistry in this scenario. There is no big difference in reduction percentages among materials and between the STEP scenario and SD scenario.

Materials	STEP scenario, NCX	STEP scenario, LFP	STEP scenario, Li-S/Air	SD scenario, NCX	SD scenario, LFP	SD scenario, Li-S/Air
Li	23.2%	23.1%	21.3% (8.4%)	21.6%	21.5%	19.9% (8.3%)
Co	28.2%	32.5%	44.0%	26.3%	29.5%	41.0%
Ni	23.6%	26.6%	37.7%	22.2%	24.6%	35.4%
Mn	28.1%	33.0%	44.1%	25.9%	29.4%	40.6%
Al	23.2%	22.6%	28.0%	21.7%	21.2%	26.0%
Cu	23.1%	22.8%	31.7%	21.6%	21.3%	29.6%
Graphite	24.2%	23.0%	38.2%	22.5%	21.5%	35.6%
Si	16.7%	18.0%	27.3%	15.9%	17.0%	25.9%

Supplementary Table 2.18: Closed-loop recycling potential (CLRP) in 2020-2029, 2030-2039, 2040-2050 in the STEP scenario by battery chemistry scenarios, recycling technologies, and second life use.

Battery scenarios		*NCX*			*LFP*			*Li-S/Air*		
Time periods		*2020-2029*	*2030-2039*	*2040-2050*	*2020-2029*	*2030-2039*	*2040-2050*	*2020-2029*	*2030-2039*	*2040-2050*
Li ion	*No second life, pyro*	0.03	0.17	0.28	0.03	0.17	0.28	0.03	0.24	0.50
	No second life, hydro	0.03	0.17	0.28	0.03	0.17	0.28	0.03	0.24	0.50
	No second life, direct	0.03	0.17	0.28	0.03	0.17	0.28	0.03	0.24	0.50
	Second life, pyro	0.01	0.04	0.13	0.01	0.04	0.10	0.01	0.06	0.26
	Second life, hydro	0.01	0.04	0.13	0.01	0.04	0.10	0.01	0.06	0.26
	Second life, direct	0.01	0.04	0.13	0.01	0.04	0.10	0.01	0.06	0.26
Li metal	*No second life, mechanical*							0.00	0.00	0.11
	Second life, mechanical							0.00	0.00	0.03
Co	*No second life, pyro*	0.04	0.19	0.36	0.06	0.33	0.38	0.04	0.28	0.71
	No second life, hydro	0.04	0.19	0.36	0.06	0.33	0.38	0.04	0.28	0.71
	No second life, direct	0.03	0.17	0.33	0.06	0.30	0.35	0.03	0.25	0.65
	Second life, pyro	0.01	0.06	0.17	0.02	0.10	0.22	0.01	0.08	0.36
	Second life, hydro	0.01	0.06	0.17	0.02	0.10	0.22	0.01	0.08	0.36
	Second life, direct	0.01	0.05	0.15	0.02	0.10	0.20	0.01	0.08	0.33
Ni	*No second life, pyro*	0.02	0.15	0.29	0.04	0.26	0.30	0.02	0.23	0.56
	No second life, hydro	0.02	0.15	0.29	0.04	0.26	0.30	0.02	0.23	0.56
	No second life, direct	0.02	0.14	0.27	0.04	0.24	0.28	0.02	0.21	0.52
	Second life, pyro	0.01	0.04	0.12	0.01	0.08	0.16	0.01	0.06	0.27
	Second life, hydro	0.01	0.04	0.12	0.01	0.08	0.16	0.01	0.06	0.27
	Second life, direct	0.01	0.04	0.11	0.01	0.07	0.15	0.01	0.06	0.25
Mn	*No second life, pyro*	0.05	0.18	0.32	0.09	0.33	0.33	0.05	0.27	0.62
	No second life, hydro	0.06	0.20	0.35	0.10	0.36	0.36	0.06	0.30	0.68
	No second life, direct	0.05	0.18	0.32	0.09	0.33	0.33	0.05	0.27	0.62
	Second life, pyro	0.01	0.07	0.18	0.02	0.13	0.24	0.01	0.10	0.39
	Second life, hydro	0.02	0.07	0.19	0.03	0.14	0.26	0.02	0.11	0.43
	Second life, direct	0.01	0.07	0.18	0.02	0.13	0.24	0.01	0.10	0.39
Al	*No second life, pyro*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	No second life, hydro	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.21	0.36
	No second life, direct	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.21	0.36
	Second life, pyro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Second life, hydro	0.02	0.11	0.21	0.02	0.09	0.18	0.02	0.13	0.27
	Second life, direct	0.02	0.11	0.21	0.02	0.09	0.18	0.02	0.13	0.27
Cu	**No second life, pyro**	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.23	0.43
	No second life, hydro	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.23	0.43
	No second life, direct	0.03	0.17	0.28	0.03	0.16	0.28	0.03	0.23	0.43
	Second life, pyro	0.01	0.06	0.15	0.01	0.04	0.11	0.01	0.08	0.24
	Second life, hydro	0.01	0.06	0.15	0.01	0.04	0.11	0.01	0.08	0.24
	Second life, direct	0.01	0.06	0.15	0.01	0.04	0.11	0.01	0.08	0.24
Graphite	**No second life, pyro**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	No second life, hydro	0.03	0.18	0.29	0.03	0.16	0.28	0.03	0.27	0.57
	No second life, direct	0.03	0.18	0.29	0.03	0.16	0.28	0.03	0.27	0.57
	Second life, pyro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Second life, hydro	0.01	0.05	0.14	0.01	0.03	0.09	0.01	0.07	0.31
	Second life, direct	0.01	0.05	0.14	0.01	0.03	0.09	0.01	0.07	0.31
Si	**No second life, pyro**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	No second life, hydro	0.01	0.08	0.20	0.01	0.13	0.21	0.01	0.13	0.38
	No second life, direct	0.01	0.08	0.20	0.01	0.13	0.21	0.01	0.13	0.38
	Second life, pyro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Second life, hydro	0.00	0.02	0.07	0.00	0.03	0.09	0.00	0.03	0.16
	Second life, direct	0.00	0.02	0.07	0.00	0.03	0.09	0.00	0.03	0.16

Supplementary Table 2.19: Annual material demand in 2050 by three battery chemistry scenarios without recycling, with recycling, and with recycling and second life, and 2019 global mining production (unit: Mt) in the STEP scenario. The annual demand in 2050 for Li, Ni, Co, and graphite (natural graphite) from EV batteries alone exceed global mining production in 2019.

Materials	*Demand sceanrios*	*Battery scenarios / Mt*			*2019 annual production / Mt*	*Demand as percent of 2019 production*		
		NCX	*LFP*	*Li-S/Air*		*NCX*	*LFP*	*Li-S/Air*
Li	*Without recycling*	0.65	0.62	0.77	0.077	848%	807%	1002%
	With recycling	0.45	0.43	0.55		590%	565%	715%
	With recycling and second life	0.55	0.54	0.66		717%	707%	863%
Co	*Without recycling*	0.62	0.25	0.25	0.14	440%	179%	176%
	With recycling	0.37	0.15	0.10		265%	107%	72%
	With recycling and second life	0.49	0.19	0.14		347%	136%	102%
Ni	*Without recycling*	3.75	1.53	1.50	2.7	139%	57%	56%
	With recycling	2.57	1.04	0.81		95%	39%	30%
	With recycling and second life	3.16	1.25	1.04		117%	46%	38%
Mn	*Without recycling*	0.40	0.16	0.16	19	2%	1%	1%
	With recycling	0.25	0.10	0.07		1%	1%	0%
	With recycling and second life	0.30	0.12	0.08		2%	1%	0%
Al	*Without recycling*	7.53	9.08	5.25	64	12%	14%	8%
	With recycling	5.25	6.37	3.45		8%	10%	5%
	With recycling and second life	5.79	7.18	3.81		9%	11%	6%
Cu	*Without recycling*	5.06	5.68	2.73	20	25%	28%	14%
	With recycling	3.55	3.99	1.70		18%	20%	8%
	With recycling and second life	4.21	4.91	2.04		21%	25%	10%
Graphite	*Without recycling*	5.11	6.31	2.04	1.1	464%	574%	186%
	With recycling	3.48	4.40	1.08		317%	400%	98%
	With recycling and second life	4.27	5.57	1.37		388%	506%	125%
Si	*Without recycling*	0.25	0.10	0.10	7	4%	1%	1%
	With recycling	0.19	0.08	0.07		3%	1%	1%
	With recycling and second life	0.22	0.09	0.08		3%	1%	1%

Supplementary Table 2.20: Annual material demand in 2050 by three battery chemistry scenarios without recycling, with recycling, and with recycling and second life, and 2019 global mining production (unit: Mt) in the SD scenario.

Materials	*Demand sceanrios*	*Battery scenarios / Mt*			*2019 annual production / Mt*	*Demand as percent of 2019 production*		
		NCX	*LFP*	*Li-S/Air*		*NCX*	*LFP*	*Li-S/Air*
Li	*Without recycling*	1.33	1.26	1.57	0.077	1724%	1641%	2038%
	With recycling	0.91	0.87	1.11		1183%	1133%	1435%
	With recycling and second life	1.23	1.19	1.46		1593%	1542%	1899%
Co	*Without recycling*	1.25	0.51	0.50	0.14	894%	364%	358%
	With recycling	0.74	0.30	0.20		527%	214%	141%
	With recycling and second life	1.12	0.45	0.40		801%	320%	283%
Ni	*Without recycling*	7.63	3.10	3.05	2.7	282%	115%	113%
	With recycling	5.15	2.09	1.60		191%	77%	59%
	With recycling and second life	7.04	2.83	2.59		261%	105%	96%
Mn	*Without recycling*	0.81	0.33	0.33	19	4%	2%	2%
	With recycling	0.49	0.20	0.14		3%	1%	1%
	With recycling and second life	0.72	0.29	0.25		4%	2%	1%
Al	*Without recycling*	15.27	18.37	10.66	64	24%	29%	17%
	With recycling	10.51	12.71	6.91		16%	20%	11%
	With recycling and second life	13.54	16.47	9.22		21%	26%	14%
Cu	*Without recycling*	10.09	11.28	5.44	20	50%	56%	27%
	With recycling	6.97	7.80	3.32		35%	39%	17%
	With recycling and second life	9.24	10.50	4.75		46%	53%	24%
Graphite	*Without recycling*	10.39	12.84	4.16	1.1	944%	1167%	378%
	With recycling	6.98	8.82	2.15		634%	802%	196%
	With recycling and second life	9.55	12.09	3.48		868%	1099%	317%
Si	*Without recycling*	0.50	0.20	0.20	7	7%	3%	3%
	With recycling	0.38	0.16	0.13		5%	2%	2%
	With recycling and second life	0.47	0.19	0.18		7%	3%	3%

Supplementary Table 2.21: Selected specific energy of Li-S and Li-Air cells used for calculating material compositions and sensitivity analysis values for specific energy(unit: Wh/kg), which is based on Supplementary Table 2.22 and Supplementary Table 2.1.

Chemistry	Baseline	Sensitivity analysis
Li-S	400	600
Li-Air	500	1000

Supplementary Table 2.22: Sensitivity analysis of lower battery lifespan (*i.e.*, one EV will use 1.5 battery packs on average after 2020, while in the baseline scenario one EV will use 1 battery pack after 2020) for cumulative demand for Li, Co, Ni, Mn, Al, Cu, graphite, and Si in 2020-2050 without recycling, compared to global known reserves in 2019 (unit: Mt). * Yearend production capacity for Al reserve. ‡ Si reserves are not available, but ample for use. Known reserves in 2019 are referred from USGS[144].

Materials	STEP scenario, NCX scenario	STEP scenario, NCX scenario, with lower battery lifespan	SD scenario, NCX scenario	SD scenario, NCX scenario, with lower battery lifespan	Known reserves in 2019
Li	7.8	8.8	16.0	18.1	17
Co	8.1	9.2	16.8	18.9	7
Ni	43.0	49.0	88.9	100.6	89
Mn	5.2	5.8	10.6	12.0	810
Al	89.3	101.6	183.8	207.6	77.9*
Cu	59.8	68.1	121.0	136.9	870
Graphite	62.4	70.9	128.8	145.3	300
Si	2.4	2.8	5.0	5.7	Ample‡

Supplementary Table 2.23: Review of cathode capacity of NCM523 (unit: mAh/g). We use the average number in this table as input into the BatPaC model to calculate battery material compositions of NCM523 chemistry.

References	Cathode capacity of NCM523
Ref1[145]	157
Ref2[146]	164
Ref3[147]	150
Ref3[147]	142
Ref3[147]	175
Average	158

Supplementary Table 2.24: Review of cathode capacity of NCM811 (unit: mAh/g). We use the average number in this table as input into the BatPaC model to calculate battery material compositions of NCM811-Graphite (Si).

References	Cathode capacity of NCM811
Ref1[148]	207
Ref2[145]	200
Ref3[147]	194
Ref3[147]	185
Ref3[147]	178
Ref3[147]	186
Ref3[147]	188
Ref3[147]	193
Ref4[149]	192
Average	191

Supplementary Table 2.25: Review of cathode capacity of NCM955 (unit: mAh/g). We use the average number in this table as input into the BatPaC model to calculate battery material compositions of NCM955-Graphite (Si).

References	Cathode capacity of NCM955
Ref1[147]	205
Ref2[149]	217
Average	211

Supplementary Table 2.26: EV battery material compositions on pack level calculated by the BatPaC model (unit: kg per battery pack). Note the material compositions of Li-S and Li-Air are calculated based on literature and report data. Table continued till Page 80.

EV types	Materials	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
Small BEVs	Li ion	3.29	3.40	4.68	4.54	3.94	4.00	3.72	3.33	0.29	0.23
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.44	3.37
	Ni	0.00	21.97	11.50	16.73	17.38	17.74	21.97	22.10	0.00	0.00
	Co	0.00	4.14	11.55	6.72	5.82	5.94	2.76	1.30	0.00	0.00
	Mn	0.00	0.00	10.77	9.40	5.42	5.53	2.57	1.15	0.00	0.00
	Al	58.66	45.71	49.02	48.42	46.33	44.33	43.23	42.23	24.63	19.83
	Cu	29.14	24.51	26.74	26.29	24.71	24.97	24.16	23.88	9.66	0.55
	Graphite	39.18	35.30	36.19	35.74	34.95	23.58	23.17	22.67	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	2.33	2.29	2.24	0.00	0.00
Mid-size BEVs	Li	6.62	6.84	9.43	9.14	7.94	8.06	7.49	6.72	0.58	0.47
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.95	6.79
	Ni	0.00	44.26	23.18	33.71	35.00	35.73	44.26	44.51	0.00	0.00
	Co	0.00	8.33	23.27	13.54	11.71	11.96	5.55	2.61	0.00	0.00

	Mn	0.00	0.00	21.70	18.93	10.92	11.15	5.18	2.32	0.00	0.00
	Al	106.87	83.41	87.69	86.68	84.12	80.35	78.98	77.11	45.30	36.50
	Cu	56.33	49.16	49.70	49.17	48.54	49.08	48.58	48.03	20.00	1.53
	Graphite	78.84	70.93	72.79	71.87	70.24	47.39	46.55	45.55	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	4.69	4.60	4.51	0.00	0.00
Large BEVs	Li	10.01	10.34	14.24	13.81	11.99	12.17	11.32	10.15	0.88	0.71
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.54	10.27
	Ni	0.00	66.86	35.02	50.93	52.88	53.97	66.86	67.25	0.00	0.00
	Co	0.00	12.59	35.16	20.46	17.70	18.06	8.39	3.95	0.00	0.00
	Mn	0.00	0.00	32.78	28.60	16.50	16.84	7.82	3.50	0.00	0.00
	Al	162.87	127.52	134.00	132.45	128.57	122.92	120.86	118.01	68.46	55.16
	Cu	92.60	80.24	81.37	80.50	79.37	79.90	79.05	78.09	32.63	4.25
	Graphite	119.32	107.42	110.22	108.83	106.37	71.77	70.51	69.00	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	7.10	6.97	6.82	0.00	0.00
Small PHEVs	Li	1.74	1.79	2.47	2.39	2.08	2.11	1.96	1.76	0.15	0.12
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.86	1.78
	Ni	0.00	11.56	6.05	8.80	9.14	9.33	11.56	11.63	0.00	0.00

	Co	0.00	2.18	6.08	3.53	3.06	3.12	1.45	0.68	0.00	0.00
	Mn	0.00	0.00	5.66	4.94	2.85	2.91	1.35	0.60	0.00	0.00
	Al	35.16	21.27	26.66	26.32	21.82	20.95	20.38	19.59	10.89	8.78
	Cu	34.72	24.49	25.98	25.65	24.76	25.30	24.74	24.02	11.27	5.24
	Graphite	20.47	18.48	18.95	18.72	18.30	12.34	12.13	11.87	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	1.22	1.20	1.17	0.00	0.00
Mid-size PHEVs	Li	0.81	0.83	1.13	1.10	0.96	0.97	0.90	0.81	0.07	0.06
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	0.82
	Ni	0.00	5.30	2.77	4.04	4.19	4.28	5.30	5.33	0.00	0.00
	Co	0.00	1.00	2.79	1.62	1.40	1.43	0.66	0.31	0.00	0.00
	Mn	0.00	0.00	2.60	2.27	1.31	1.33	0.62	0.28	0.00	0.00
	Al	23.16	15.10	15.59	15.40	15.01	12.41	12.30	12.23	5.95	4.79
	Cu	29.89	20.06	20.05	19.82	19.63	20.37	20.32	20.35	6.76	3.67
	Graphite	9.43	8.55	8.77	8.66	8.46	5.71	5.61	5.49	0.00	0.00
	Si	0.00	0.00	0.00	0.00	0.00	0.56	0.55	0.54	0.00	0.00
Large PHEVs	Li	1.21	1.24	1.71	1.66	1.44	1.46	1.36	1.22	0.11	0.09
	Li metal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.98	1.23

Ni	0.00	7.99	4.18	6.09	6.32	6.45	7.99	8.04	0.00	0.00
Co	0.00	1.50	4.20	2.44	2.11	2.16	1.00	0.47	0.00	0.00
Mn	0.00	0.00	3.92	3.42	1.97	2.01	0.93	0.42	0.00	0.00
Al	35.69	20.27	21.45	21.17	20.16	19.75	19.56	19.41	8.23	6.63
Cu	44.74	30.21	30.86	30.52	29.50	30.42	30.39	30.45	10.90	6.10
Graphite	14.18	12.84	13.17	13.01	12.72	8.58	8.42	8.24	0.00	0.00
Si	0.00	0.00	0.00	0.00	0.00	0.85	0.83	0.82	0.00	0.00

Supplementary Table 2.27: Al and Cu compositions in EV batteries on module level as results of BatPaC model (unit: kg in battery modules). We include this table only for Al and Cu here as the second-use of EV batteries are assumed to happen on battery module level which will delay materials available for recycling. Note Li, Co, Ni, Mn, graphite, and Si compositions on battery module level are the same as that on the battery pack level in Supplementary Table 2.11.

EV types	Materials	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
Small BEVs	Al	27.06	20.41	22.42	22.06	20.77	19.99	19.36	18.90	10.29	8.36
	Cu	28.24	23.73	25.95	25.50	23.93	24.17	23.36	23.09	9.22	0.19
Mid-size BEVs	Al	52.23	40.25	42.11	41.63	40.40	38.81	38.09	37.19	20.58	16.72
	Cu	53.87	47.07	47.58	47.07	46.45	46.94	46.46	45.92	18.79	0.57
Large BEVs	Al	79.49	61.56	64.36	63.64	61.78	59.43	58.36	57.00	30.95	25.15
	Cu	88.86	77.00	78.10	77.24	76.13	76.60	75.77	74.83	30.78	2.77
Small PHEVs	Al	18.18	11.30	12.69	12.47	11.71	11.30	10.91	10.37	5.30	4.30
	Cu	22.28	13.71	15.45	15.18	14.22	14.39	13.89	13.18	6.55	5.24
Mid-size PHEVs	Al	13.61	7.70	7.90	7.77	7.57	7.55	7.50	7.51	2.55	2.07
	Cu	19.41	10.42	10.37	10.19	10.04	10.49	10.52	10.69	4.59	3.67
Large PHEVs	Al	19.30	10.76	11.48	11.29	10.61	10.55	10.46	10.45	3.73	3.03
	Cu	27.58	14.55	15.29	15.02	14.07	14.63	14.65	14.85	7.62	6.10

Supplementary Table 2.28: EV battery pack weight as result of the BatPaC model (unit: kg). PHEV battery weight is much smaller than that of BEVs because of the difference in required battery capacity between BEVs and PHEVs. For any car type and segment, we can see a decrease in battery pack weight to provide the same energy capacity due to the improvements of the specific energy of battery chemistries (see Supplementary Table 2.27).

EV types	LFP	NCA	NCM111	NCM523	NCM622	NCM622-Graphite (Si)	NCM811-Graphite (Si)	NCM955-Graphite (Si)	Li-Sulphur	Li-Air
Small BEVs	269.94	194.99	218.63	214.67	200.36	187.16	180.17	172.00	111.75	90.20
Mid-size BEVs	514.05	373.09	413.66	406.40	382.34	355.97	344.24	328.02	215.36	173.08
Large BEVs	782.36	568.63	630.24	619.15	582.64	542.50	524.53	499.89	325.13	260.91
Small PHEVs	171.05	114.88	131.51	129.27	118.20	111.85	108.01	102.71	65.34	53.07
Mid-size PHEVs	107.49	72.79	77.61	76.44	73.27	68.69	67.34	65.64	35.56	29.25
Large PHEVs	159.24	104.21	112.76	111.01	104.89	101.28	99.25	96.66	51.20	41.76

2.6.3 Supplementary Methods

Battery and EV lifespans

The probability of Weibull lifespan distribution[79] is given by equation (1):

$$f(y) = \begin{cases} \alpha\beta^{-\alpha}(y-a)^{\alpha-1}exp\left\{-\left(\frac{y-a}{\beta}\right)^{\alpha}\right\} & if\ y > a; \\ 0 & otherwise. \end{cases} \quad (1)$$

where α is the shape parameter (α > 0); β is the scale parameter (β > 0); y is the year; a is the minimum lifespan.

By assuming the cumulative probability of Weibull lifespan distribution function between the minimum and the maximum lifespans as 99.7% (based on the normal distribution), the α and β in the Weibull lifespan distribution can be calculated by equations (2) and (3)[79]:

$$1 - exp\left\{-\left(\frac{c-a}{\beta}\right)^{\alpha}\right\} = 99.7\% \quad (2)$$

$$d = a + \beta\left(\frac{\alpha-1}{\alpha}\right)^{1/\alpha} \quad (3)$$

where c is the maximum lifespan; d is the most likely lifespan.

Battery replacement and reuse

Supplementary Table 2.29: Assumptions of battery replacement rate, based on the assumptions of EV and battery lifespan distribution (Supplementary Table 2.19 and Supplementary Table 2.20).

Period	Battery replacement rate
2005-2019	50%
2020-2050	0%

Battery stock dynamics model

Based on assumptions on lifespan distributions of EVs and replacement rate and reuse rate of EV batteries, we calculate the battery flows by equations (4) and (5):

$$B_{e,b,out}(y) = B_{e,b,in}(y) - \Delta B_{e,b,stk}(y) \quad (4)$$

$$B_{e,b,out}(y) = 1.5 * (B_{e,b,in}(2005) \times \int_{y-2005}^{y-2004} f_E(y)dy + B_{e,b,in}(2006) \times \int_{y-2006}^{y-2005} f_E(y)dy + \cdots + B_{e,b,in}(y-1) \times \int_{1}^{2} f_E(y)dy \quad (5)$$

where E, B, in, stk, and out are abbreviations of EV, battery, inflow, stock, and outflow respectively; e and b are the categories of EV and battery; $f_E(y)$ are lifespan distributions of EVs. 1.5 in equation (5) refers to battery replacement means one single EV uses 1.5 battery packs on average during EV lifespan.

2.6.4 Supplementary Notes

Supplementary Note 2.1

Average battery cell voltage = Average voltage of cathode – average voltage of anode. Relative to Li^+/Li, the average voltage of graphite (360 mAh/g) and Si are 0.15 V and 0.4 V. The average voltage of the graphite (Si) anode with 517 mAh/g active capacity can be estimated as (360/517)*0.15 + (157/517)*0.4 = 0.226 (V), based on assumption of a capacity averaged linear combination of graphite and Si[150]. Therefore, compared to NCM622-Graphite, the open circuit voltage of NCM622-Graphite (Si) will be reduced by 0.226-0.15 = 0.076 (V)[150].

Supplementary Note 2.2

The cell material compositions of Li-S batteries are obtained from[140], where required cell materials are scaled linearly by a factor between cell level energy capacity and required capacity of BEVs/PHEVs). The pack components of Li-S are calculated based on the pack configurations of default NCA chemistry in the BatPaC model[70], which means the weight ratio of cell components and pack components, as well as the weight ratios of various components/materials in the pack configurations for Li-S are assumed equal to the NCA chemistry in the BatPaC model[70]. Similarly, we also use the same calculation methods for the material compositions of Li-Air packs, based on the cell level material compositions of the Li-Air battery from[141].