Supplementary Information *for*

Lithium-ion battery recycling relieves the threat to material scarcity amid China's electric vehicle ambitions

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Table of Contents

Supplementary Figures 1-31

Supplementary Notes

Supplementary Note 1. Modelling overview

We comprehensively consider the dynamics of critical materials, environmental impact assessment, geospatial optimization, and economic feasibility of electric vehicle (EV) battery recycling under the constraints of carbon neutrality targets. This work constructs a panoramic framework that interlinks resource efficiency, emission mitigation, geographic planning, and economic sustainability. To do this, we develop an integrated top-down and bottom-up model, containing six major modules related to future electric vehicle demand, battery scrappage dynamics, critical materials cycle, life-cycle CO_2 emissions, recycling layout optimization, and cost-effectiveness assessment. The modelling framework can be found in Supplementary Figure 1.

Specifically, we first develop a top-down and bottom-up combined EV demand projection model for capturing the future EV demand trajectory in China's carbon neutrality (CN60) target. Based on the pattern of EV and lithium-ion batteries (LIBs) retirement, we simulate the annual inflow-outflow relationship of LIBs and calculate the volumes of battery decommissioning and recycling.

To evaluate the integrated influence of technical, economic, environmental, and spatial factors, we adopt the explorative scenario-based analysis. Given the uncertainty of forecasts of markets and technologies, we define two LIB retirement patterns (low and high battery service life), four changing cathode chemistries (business-as-usual, LFP-dominated, NMC-dominated and NCA-dominated cathode), three recycling processes (pyrometallurgical recycling process, hydrometallurgical recycling process and direct cathode recycling process), two critical material recycling technology, and three battery collection rates driven by the assumption of recycling infrastructure advancement (low, medium, and high battery collection rate).

We then examined the material demand and recovery of cobalt, lithium, nickel, and manganese at the pack level at the boundary of life-cycle process of EVs, including the EVs manufacture and use, LIBs use, LIBs secondary use, as well as waste management and recycling, based on dynamic material flow analysis (dMFA); life-cycle estimates of the co-benefits associated with CO_2 reduction were also considered, including battery production, transportation, collection, and recycling, via life-cycle assessment (LCA). Since LCA operates on a static basis, we simulate the future electricity supply mix and update carbon emission factors every five years. These periodic updates enable the transformation of the static LCA model into a dynamic model for analyzing CO_2 emissions over time.

Moreover, we also optimize the locations of EV battery recycling facilities to reduce transportation costs and emissions, while minimizing safety risks during battery transport. We collect data on plant-level battery collection points and potential recycling facility sites. By considering factors such as plant-level battery inflow volumes, road connectivity, transportation infrastructure accessibility, and proximity to energy facilities, we calculate a weighted score for each collection point. The optimal geographic configuration and capacity of recycling facilities are determined by minimizing transportation distances and costs.

In addition, we also estimate the cost-benefit related to three battery recycling processes in order to explore whether these recycling selections are cost-effective. we utilize the EverBatt model for the cost assessment of battery recycling, which offers greater flexibility in customizing cost parameters, including those related to economies of scale and logistics distance. EverBatt model provides detailed process-level cost breakdowns for both manufacturing and recycling, accounting for capacity constraints and technical assumptions.

Based on scenario analysis with these key element combinations, we exploit a range of possible outcomes and found the optimal pathway for the LIB closed-loop recycling system to assist in EV adoption under carbon neutrality. The temporal boundary is set from 2010 to 2060, and the spatial boundary is limited to the Chinese market due to its large-scale EV employment ambition to support planned carbon neutrality. We consider a range of vehicle technologies, consisting of compact battery electric car (Car BEV), compact plug-in hybrid electric car (Car PHEV), battery electric large car and sport utility vehicle (Large Car BEV), plug-in hybrid electric large car and sport utility vehicle (Large Car PHEV), mini-sized battery electric car (Mini Car BEV), mini-sized plug-in hybrid electric car (Mini Car PHEV), battery electric light truck, battery electric medium truck, and battery electric heavy truck. For the battery technology, six types of LIBs are investigated, including four cathodes of nickel cobalt manganese (NMC111, NMC 523, NCM622, and NCM811), nickel cobalt aluminium (NCA), and lithium iron phosphate (LFP).

Supplementary Note 2. Scenario settings

Given the uncertainty of forecasts of markets and technologies, we take diverse aspects of latent scenarios, involving LIB retirement patterns, cathode chemistries, recycling processes, and recycling advancement, into consideration, as listed in Table 1 and Supplementary Table 1. For LIB retirement patterns, we set two scenarios based on elevating technological progress in terms of prolonged battery lifespan: one as the low service life, and the other as the high battery service life accompanied by advanced technologies, e.g., atom-thin layer on battery cathode[1].

We define four changing cathode chemistry scenarios because battery cathode technology is a key determinant shaping critical material inflows and outflows, as well as ambient emissions in the recycling process.

Business-as-usual cathode scenario (CBAU) assumes that the 2020 market share remains unchanged until 2060: 48% LFP, 6% NMC111, 9% NMC523, 24% NMC622, 7% NMC811, and 6% NCA cathode[2].

The LFP-dominated cathode scenario (CLFP) indicates that the cathode chemistry market turns to developing cobalt-free battery technology to reduce cost and high-value material supply risk[3]. The mature LFP cathode gradually replaces NMC and NCA from 2020 onwards and will constitute 80% of the cathode market by 2060.

The NMC-dominated cathode scenario (CNMC) supposes the evolution of cathode technology to “low cobalt and high nickel”, such as NMC811 and advanced NCA[4]. Market shares are assumed to transition to 80% NMC811, 10% LFP and 10% NCA by

2060.

The NCA-dominated cathode scenario (CNCA) considers the widespread availability of cutting-edge battery technology with low-cobalt and manganese-free equipment, high energy capacity and security of LIBs[4]. We assume that this wide breakthrough will constitute an 80% market share by 2060, with 10% shares of NMC811 and LFP each.

Then, three recycling processes (pyrometallurgical, hydrometallurgical, and direct cathode recycling) are considered due to their discrepant contents of substance recovery, energy input and environmental implications[5]. For example, the pyrometallurgical process can recover cobalt and nickel from LIBs, but this process cannot recover lithium[6]. The direct cathode recycling process could retain the structure and properties embodied in the primal production process of the battery, achieving effective recovery of high-value materials[7]. Pyrometallurgical and hydrometallurgical processes are current mainstream recycling processes that are commercial, whereas direct cathode recycling processes are under development.

Two material recycling rates are proposed to account for anticipated recycling technologies advancement. The baseline material recycling rates of cobalt, lithium, nickel, and manganese are established at 95%, 80%, 95%, and 95%, respectively[8]. In comparison to the default condition, the progressive material recycling rates scenario realizes the complete recovery of critical materials.

Three battery collection rates driven by public recycling awareness improvement and infrastructure advancement are assumed, identifying the contrast from the conservative benchmarks to theoretically most efficient practice. The benchmark collection rate is supposed to be 65% of LIBs being recycled for all years (low collection level). In progressive and ideal conditions, the battery recycling rate would be achieved 85% (medium level) and complete recovery (high level) respectively[3, 9, 10].

Supplementary Note 3. EV adoption trajectory in China's carbon neutrality path

We adopt an integrated top-down and bottom-up model to simulate the EV demand at a yearly interval from 2020 to 2060. We derive the future population, economic development, electricity demand in the transportation sector, and carbon price under China's carbon neutrality from the top-down Global Change Assessment Model (GCAM) model. Then, we input these key parameters into the EV forecasting model to interact with this top-down and bottom-up combined projection model. In the bottom-up part, we adopt the Bass model to forecast the EV demand trajectory, which allows us to consider the impact of vehicle ownership costs, infrastructure factors, user driving behaviour, etc. In this way, the EV demand is assessed under China's climate mitigation commitment.

3.1 Top-down model: China's carbon neutrality construction

The GCAM model is a coupling cross-systems (including economic, energy, climate, agriculture & land, and water) model, providing a series of global and regional parameters relevant to socioeconomic development, energy supply and demand, climate change assessment and so on under future SSP-climate-energy policies. In our work, we construct the net zero emissions scenario following SSP1 (the most sustainable) in China. China's specific parameters such as socioeconomic development, population, energy and carbon price under future SSP1-carbon neutrality are thereby directly obtained. Note that these parameters under China's carbon neutrality every 5 years from 2020-2060. We linearly interpolate the 5-year interval data to obtain China's annual relevant data. These scaled parameters are used as the input of our annual bottom-up EV demand projection model.

3.2 Bottom-up model: annual EV adoption forecast based on Bass model

The Bass model is extensively applied in research on market share, technology adoption, and diffusion of innovative products, including EVs[11, 12, 13]. Two key parameters of the Bass model are: i) the innovation coefficient p, reflecting the propensity of EV adopters to independently embrace EVs; and ii) the imitation coefficient q, reflecting the influence of external factors (e.g. mass media or advertisement) on the decision of EV adopters to embrace EVs[13, 14]. This model captures the long-term EV S-shape growing trend. Specifically, the S-shaped growth trend of the adoption curve signifies a gradual initial growth phase (driven by innovators' personal interests and technological distinctiveness), followed by rapid acceleration (influenced by promotional measures, prompting rapid imitation by followers), ultimately culminating in a stable trend. The representation of the Bass model is as follows:

$$\frac{dY(t)}{dt} = [p + \frac{q}{m(t)} Y(t)][m(t) - Y(t)]x(t) \tag{1}$$

where $\frac{dY(t)}{dt}$ is the rate of EV diffusion; $Y(t)$ is the cumulative adoption at time t. The EV automobile market space m indicates the future demand potential. The term of $p[m(t) - Y(t)]$ represents the number of adopters whose EV purchase is influenced by external factors, which are called innovation adopters. The term of $\frac{q}{m(t)} Y(t)[m(t) - Y(t)]$ stands for EV adoptions owing to internal influence by existing adopters, which are called imitators.

In the Supplementary Equation (1), the speed of diffusion is also influenced by the change in price variable, $x(t)$, which is obtained as follows:

$$x(t) = 1 + \beta_1 \frac{\Delta Cr(t)}{Cr(t-1)} + \beta_2 \frac{\Delta P(t)}{P(t-1)}, \tag{2}$$

where $Cr(t) = \frac{C_{ev}(t)}{C_{icev}(t)}$ denotes the cost of shifting from an internal combustion engine vehicle (ICEV) to an EV ($C_{ev}(t)$ donates the total ownership cost of EV, $C_{icev}(t)$ represents the total ownership cost of ICEV), and $P(t)$ is the number of charging points, a key factor influencing charging accessibility. Additionally, $\Delta Cr(t) = Cr(t) - Cr(t-1)$ measures the change in cost ratios between two consecutive years. Similarly, $\Delta P(t) = P(t) - P(t-1)$ measures the growth in charging infrastructure between two consecutive time periods. $\frac{\Delta Cr(t)}{Cr(t-1)}$ and $\frac{\Delta P(t)}{P(t-1)}$ are relative changes in the cost ratios and charging infrastructure. Correspondingly, the β_1 and β_2 represent the relative effect of percentage changes in cost ratios and charging infrastructure on price, respectively.

3.3 Integrated top-down and bottom-up model: EV adoption trajectory under

China's carbon neutrality target

To predict the developmental trajectory of EVs under climate goals, we integrate the top-down GCAM model with the bottom-up Bass model driven by vehicle ownership costs, infrastructure factors, and user's driving behavior. We simulate future scenarios of macroeconomic, societal, and climate adaptation under given SSP and RCP combinations. The GCAM model outputs key parameters such as economic development level, population, carbon emission prices, and energy price under the set climate mitigation goals. These parameters are linked to the Bass model, providing a context for predicting the future growth trajectory of EVs under climate goals.

The parameter of market space is calculated by vehicle ownership per 1,000 capita multiplied by the further population. Assuming the lifespan of EVs is 15 years, the relationship between the annual scrappage and the new additions is characterized by the Weibull distribution.

3.4 The forecast of ownership of trucks under China's carbon neutrality target

Due to the later stage of electric truck electrification, there is not enough historical data to use the GCAM model coupled with a technologically detailed Bass model for prediction. For example, according to the data from the China Association of Automobile Manufacturers, the penetration rate of new energy light trucks and heavy trucks is only 6.2% and 5.3% among truck fleets in 2022. However, due to trucks contributing a noteworthy proportion of annual greenhouse gas emissions, the electrification of trucks is pivotal in limiting global warming[15]. Thus, electrified trucks will experience rapid growth in the coming decades and will greatly increase the prediction of future demand for batteries and materials. Here, we adopt the stock-driven dynamic dMFA model to forecast the electric truck stock and sale[16, 17]. We first calculate the vehicle-specific stock using the equations:

$$Truck_i(t) = D_i(t) \cdot L_i^{-1}(t) \cdot VKT_i^{-1}(t) \tag{3}$$

That is, the truck stock related to vehicle type i in year t is connected with the transportation demand, D_i, load factor, L_i, and the vehicle traveled kilometer, VKT_i. Although the GCAM does not count the stock of trucks explicitly, it provides the parameters of transportation demand and load factor with various truck fleets under China's CN60 target. Then, we use the stock-driven dMFA model to estimate the sale (inflow) and scrappage (outflow) of trucks:

$$truck_{i,in}(t) = truck_i(t) - truck_i(t-1) + truck_{i,out}(t) \tag{4}$$

$$truck_{i,out}(t) = \sum_{s=t-w}^{s=t-1} truck_{i,in}(t) \times F_i(t,s) \tag{5}$$

Where the $truck_{i,in}$ is the number of sales of vehicle type *i*; $truck_{i,out}$ donates the scrappage. $F_i(t,s)$ is the vehicle survival distribution of vehicle type *i* at year *s* for vehicles sold in year *t*, and *w* represents the vehicle lifespan. Vehicle survival patterns are subjected to Weibull distribution. The average life is assumed to be 8 years, 10 years, and 12 years, for light trucks, medium trucks, and heavy truck[18].

Supplementary Note 4. Roadmap of lithium-ion battery second use and recycling

The end-of-life options for collected LIBs are crucial for the demand and supply circularity of critical material, which plays a vital role in the adoption of EVs under China's carbon neutrality ambition. Therefore, we couple the battery service lifespan and battery state of health (SOH) distribution model, taking the battery secondary and recycling use into account. Further, combined with the material flow analysis, we investigate the demand for critical material from EV transition and the self-sufficiency potential (SP) from closed-loop recycling of battery materials.

The stages of the battery pack calendar and cycle lifetime for LIBs are illustrated in Supplementary Figures 2-3. The wasted batteries could be recycled from three sources: Battery replaced by early failure, direct recycling, and recycling from the echelon. To extend the battery lifespan and maximum flexibility in applications, most part of battery is prioritized second-life use before recycling. The batteries enter into echelon accounting the 1-p proportion from overall normal failure batteries. We divide batteries entered echelon utilization into direct reuse (SOH above 85%) and indirect reuse (SOH between 80% and 85%) according to the battery SOH. According above assumption, we design the process of cascaded utilization, indicating that wasted batteries are utilized as direct reuse first, and then proceed with indirect utilization. When SOH below 80% is satisfied, the batteries then flow into the recycling market. Specifically:

The amount of early failure batteries, $B_{ef}(t)$, at year t for batteries sold in year *s* is calculated in Supplementary Equation (6).

$$B_{ef}(t) = \sum_{s=t-8}^{s=t-1} EV_{sale}(s) \times F(t,s) \tag{6}$$

Where the $EV_{sale}(s)$ is the sale of EV in year *t*, and the $F(t,s) = 1 - \exp(-((t-s)/\alpha)^{\beta})$ is the EV survival probability, which describes the simulation of EV lifetime distribution. This method consists of two key parameters, a shape parameter α (indicating the time at which a majority of EVs have failed) and a scale parameter β. We assume the α and β based on different vehicle types, which is summarized in Supplementary Table 2.

Then, the amounts of replaced batteries, $RL(t)$, at year *t* for batteries sold in year *s* could be estimated as the following equation:

$$RL(t) = \sum_{t-8}^{t-1} EV_{sale}(s) \times F(t,s) \times (1 - r(s)) \tag{7}$$

Correspondingly, the repaired battery, $RA(t)$, at year *t* for batteries sold in year *s* could be obtained:

$$RA(t) = \sum_{s=t-8}^{s=t-1} EV_{sale}(s) \times F(t,s) \times r(s) \tag{8}$$

The part of the normal failure of LIBs, $B_{nf}(t)$, includes the battery failure with the EV retirement and the repaired battery in year *t*, which could be formulated by Supplementary Equation (9):

$$B_{nf}(t) = \sum_{s=1}^{s=t-9} (EV_{sale}(s) + RA(s)) \times F(t,s) \tag{9}$$

The battery processed by first use and then flowing into the recycling market directly, $RE_1(t)$, could be estimated by Supplementary Equation (10):

$$RE_1(t) = p(t) \times B_{nf}(t) = p(t) \times \sum_{s=1}^{s=t-9} (EV_{sale}(s) + RA(s)) \times F(t,s) \tag{10}$$

Where the $p(t)$ is the share of normal failure batteries on the recycling market.

The battery processed by secondary use, $SU(t)$, could be estimated by Supplementary Equation (11):

$$SU(t) = [1 - p(t)] \times B_{nf}(t) = [1 - p(t)] \times \sum_{s=1}^{s=t-9} (EV_{sale}(s) + RA(s)) \times F(t,s) \qquad (11)$$

When the wasted batteries flow into the secondary use stage, they are repurposed into the direct reuse area for low-speed EV, $DR(t)$, or into the indirect area for the energy storage system (ESS), $IR(t)$, depending on their SOH, which could be estimated by Supplementary Equation (12) and Supplementary Equation (13), respectively:

$$DR(t) = [1 - p(t)] \times (EV_{sale}(t-9) + RA(t-9)) \times F(t,9) \quad for\ SOH(t) > 85\% \qquad (12)$$

$$IR(t) = [1 - p(t)] \times \sum_{s=t-12}^{s=t-10} (EV_{sale}(s) + RA(s)) \times F(t,s) \quad for\ 80\% \leq SOH(t) < 85\% \qquad (13)$$

Where the relationship between battery lifespan and their SOH is modeled on the basis of Schmidt et al[19]. due to missing long-term experiences of EV battery calendar aging and uncertainties in battery aging models[20]. That is, all batteries would expect to reach 80% of their capacity within 12 years, and annual capacity loss shows a linear decrease[3].

The third recycling source of LIBs is from batteries retired after cascaded utilization in ESS, $RE_{ir}(t)$, which could be represented by Supplementary Equation (14):

$$RE_{ir}(t) = \sum_{s=1}^{s=t-1} IR(s) \times G(t,s) \qquad (14)$$

In which the $G(t,s)$ is the probability of product failure in year t and starting its application in year s. The scrapped curve of ESS is subjected to a normal distribution, whose average lifetime is set to 10[4], and the standard deviation is set to 2.6[21].

In summary, the total amount of wasted LIBs in EVs returning to recycling in year t, $RE(t)$, counted as the sum of three sources, including recycling batteries from the replaced battery in the early failure stage, $RL(t)$, recycling batteries from direct recycling in the normal failure stage, $RE_1(t)$, and recycling batteries from secondary use on the basis of ESS application, $RE_{ir}(t)$, could be given by Supplementary Equation (15):

$$RE(t) = RL(t) + RE_1(t) + RE_{ir}(t) \quad (15)$$

After modeling the LIB flow roadmap, the amount of critical material in year t could be derived from the Supplementary Equation (16):

$$RE_{v,i,j,m}(t) = RE_{v,i}(t) \cdot BC_v(s) \cdot CM_{v,i,j,m}(t) \cdot BCR_{v,i,j}(t) \cdot MRR_{v,i,j,m} \quad (16)$$

Where v = vehicle type, i = LIBs, j = recycling process, t = year, m = cobalt, lithium, nickel, manganese. $CM_{v,i,j,m}(t)$ is the specific material density of critical material m embodied in LIB for EV adoption in year t, which is summarized in supplementary Table 4. $BC_v(s)$ is the average capacity of EV, which is shown in supplementary Table 7. $BCR_{i,j,t}$ is battery collection rate; and $MRR_{v,i,j,m}$ is the material extraction rate via various recycling technology, which is set according to the regulations on batteries and wasted batteries issued from European Union[8].

Supplementary Note 5. Impacts of battery recycling on critical materials circularity for EVs

dMFA is used to evaluate the flow of critical materials of cobalt, lithium, nickel and manganese for lithium-ion batteries. First, retrospective dMFA is used to analyse the material inflows, outflows, and stocks of critical materials. Then, based on prospective dMFA, we quantify the amount of cobalt, lithium, nickel and manganese required for EV deployment on the path to China's carbon-neutral ambition. Furthermore, combined with the scenario analysis method, the supply of critical materials for EV power batteries is forecasted according to the retirement mode of LIB, the evolution of the battery cathode market, the recycling technology level and the development of recycling infrastructure.

We further define the equation of the critical material SP, that is, the percentage of the critical materials recycled by LIB recycling to demand for the deployment of EVs in one year, reflecting the availability and sustainability of critical materials and the degree of eliminating import dependence. SP index is presented in Supplementary Equation (17) below:

$$SP_{v,i,j,t,m} = \frac{Supply_{v,i,j,t,m}}{Demand_{v,i,j,t,m}} \times 100\% = \frac{CM^{recycled}_{v,i,j,m} \cdot BC_{v,i} \cdot RE_{v,i,t} \cdot BCR_{v,i,j,t} \cdot MRR_{v,i,j,m}}{CM^{input}_{v,i,j,m} \cdot BC_{v,i} \cdot RE_{v,i,t} \cdot BCR_{v,i,j,t} \cdot MRR_{v,i,j,m}} \times 100\% \quad (17)$$

where $Supply_{i,j,t,m}$ is the material supply via closed-loop recycling; $Demand_{i,j,t,m}$ is the material demand for the deployment of EVs.

Supplementary Note 6. Life-cycle CO_2 emissions of lithium-ion battery

To estimate the life cycle of carbon emission of LIBs, we consider the four battery phases related to the production, transportation, collection, and recycling of batteries. We especially, attach importance to the stage of battery recycling given that it provides a pathway to achieve carbon mitigation, besides its critical material relief potential, meaning that the co-benefit of resource and CO_2 reduction are expected to meet China's EV deployment ambition.

The LCA method is widely used to evaluate the environmental impact of a product throughout its entire life cycle. We calculate the carbon emission in the aforementioned four flow stages of unit batteries (1 kg), which comprises the cradle-to-grave stage, helping us illustrate the comprehensive results of LIBs. The spatial boundary is limited to China; and the temporal boundary is defined over a 40-year period, from 2020 to 2060. Note that the environmental impact is evolving with the energy transition, and thus the future electricity system will transit towards cleanliness coupled with a high proportion of renewable energy. Therefore, we construct two electricity carbon emission mixes (BAU electricity mix and CN60 electricity mix), considering the dynamics of carbon emission factors[22]. We employ the GCAM model to simulate the electricity energy mix under the China's CN60 target, and the penetration of renewable energy is steadily rising, thereby achieving the electricity decarbonization over time. Because the LCA model operates statically, we update its carbon emission factors every five years, enabling the transition from a static to a dynamic emission evaluation model.

For the process of battery production and recycling, the carbon emission is determined by Simpro 9 software (with ecoinvent 3.8 database updated on September 2021 for up-to-date battery data module; https://simapro.com/), facilitating modular modelling on the cathode-specific or technology-specific base. For the process of transportation of collection, we used the GREET 2023 model (https://www.anl.gov/topic/greet) developed by Argonne National Laboratory and designed to evaluate the energy and environmental impacts of various vehicle and fuel technologies.

Unit carbon emissions from lithium-ion battery production: We consider the six cathode chemistries, that is, LFP, NCA, NMC111, NMC523, NMC622, and NMC811. The bills of material and energy and correspondingly embodied emission are obtained from EverBatt2023 (Argonne National Laboratory; https://www.anl.gov/amd/everbatt), a closed-loop battery life-cycle model to evaluate battery-related environmental impact and technology cost.

CO_2 emissions from lithium-ion battery transportation: The battery transportation stage includes the process of transporting power batteries from the battery manufacturers to the EV manufacturers, and then, accompanying the EV sales, LIBs could be transported to the EV dealers. There are numerous LIB manufacturers in China, and we focus on Build Your Dreams (BYD), with the well-established industrial chain of LIB and EV. Since BYD is not only the leading LIBs manufacturer but the largest EV manufacturer and seller in China. Therefore, when the batteries are manufactured, we assume they are directly supplied to downstream EV manufacturing companies. After the EVs are manufactured, they are transported to the EV dealers for sale.

Here, combined with the aforementioned networks from LIB manufacture to EV sales, we collect the location information of LIB manufacturers, EV manufacturers, and EV dealers from BYD's official website (https://www.bydauto.com.cn/pc/) using Python web crawlers. Next, we utilize reverse geocoding to transform the given location information into latitude and longitude coordinates, revealing the spatial distribution of upstream and downstream companies along the industrial chain.

We consider the distance from LIB manufacturers to EV manufacturers and then to EV dealers as a measure of the transportation distance for EV batteries. Using ArcGIS, we assess transportation distances by integrating various factors, including road networks, population distribution, automotive service centers, and energy infrastructure. The closest facility analysis in ArcGIS is employed to model and identify the shortest possible transportation routes. The weighted average distance from LIB manufacturer to EV manufacturer is 301 km; The weighted average distance from EV manufacturer to EV dealers is 392 km. This transportation would be entirely by truck, and the carbon emission is 0.203 kg CO_2-eq·ton^{-1}·mile^{-1} [23]. The detailed distance information of LIB manufacturers, EV makers, and EV dealers, is shown in Supplementary Data 1-6.

CO_2 emissions from lithium-ion battery collection: When the LIBs are retired, they will be collected and sent to authorized waste LIB recycling operators for material recycling. In China, the extended producer responsibility is complemented, meaning that automobile manufacturer enterprises bear the main responsibility of LIB recycling. Currently, the EV manufacturers are working with their EV dealers to recycle wasted LIBs from EVs. Provided that the waste LIBs would be collected by the EV dealers first, and then, they will send waste LIBs to authorized waste LIB recycling operators. According to policy regulations, there are a cumulative 156 waste LIB recycling operators (including recycling and second-life applications) authorized by the Chinese government until 2024. Therefore, we assume wasted LIB would be collected by the EV dealers and then sent to these authorized LIB recycling operators based on the shortest transportation distance. We also use Python web crawlers and reverse geocoding to obtain the geospatial location of LIB recycling operators. The weighted average distance to collect the LIBs from EV dealers to LIB recycling operators is 231 km. The LIBs are collected also by truck. The detailed distance information between LIB recycling operators and EV dealers is shown in Supplementary Data 1-6.

Unit CO_2 emissions from lithium-ion battery recycling: The LCA method is used to calculate the carbon emissions of 1 kg batteries in three battery recycling technologies, including pyrometallurgy, hydrometallurgy, and direct cathode recycling process. The measurement of carbon emissions depends on the substances and energy input-output flows of lithium-ion batteries, including LFP, NMC, and NCA batteries, under different recycling processes.

Calculation of CO_2 emissions in production and recycling process: Based on the CO_2 emissions obtained for every 1 kWh lithium-ion battery, we considered factors, such as overall spent battery, battery capacity by different vehicle fleet types, battery density, cathode chemistry market, to evaluate the production and recycling carbon emissions. The environmental impact is assessed from 2020 to 2060 under various assumptions. The production and recycling emissions are presented in Supplementary Equation (18) and Supplementary Equation (19), respectively:

$$Carbon\_prod_{v,i,t} = RE_{v,i,t} \cdot BC_v \cdot carbon^p_{i,t} / BD_v \tag{18}$$

where $Carbon\_prod_{v,i,j,t}$ is the overall production carbon emissions of vehicle type v equipped with cathode *i* in year *t*. $carbon^p_{i,t}$ donates the unit production emission. $BC_{v,t}$ is the average capacity of vehicle type v, and BD_v means battery density.

$$Carbon\_recy_{v,i,t,j} = RE_{v,i,t} \cdot BC_v \cdot carbon^r_{i,t,j} \cdot BRR_t / BD_v \tag{19}$$

where $Carbon\_recy_{v,i,j,t}$ is the overall recycling carbon emissions of vehicle type *v* equipped with cathode *i* in year *t*. BRR_t represents the yearly battery recycling rate.

Supplementary Note 7. Optimizing geospatial configuration of battery recycling

In this study, the Location-Allocation analysis within ArcGIS is used to optimize the spatial configuration of battery recycling sites by identifying the most suitable facility locations and minimizing transportation distances/costs between battery collection points and recycling facilities. The integrated datasets include candidate recycling facility locations, battery collection points, and transportation networks (e.g., highways and general roads). We utilize high-resolution road data to build a network dataset in ArcGIS, accurately reflecting the connectivity of real-world road networks. To enhance the analysis, demographic distribution, automotive service facilities, and energy infrastructure networks were incorporated, allowing for a more comprehensive assessment of site suitability based on multiple geospatial factors.

Since China urges EV manufacturers to collect wasted batteries based on their sales networks. BYD Auto, with its extensive nationwide sales network, is leveraged by treating its dealer locations as proxies for battery collection points. Authorized waste LIB recycling operators are identified as potential sites for both battery recycling or second-life applications. To distribute the capacity of retired power batteries efficiently, we allocate the estimated volumes of waste batteries to each collection point based on the population distribution of cities.

We calculate the capacity of retired batteries at each collection point, along with proximity to automotive service facilities and the accessibility of energy infrastructure. Using weighted overlay analysis, we assign a weight to each battery collection point, reflecting its significance within the battery recycling and second-life utilization network.

The candidate recycling sites are set as facilities, and the battery collection points are assigned as demand points in the Location-Allocation model. Executing the Location-Allocation analysis to minimize total travel distance and logistics costs, the optimal spatial layout and size of recycling facilities, and the corresponding transportation routes from collection points is obtained. We optimize the layout of power battery recycling facilities every decade, dynamically providing snapshots of the optimal spatial configuration of LIB recycling and second-life utilization industries from 2021 to 2060.

Supplementary Note 8. Cost-benefit analysis for the battery recycling process

We conduct a comprehensive lifetime cost-benefit analysis through the method of EverBatt model[24], a process-based cost model developed by Argonne National Laboratory. We consider the process related to recycling, including transportation and collection, disassembly, and recycling process. Three recycling processes are considered, including pyrometallurgical, hydrometallurgical, and direct recycling by process-based cost model[7], taking the recycling step, material, and utility costs of the LFP battery, NMC battery and NCA battery into consideration. The transportation distance of wasted LIB is obtained from the result of spatial configuration optimization, minimizing logistics costs of battery recycling.

Process-based cost models disaggregate the inputs that constitute together in the battery recycling process into a discrete unit. We calculate the value of per tonne of spent battery recycling. This type of bottom-up modelling makes it possible to make more granular comparisons between process technologies. In our breakdown model, the costs include step-by-step expenses, material costs, and utility expenses, along with the revenues generated from the materials recovered through battery recycling. We consider every step cost related to different recycling technologies. For example, in hydrometallurgical recycling, we access the equipment inputs according to every step process, including the conveyor, shredder, low-temperature calciner, gas treatment, wet granulator, wastewater treatment, density separator, froth flotation, filter, precipitation tank, solvent extraction unit, and leaching tank. The overall cost of every equipment integrates the direct cost, indirect costs, fixed capital investment, working capital, and manufacturing cost. The material and utilities costs incorporate the cost of material and energy respectively during the battery recycling process. For pyrometallurgical recycling and direct cathode recycling, we comply with consistent modelling techniques.

The recycling plant is assumed to operate 300 days a year with 8-hour shifts per day to ensure continuous running. The equipment costs are adjusted with the location assumption in China. The equipment's useful life is 10 years.

Supplementary Tables

Supplementary Table 1. Main assumptions of key model parameters.

Parameters	Main assumption
Critical materials intensity	The critical materials intensity varies by different cathode chemistries and is assumed to remain at a current level from now to 2060.
Market shares of battery cathode chemistry	CBAU: The market shares of battery cathode chemistry are gradually turned to "low-cobalt and high-nickel"[2]. CLFP: The cathode chemistry market turns to developing cobalt-free battery technology to reduce cost and high-value material supply risk[3]. The mature LFP cathode is gradually in place of NMC and NCA from 2020 onward[4] and will take up an 80% share of the whole cathode market by 2060. CNMC: The evolution of cathode technology to "low-cobalt and high-nickel", such as NMC811, and advanced NCA[4]. CNCA: Widespread availability of cutting-edge battery technology with low-cobalt and manganese-free equipment, high energy capacity and security of LIB[4].
The share of vehicle type in EV sales	The shares of compact car, large car and sport utility vehicle, mini-sized car, light truck, medium truck, and heavy truck are obtained from the Global Change Assessment Model. The current share of BEV and PHEV is on account of 63% and 37% respectively[25]. The HPEV is assumed to turn gradually to BEV in the future, and the share of BEV will reach 80%[26].
Battery capacity and density of vehicle	We set current and future vehicle fleets by segment according to ICCT[3]. See details in Supplementary Table 7.

Battery lifetime	The battery's average lifetime is assumed to be 15 years, and in the high battery service life scenario, the battery life is extended by an additional two years based on this foundation.
Battery collection rate	The historical level of battery recycling rate in China is 20%. Collection rates are uncertain due to a lack of reporting and uncertain export rates. Therefore, the collection rate is evaluated under three scenarios, including low (65%), medium (85%), and high (100%) battery collection rate[9].
Critical materials recycling rate	The critical materials recovery rates of lithium, cobalt, nickel, and manganese are set to 80%, 95%, 95%, and 95% respectively, complying with the requirement of EU standard[8]. With the advanced technology, all critical materials could be recycled in a progress material recovery rate scenario.
Recycling processes	Three different recycling processes, pyrometallurgy, hydrometallurgy, and direct cathode recycling, are considered due to their discrepant contents of substance recovery, energy input and environmental implications. Pyrometallurgy and hydrometallurgy are current mainstream recycling processes that are commercial, whereas direct cathode recycling is under development[5, 7, 27].

Note: CBAU refers to the business-as-usual cathode scenario; CLFP, CNMC, and CNCA refer to cathode scenarios dominated by LFP (lithium iron phosphate), NMC (nickel manganese cobalt), and NCA (nickel cobalt aluminum), respectively. EV refers to electric vehicle, BEV refers to battery electric vehicle, and PHEV refers to plug-in hybrid electric vehicle.

Supplementary Table 2. Vehicle survival patterns with various vehicle type[18, 28].

Vehicle type	Shape parameter	Scale parameter
Passenger car	2.07	14.46
Light truck	5.58	8.02
Medium truck	5.58	10.09
Heavy truck	5.58	12.8

Supplementary Table 3. Market shares of LIB cathode chemistry in 2020-2060[4, 28].

Cathode scenarios	Cathode chemistry	2020	2030	2040	2050	2060
CBAU	LFP	0.480	0.480	0.480	0.480	0.480
	NCA	0.060	0.060	0.060	0.060	0.060
	NMC111	0.060	0.060	0.060	0.060	0.060
	NMC523	0.090	0.090	0.090	0.090	0.090
	NMC622	0.240	0.240	0.240	0.240	0.240
	NMC811	0.070	0.070	0.070	0.070	0.070
CLFP	LFP	0.480	0.560	0.640	0.720	0.800
	NCA	0.060	0.070	0.080	0.090	0.100
	NMC111	0.060	0.045	0.030	0.015	0
	NMC523	0.090	0.068	0.045	0.023	0
	NMC622	0.240	0.180	0.120	0.060	0
	NMC811	0.070	0.078	0.085	0.093	0.100
CNMC	LFP	0.480	0.385	0.290	0.195	0.100
	NCA	0.060	0.070	0.080	0.090	0.100
	NMC111	0.060	0.045	0.030	0.015	0
	NMC523	0.090	0.068	0.045	0.023	0
	NMC622	0.240	0.180	0.120	0.060	0
	NMC811	0.070	0.253	0.435	0.618	0.800
CNCA	LFP	0.480	0.385	0.290	0.195	0.100
	NCA	0.060	0.245	0.430	0.615	0.800
	NMC111	0.060	0.045	0.030	0.015	0

NMC523	0.090	0.068	0.045	0.023	0
NMC622	0.240	0.180	0.120	0.060	0
NMC811	0.070	0.078	0.085	0.093	0.100

Note: CBAU refers to the business-as-usual cathode scenario; CLFP, CNMC, and CNCA refer to cathode scenarios dominated by LFP (lithium iron phosphate), NMC (nickel manganese cobalt), and NCA (nickel cobalt aluminum), respectively.

Supplementary Table 4. Assumption of critical materials intensity embodied in LIBs[10, 21].

Materials ($kg\cdot kwh^{-1}$)	LFP	NCA	NMC111	NMC523	NMC622	NMC811
Cobalt	0	0.117	0.313	0.20	0.17	0.076
Lithium	0.087	0.106	0.118	0.14	0.1	0.09
Nickel	0	0.618	0.312	0.51	0.508	0.608
Manganese	0	0	0.292	0.28	0.159	0.071

Note: NCA refers to nickel cobalt aluminium; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 5. Assumption of recycling efficiency in different recycling technology[10, 29].

Recycling rate	Cobalt	Lithium	Nickel	Manganese
Pyro	98%	0%	98%	0%
Hydro	98%	90%	98%	98%
Direct	90%	90%	90%	90%

Note: Pyro refers to pyrometallurgical recycling process; Hydro Refers to hydrometallurgical recycling process; Direct refers to direct cathode recycling process.

Supplementary Table 6. Assumption of critical material recycling rate[8].

Scenarios	Cobalt	Lithium	Nickel	Manganese
Default	95%	80%	95%	95%
Progressive	100%	100%	100%	100%

Supplementary Table 7. Assumption of LIB capacity and density[3, 21].

	battery capacity (kWh)		battery density ($kWh \cdot kg^{-1}$)	
	Low	High	Low	High
Car BEV	36	69	0.118	0.235
Car PHEV	18	34.5	0.118	0.235
Large Car BEV	77	116	0.142	0.235
Large Car PHEV	38.5	58	0.142	0.235
Mini Car BEV	17	41	0.104	0.235
Mini Car PHEV	8.5	20.5	0.104	0.235
Light truck	36	69	0.118	0.235
Medium truck	80	120	0.157	0.235
Heavy truck	270	423	0.15	0.235

Note: Car BEV refers to compact battery electric car; Car PHEV refers to compact plug-in hybrid electric car; Large Car BEV refers to battery electric large car and sport utility vehicle; Large Car PHEV refers to plug-in hybrid electric large car and sport utility vehicle; Mini Car BEV refers to mini-sized battery electric car; Mini Car PHEV refers to mini-sized plug-in hybrid electric car.

Supplementary Table 8. Assumption of nine selected LIB recycling scenarios.

Scenarios	RS	CC-LFP	CC-NMC	CC-NCA	SL-HIGH
Cathode chemistry	CBAU	CLFP	CNMC	CNCA	CBAU
Battery lifespan	Low	Low	Low	Low	Long
Recycling technology	Hydro	Hydro	Hydro	Hydro	Hydro
Battery recycling rate	Low	Low	Low	Low	Low
Material recycling rate	Low	Low	Low	Low	Low
Scenarios	RP-PYR	RP-DIR	MRR-PRO	OPT	
Cathode chemistry	CBAU	CBAU	CBAU	CNCA	
Battery lifespan	Low	Low	Low	Long	
Recycling technology	Pydro	Direct	Hydro	Direct	
Battery recycling rate	Low	Low	Low	High	
Material recycling rate	Low	Low	High	High	

Note: CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate. CBAU refers to the business-as-usual cathode scenario; CLFP, CNMC, and CNCA refer to cathode scenarios dominated by LFP (lithium iron phosphate), NMC (nickel manganese cobalt), and NCA (nickel cobalt aluminum), respectively. Pyro refers to pyrometallurgical recycling process; Hydro Refers to hydrometallurgical recycling process; Direct refers to direct cathode recycling process.

Supplementary Table 9. Information on material and energy demand in LIB cathode production (per kg cathode materials produced)[24].

Cathode chemistry	NMC111	NMC532	NMC622	NMC811	NCA	LFP
Material inputs (kg)						
Sodium Hydroxide	0.844	0.844	0.844	0.845	0.836	
Lithium Hydroxide				0.246	0.250	0.268
Lithium Carbonate	0.383	0.383	0.381			
Hydrochloric Acid						
Sodium Chlorate						
Cobalt Oxide						
Oxygen					0.040	
Nickel Sulfate	0.535	0.801	0.958	1.273	1.292	
Cobalt Sulfate	0.536	0.321	0.320	0.159	0.247	
Manganese Sulfate	0.522	0.469	0.312	0.155		
Ammonium Hydroxide	0.117	0.117	0.117	0.117		
Aluminum Sulfate					0.086	
Ammonia					0.352	
Manganese Oxide						
Phosphoric Acid						0.366
Iron Sulfate						0.567
Process water (gal)	0.2	0.2	0.2	0.2	0.2	
Energy inputs (MJ)						
Electricity	25.20	25.20	25.20	28.80	28.80	
Natural gas	42.62	42.62	42.63	42.62	42.66	36.54
Process non-combustion emissions (g)						
CO_2	228	228	227			

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 10. Bill of materials for LIB production[7].

Input	Units	NMC	NCA	LFP
Steel	g	13.23	13.23	13.23
Aluminum	g	1.65	1.65	1.24
Copper wire	g	4.97	4.97	3.73
Cathode Active	g	14.93	15.33	9.98
Graphite	g	6.78	6.78	7.28
PVDF	g	1.2	2.25	0.88
$LiPF_6$	g	0.81	0.81	0.82
Electrolyte	g	4.43	4.43	4.48
Polypropylene	g	0.84	0.84	0.63

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt. PVDF is polyvinylidene fluoride, and $LiPF_6$ is lithium hexafluorophosphate.

Supplementary Table 11. Embodied emissions for LIB production (excluding cathode production kg CO_2-eq·kg^{-1})[8].

Cathode chemistry	LFP	NCA	NMC111	NMC523	NMC622	NMC811
Steel	1.52	1.28	1.32	1.32	1.32	1.32
Aluminum	0.64	0.72	0.74	0.74	0.74	0.74
Copper wire	0.51	0.57	0.59	0.59	0.59	0.59
Graphite	0.35	0.27	0.28	0.28	0.28	0.28
PVDF	0.32	0.69	0.38	0.38	0.38	0.38
$LiPF_6$	0.42	0.35	0.36	0.36	0.36	0.36
Electrolyte	0.49	0.41	0.42	0.42	0.42	0.42
Polypropylene	0.03	0.04	0.04	0.04	0.04	0.04

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt. PVDF is polyvinylidene fluoride, and $LiPF_6$ is lithium hexafluorophosphate.

Supplementary Table 12. Embodied emissions for LIB cathode production (kg CO_2-eq·kg^{-1}).

Cathode chemistry		LFP	NCA	NMC111	NMC523	NMC622	NMC811
BAU electricity mix	2020	1.75	7.62	8.79	7.56	7.69	6.91
	2025	1.75	7.25	8.46	7.23	7.36	6.54
	2030	1.75	7.14	8.36	7.14	7.26	6.43
	2035	1.75	7.04	8.28	7.05	7.18	6.33
	2040	1.75	6.93	8.18	6.96	7.08	6.22
	2045	1.75	6.84	8.10	6.87	6.99	6.12
	2050	1.75	6.76	8.03	6.80	6.93	6.04
	2055	1.75	6.61	7.90	6.68	6.80	5.90
	2060	1.75	6.47	7.77	6.55	6.67	5.75
CN60 electricity mix	2020	1.75	7.53	8.70	7.48	7.60	6.82
	2025	1.75	7.29	8.50	7.27	7.39	6.58
	2030	1.75	6.85	8.11	6.89	7.01	6.14
	2035	1.75	6.54	7.84	6.61	6.74	5.83
	2040	1.75	6.41	7.72	6.50	6.62	5.70
	2045	1.75	6.35	7.67	6.44	6.57	5.63
	2050	1.75	6.32	7.64	6.42	6.54	5.60
	2055	1.75	6.30	7.63	6.40	6.53	5.59
	2060	1.75	6.29	7.62	6.39	6.52	5.58

Note: BAU electricity mix refers to China's baseline electricity mix; CN60 electricity mix refers to the China's carbon neutrality electricity mix. NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 13. Information on material and energy demand in hydrometallurgical recycling process[30].

Cathode chemistry	NMC111	NMC532	NMC622	NMC811	NCA	LFP
1.1) Material Inputs($kg \cdot kg^{-1}$)						
Hydrogen peroxide	0.075	0.074	0.071	0.07	0.091	0.075
Lime	0.037	0.037	0.037	0.037	0.036	0.039
Limestone	0	0	0	0	0	0
Lithium hydroxide	0	0	0	0	0	0
Nitrogen	0.05	0.05	0.05	0.05	0.05	0.05
Sand	0	0	0	0	0	0
Soda ash	0.233	0.231	0.22	0.229	0.141	0.233
Sodium hydroxide	0.708	0.7	0.667	0.659	0.86	0.708
Sulfuric acid	1.083	1.07	1.021	1.018	1.184	1.083
Water (gallons)	1.499	1.499	1.499	1.505	1.473	1.499
1.2) Energy Inputs ($MJ \cdot kg^{-1}$)						
Diesel(g)	20.346	20.346	20.346	20.346	20.370	19.929
Natural gas	2.9	2.881	2.875	2.85	2.873	2.639
Electricity	0.713	0.713	0.713	0.713	0.716	0.687
1.3) Process Outputs($kg \cdot kg^{-1}$)						
Cathode	0	0	0	0	0	0
Cobalt sulfate	0.088	0.051	0.051	0.024	0.038	0
Copper	0	0	0	0	0	0
Graphite	0.216	0.229	0.232	0.249	0.241	0.193
Lithium carbonate	0.151	0.147	0.145	0.138	0.144	0.091
Manganese sulfate	0.082	0.072	0.047	0.023	0	0
Nickel sulfate	0.088	0.128	0.151	0.193	0.2	0
1.4) Process Emissions ($kg \cdot kg^{-1}$)						
CO_2	0.000	0.000	0.000	0.000	0.000	0.000

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 14. Information on material and energy demand in pyrometallurgical recycling process[30].

Cathode chemistry	NMC111	NMC532	NMC622	NMC811	NCA	LFP
1.1) Material Inputs($kg \cdot kg^{-1}$)						
Hydrogen peroxide	0	0	0	0	0	0
Lime	0.074	0.074	0.074	0.073	0.073	0.079
Limestone	0.27	0.272	0.297	0.311	0.333	0.096
Lithium hydroxide	0	0	0	0	0	0
Nitrogen	0	0	0	0	0	0
Sand	0.405	0.408	0.445	0.466	0.499	0.144
Soda ash	0	0	0	0	0	0
Sodium hydroxide	0	0	0	0	0	0
Sulfuric acid	0.438	0.441	0.483	0.506	0.543	0.147
Water (gallons)	1	1	1	1	1	1
1.2) Energy Inputs ($MJ \cdot kg^{-1}$)						
Diesel(g)	11.971	11.971	11.971	11.971	11.971	11.971
Natural gas	0.232	0.234	0.255	0.267	0.286	0.083
Electricity	0.93	0.923	0.922	0.913	0.908	1.026
1.3) Process Outputs ($kg \cdot kg^{-1}$)						
Cathode	0	0	0	0	0	0
Cobalt sulfate	0.09	0.052	0.052	0.025	0.038	0
Copper	0.077	0.076	0.076	0.074	0.073	0.091
Graphite	0	0	0	0	0	0
Lithium carbonate	0	0	0	0	0	0
Manganese sulfate	0	0	0	0	0	0
Nickel sulfate	0.09	0.13	0.155	0.197	0.204	0
1.4) Process Emissions ($kg \cdot kg^{-1}$)						
CO_2	1.163	1.213	1.234	1.306	1.284	1.022

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 15. Information on material and energy demand in direct cathode recycling process[30].

Cathode chemistry	NMC111	NMC532	NMC622	NMC811	NCA	LFP
1.1) Material Inputs($kg \cdot kg^{-1}$)						
Hydrogen peroxide	0	0	0	0	0	0
Lime	0.037	0.037	0.037	0.037	0.036	0.039
Limestone	0	0	0	0	0	0
Lithium hydroxide	0.031	0.03	0.031	0.019	0.02	0
Nitrogen	0.05	0.05	0.05	0.05	0.05	0.05
Sand	0	0	0	0	0	0
Soda ash	0	0	0	0	0	0
Sodium hydroxide	0	0	0	0	0	0
Sulfuric acid	0	0	0	0	0	0
Water (gallons)	0.799	0.8	0.802	0.786	0.765	0.1
1.2) Energy Inputs ($MJ \cdot kg^{-1}$)						
Diesel (g)	20.346	20.346	20.346	20.346	20.370	19.929
Natural gas	2.716	2.692	2.687	2.656	2.675	2.689
Electricity	5.951	5.78	5.74	5.518	5.653	5.828
1.3) Process Outputs ($kg \cdot kg^{-1}$)						
Cathode	0.398	0.386	0.383	0.367	0.376	0.39
Cobalt sulfate	0	0	0	0	0	0
Copper	0	0	0	0	0	0
Graphite	0.216	0.229	0.232	0.249	0.241	0.193
Lithium carbonate	0	0	0	0	0	0
Manganese sulfate	0	0	0	0	0	0
Nickel sulfate	0	0	0	0	0	0
1.4) Process Emissions ($kg \cdot kg^{-1}$)						
CO_2	0	0	0	0	0	0

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 16. Unit CO_2 emission in hydrometallurgical recycling process (kg CO_2-eq·kg^{-1}).

Cathode chemistry	LFP	NCA	NMC111	NMC523	NMC622	NMC811
Hydrogen peroxide	0.107	0.130	0.107	0.105	0.101	0.100
Lime	0.002	0.002	0.002	0.002	0.002	0.002
Nitrogen	0.021	0.021	0.021	0.021	0.021	0.021
Soda ash	0.288	0.174	0.288	0.286	0.272	0.283
Sodium hydroxide	0.898	1.090	0.898	0.887	0.846	0.835
Sulfuric acid	0.174	0.190	0.174	0.172	0.164	0.163
Diesel	0.010	0.010	0.010	0.010	0.010	0.010
Natural gas	0.207	0.225	0.227	0.226	0.225	0.223
Cobalt sulfate	0	-0.911	-2.110	-1.223	-1.223	-0.575
Graphite	-0.391	-0.488	-0.437	-0.464	-0.470	-0.504
Lithium carbonate	-0.689	-1.091	-1.144	-1.113	-1.098	-1.045
Manganese sulfate	0	0	-0.066	-0.058	-0.038	-0.018
Nickel sulfate	0	-0.923	-0.406	-0.591	-0.697	-0.891

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 17. Unit CO_2 emission in pyrometallurgical recycling process (kg CO_2-eq·kg^{-1}).

Cathode chemistry	LFP	NCA	NMC111	NMC532	NMC622	NMC811
Lime	0.003	0.003	0.003	0.003	0.003	0.003
Limestone	0.000	0.001	0.001	0.001	0.001	0.001
Sand	0.002	0.006	0.005	0.005	0.005	0.005
Sulfuric acid	0.024	0.087	0.070	0.071	0.077	0.081
Diesel	0.006	0.006	0.006	0.006	0.006	0.006
Natural gas	0.007	0.022	0.018	0.018	0.020	0.021
Cobalt sulfate	0	-0.911	-2.158	-1.247	-1.247	-0.599
Copper	-0.525	-0.422	-0.445	-0.439	-0.439	-0.427
Nickel sulfate	0	-0.941	-0.415	-0.600	-0.715	-0.909
CO_2	1.022	1.284	1.163	1.213	1.234	1.306

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 18. Unit CO_2 emission in direct cathode recycling process ($kg\ CO_2\text{-}eq \cdot kg^{-1}$).

Cathode chemistry	LFP	NCA	NMC111	NMC532	NMC622	NMC811
Hydrogen peroxide	0	0.002	0	0	0	0
Lime	0.002		0.002	0.002	0.002	0.002
Limestone	0	0	0	0	0	0
Lithium hydroxide	0	0.292	0.452	0.438	0.452	0.277
Nitrogen	0.021	0.021	0.021	0.021	0.021	0.021
Diesel	0.010	0.010	0.010	0.010	0.010	0.010
Natural gas	0.211	0.210	0.213	0.211	0.210	0.208
cathode	-2.897	-10.749	-12.706	-10.791	-10.863	-9.645
Cobalt sulfate	0	0	0	0	0	0
Graphite	-0.391	-0.488	-0.437	-0.464	-0.470	-0.504

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt.

Supplementary Table 19. Electricity carbon emission and electricity mix in CN60 electricity mix.

Energy	2020	2025	2030	2035	2040	2045	2050	2055	2060
Hydro power	16.1%	13.7%	11.7%	10.4%	9.3%	8.5%	8.0%	7.8%	7.6%
PV utility	3.0%	9.5%	17.3%	22.4%	25.5%	28.3%	29.7%	30.0%	30.7%
Wind onshore	3.9%	8.6%	18.5%	25.6%	28.6%	29.6%	30.2%	29.9%	27.8%
Nuclear	4.2%	7.0%	13.3%	18.8%	21.3%	22.9%	23.6%	24.8%	26.4%
Biomass	1.1%	1.6%	2.8%	3.7%	3.6%	3.3%	3.1%	3.4%	4.1%
Coal	69.7%	57.5%	33.5%	16.2%	8.9%	5.1%	3.3%	2.4%	1.7%
Gas	2.3%	1.8%	1.8%	1.7%	1.5%	1.4%	1.3%	1.2%	1.2%
Refined liquids	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%
Carbon emission factor	0.560	0.456	0.262	0.125	0.069	0.039	0.026	0.019	0.015

Note: CN60 electricity mix refers to the China's carbon neutrality electricity mix. PV denotes photovoltaic power.

Supplementary Table 20. Electricity carbon emission and electricity mix in BAU electricity mix.

Energy	2020	2025	2030	2035	2040	2045	2050	2055	2060
Hydro power	16.1%	15.4%	13.5%	11.4%	9.9%	8.6%	7.6%	7.6%	7.6%
PV utility	2.0%	8.5%	16.2%	22.2%	26.5%	29.2%	29.6%	29.6%	29.6%
PV distributed	0.0%	3.0%	2.7%	3.7%	6.3%	8.3%	10.0%	10.0%	10.0%
Wind onshore	3.9%	12.4%	10.9%	9.7%	9.6%	11.3%	14.3%	14.3%	14.3%
Wind offshore	0.0%	0.4%	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%
Nuclear	4.2%	4.1%	5.2%	5.7%	5.6%	4.9%	4.3%	4.3%	4.3%
Biomass	1.1%	1.3%	1.2%	1.0%	0.8%	0.7%	0.6%	0.6%	0.6%
Coal	69.7%	49.7%	45.6%	42.3%	37.9%	34.0%	30.7%	30.7%	30.7%
Gas	2.3%	5.1%	4.4%	3.7%	3.2%	2.9%	2.6%	2.6%	2.6%
Carbon emission factor	0.560	0.406	0.363	0.322	0.276	0.237	0.205	0.205	0.205

Note: BAU electricity mix refers to China's baseline electricity mix; PV denotes photovoltaic power.

Supplementary Table 21 The demand-supply gap of critical materials in status quo (Unit: kt).

Year	Materials	Demand	Recycling	Demand-supply difference	Cumulative difference
2040	Cobalt	140.23	17.37	-122.86	2081.24
	Lithium	152.10	14.57	-137.53	2283.93
	Nickel	413.19	51.17	-362.02	6132.32
	Manganese	134.06	16.60	-117.46	1989.68
2060	Cobalt	163.83	43.96	-119.87	4637.88
	Lithium	177.69	36.87	-140.82	5225.81
	Nickel	482.72	129.53	-353.19	13665.41
	Manganese	156.62	42.03	-114.60	4433.85

Supplementary Table 22. Comparison with results from literature for the EV forecast[21, 31].

Reference	Scenario	EV stock in 2050 (Million)	EV stock in 2060 (Million)
Liu et al.	NMC	685.8	
	LS	226.1	
	HS	301.2	
Wang et al.	BLS	489.8	547.0
	High	424.6	388.7
	Medium	394.7	483.3
	Low	478.5	536.6
This study	Long-lifespan	539.6	638.4
	Low-lifespan	469.9	542.3

Supplementary Table 23. Reference of battery collection rate from literature.

Reference	Scenario
Liu et al., (2023)[9]	Low: 65% Medium: 85% High: 100%
Xu et al., (2020)[10]	100%
Dunn et al., (2021)[3]	100%
Kamran et al., (2021)[32]	from 80% in 2020 to 99% in 2050
Dunn et al., (2022)[29]	Step increase from 65% in 2025 to 90% in 2050 by 5% increments Flat collection rate from 2020 to 2050 analyzed for 7 different rates/scenarios: 65%, 70%, 75%, 80%, 85%, 90%, 95%.

Supplementary Table 24. Comparison with results from literature for the critical material supply.

Year	Reference	Scenario	Material	Self-sufficiency potential
2040	Baars et al., (2021)[3]	Idealized scenario	Co	60%
			Li	53%
			Ni	57%
			Mn	53%
2050	Zeng et al., (2022)[4]	The most optimistic technology scenario	Co	>100%
2050	Qiao et al., (2021)[33]	Optimistic scenario	Li	49%
		Neutral scenario	Li	53%
		Pessimistic scenario	Li	60%
2050	Liu et al., (2023)[9]	Improved battery technology scenario	Co	77%
			Li	42%
			Ni	78%
			Mn	78%
			Cu	69%
			Al	68%
			Fe	40%
2050	This study	Reference scenario (RS)	Co	71-110%
			Li	55-85%
			Ni	71-110%

			Mn	71-110%
	This study	Reference scenario (RS)	Co	87-134%
			Li	67-103%
			Ni	87-134%
			Mn	87-134%
2050	This study	Optimal technology scenario (OPT)	Co	53-82%
			Li	53-82%
			Ni	53-82%
			Mn	53-82%
2060	This study	Optimal technology scenario (OPT)	Co	63-97%
			Li	63-97%
			Ni	63-97%
			Mn	63-97%

Note: Co cobalt, Li lithium, Ni nickel, Mn manganese.

Supplementary Table 25. Comparison with results from literature for the CO_2 emissions (kg CO_2-eq·kg^{-1}).

Process	Reference	Cathode chemistry	Carbon emission
Lithium-ion battery manufacturing	Ciez and Whitacre (2019)[7]	LFP (Cylindrical)	4.500
		NMC (Cylindrical)	8.820
		NCA (Cylindrical)	9.310
		LFP (Pouch)	7.030
		NMC (Pouch)	9.720
		NCA (Pouch)	10.660
	This study (BAU electricity mix in 2020)	LFP	6.044
		NCA	11.951
		NMC111	12.909
		NMC523	11.687
		NMC622	11.809
		NMC811	11.036
	This study (BAU electricity mix in 2060)	LFP	6.044
		NCA	10.795
		NMC111	11.895
		NMC523	10.672
		NMC622	10.795
		NMC811	9.877
	This study	LFP	6.044
		NCA	11.857
		NMC111	12.827

	(CN60 electricity mix in 2020)	NMC523		11.604
		NMC622		11.726
		NMC811		10.941
	This study (CN60 electricity mix in 2060)	LFP		6.044
		NCA		10.618
		NMC111		11.740
		NMC523		10.517
		NMC622		10.639
		NMC811		9.699
Lithium-ion battery recycling	Rosenberg et al., (2023)[34]	Hydro	NMC111	-3.000
			NMC811	-2.760
		Direct	NMC111	-4.550
			NMC811	-4.450
	Mohr et al., (2020)[27]	Pyro	LFP	0.050
			NMC	-2.348
			NCA	-2.751
		Hydro	LFP	-0.387
			NMC	-2.796
			NCA	-3.159
		Advanced hydro	LFP	-1.180
			NMC	-3.577
			NCA	-4.233
	This study (BAU electricity mix in 2060)	Pyro	LFP	0.562
			NCA	-0.843
			NMC111	-1.730
			NMC523	-0.947
			NMC622	-1.032
			NMC811	-0.491
		Hydro	LFP	0.642
			NCA	-1.553
			NMC111	-2.419
			NMC523	-1.722
			NMC622	-1.867
			NMC811	-1.379
		Direct	LFP	-2.905
			NCA	-7.797
			NMC111	-9.716
			NMC523	-7.913
			NMC622	-7.995
			NMC811	-6.549
	This study	Pyro	LFP	0.542
			NCA	-0.861

	(CN60 electricity mix in 2060)		NMC111	-1.748
			NMC523	-0.965
			NMC622	-1.051
			NMC811	-0.509
		Hydro	LFP	0.628
			NCA	-1.568
			NMC111	-2.434
			NMC523	-1.737
			NMC622	-1.882
			NMC811	-1.393
		Direct	LFP	-3.023
			NCA	-7.693
			NMC111	-9.645
			NMC523	-7.834
			NMC622	-7.916
			NMC811	-6.447

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt. BAU electricity mix refers to China's baseline electricity mix; CN60 electricity mix refers to the China's carbon neutrality electricity mix. Pyro refers to pyrometallurgical recycling process; Hydro Refers to hydrometallurgical recycling process; Direct refers to direct cathode recycling process.

Supplementary Table 26. Comparison with results from literature for the cost analysis ($\$\cdot ton^{-1}$).

Reference	Recycling technology	Cathode	Cost	Revenue	Profit
Zou et al., (2013)[35]	Hydro	NMC	6195	5023	
Fan et al., (2020)[36]	Hydro	LFP	804	196	
Laura et al., (2021)[37]	Pyro	LFP			-2285
		NCA			946
		NMC622			1126
		NMC811			425
	Hydro	LFP			-1181
		NCA			2078
		NMC622			2359
		NMC811			1598
	Direct	LFP			2585
		NCA			5256

		NMC622			3566
		NMC811			3065
Dunn et al., (2022)[29]	Pyro	LFP	4010		
		NCX	4040		
	Hydro	LFP	3910		
		NCX	3950		
	Direct	LFP	5460		
		NCX	5520		
This study (RS scenario)	Pyro	LFP	2800	1180	-1620
		NCA	5560	6130	570
		NMC111	5530	6250	720
		NMC532	4640	5640	1000
		NMC622	4640	6030	1390
		NMC811	5310	5450	140
	Hydro	LFP	3300	1250	-2050
		NCA	5910	6650	740
		NMC111	5820	7490	1670
		NMC532	4960	6350	1390
		NMC622	4990	6630	1640
		NMC811	5560	5940	380
	Direct	LFP	3200	4110	910
		NCA	6350	9500	3150
		NMC111	6800	9790	2990
		NMC532	5760	9020	3260
		NMC622	5900	9300	3400
		NMC811	6080	9320	3240

Note: NCA refers to nickel cobalt aluminum; LFP refers to lithium iron phosphate; NMC refers to Nickel Manganese Cobalt; NCX refers to aggregated category for NCA and NMC cathodes. Pyro refers to pyrometallurgical recycling process; Hydro Refers to hydrometallurgical recycling process; Direct refers to direct cathode recycling process. RS scenario refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency.

Supplementary Table 27. Comparison of self-sufficiency potential in 2060 among LIB recycling strategies.

Self-sufficiency potential (%)

Scenario	RS	CC-LFP	CC-NMC	CC_NCA	SL-HIGH	RP-PYR	RP-DIR	MRR-PRO	OPT
Co	114%	114%	114%	114%	86%	114%	105%	120%	83%
Li	88%	88%	88%	88%	66%	\	88%	110%	83%
Ni	114%	114%	114%	114%	86%	114%	105%	120%	83%
Mn	114%	114%	114%	114%	86%	\	105%	120%	83%
Average	108%	108%	108%	108%	81%	57%	101%	118%	83%

Note: RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. Co cobalt, Li lithium, Ni nickel, Mn manganese.

Supplementary Table 28. Comparison of cumulative CO_2 emissions among LIB recycling strategies.

Cumulative CO_2 emission (mt)

Scenario	RS	CC-LFP	CC-NMC	CC-NCA	SL-HIGH	RP-PYR	RP-DIR	MRR-PRO	OPT
Manufacturing	2999	2585	3270	3440	2297	2999	2999	2999	2634
Transportation	35	35	35	35	27	35	35	35	27
Collection	5	5	5	5	4	5	5	5	4
Recycling	-192	-1	-319	-346	-147	-79	-1671	-192	-1550
Life-cycle emission	2848	2624	2992	3134	2181	2961	1369	2848	1114

Note: RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition.

Supplementary Table 29. Comparison of cost associated with recycling among LIB recycling strategies.

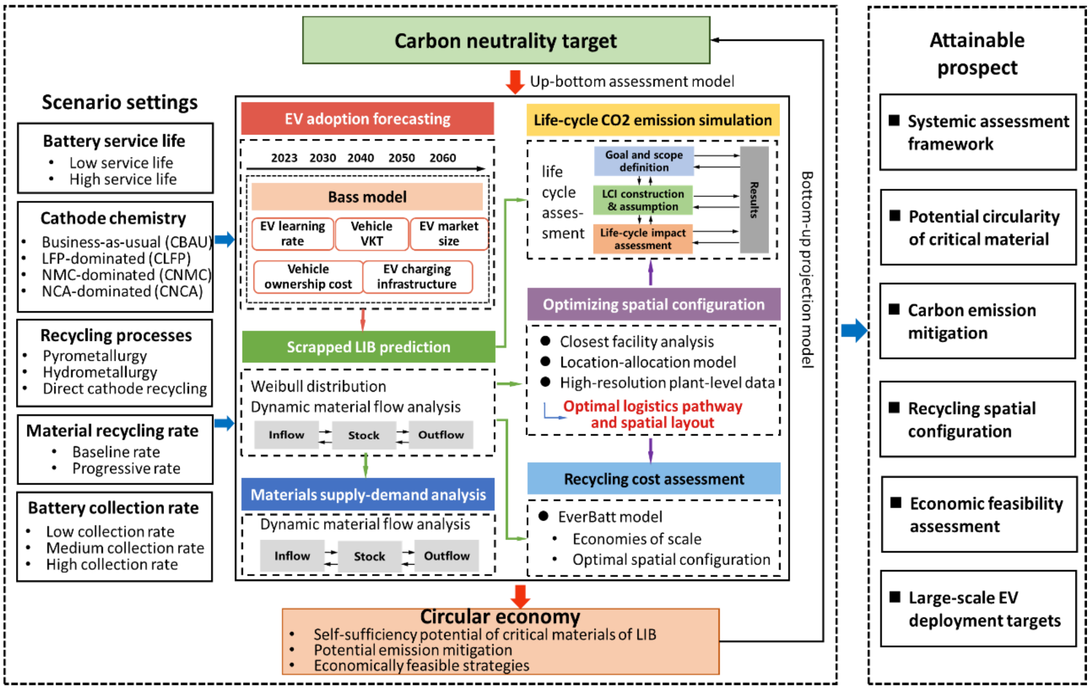
Recycling cost assessment (billion USD)

Scenario	RS	CC-LFP	CC-NMC	CC-NCA	SL-HIGH	RP-PYR	RP-DIR	MRR-PRO	OPT
Collection & Transportation	-20	-20	-21	-20	-15	-20	-20	-20	-15
disassembly	-25	-23	-29	-29	-19	-25	-25	-25	-22
Recycling process	40	13	56	61	30	43	87	51	94
Aggregated recycling costs	-4	-29	6	12	-3	-2	43	6	58

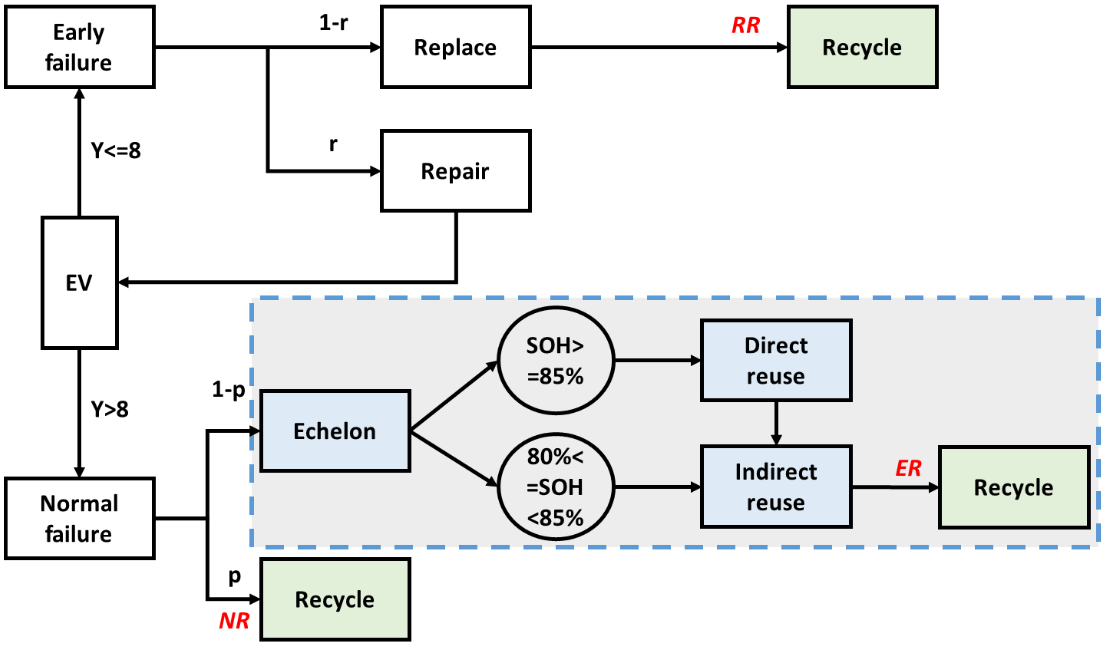
Note: RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition.

Supplementary Figures

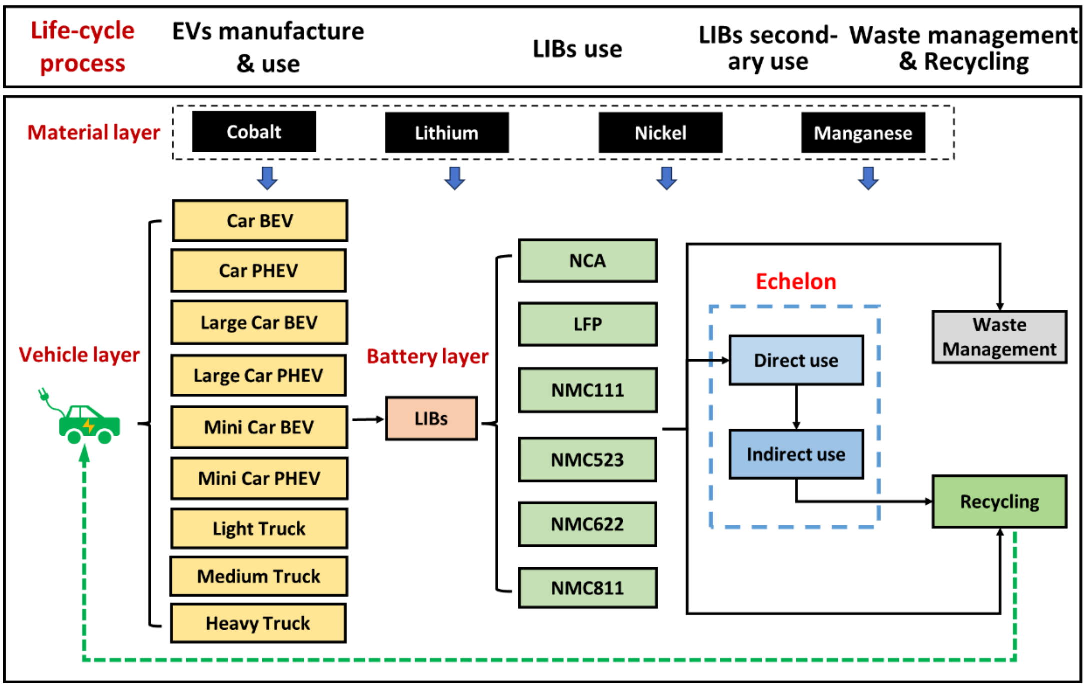
Modelling framework



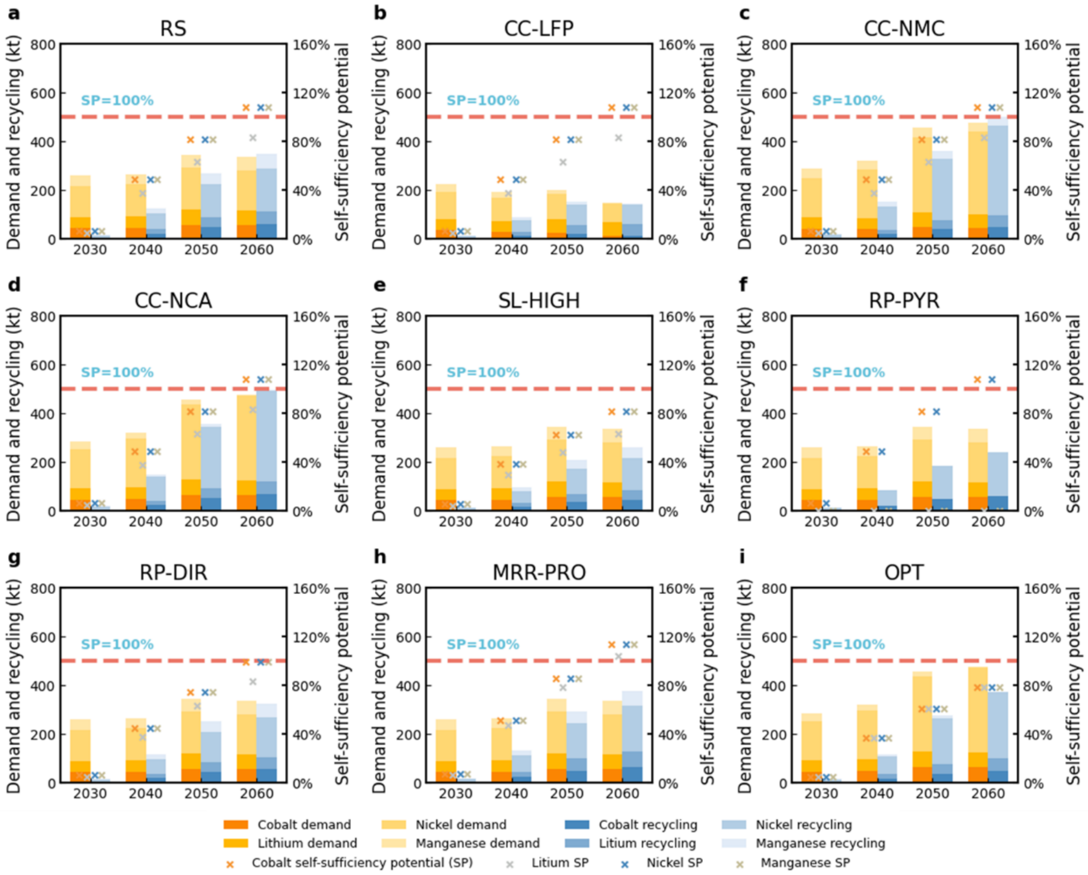
Supplementary Figure 1. The integrated modelling framework and scenario setting. An integrated top-down and bottom-up model is developed for analysis of the critical materials and environmental assessment of electric vehicle battery recycling under China's carbon neutrality (CN60) target. Based on China's CN60 target and scenario mix, this integrated model contains six dynamic modules related to future electric vehicle uptake, battery scrappage dynamics, critical materials cycle, life-cycle CO_2 emissions, recycling layout optimization, and cost-effectiveness quantification. As scenario settings, we define two lithium-ion battery retirement patterns (low and high battery service life), four changing cathode chemistries (business-as-usual, LFP-dominated, NMC-dominated and NCA-dominated cathode), three recycling processes (pyrometallurgy, hydrometallurgy and direct cathode recycling), two critical material recycling rate (baseline and progressive critical material recycling rate), and three battery collection rates driven by recycling infrastructure advancement (low, medium, and high battery collection rate).



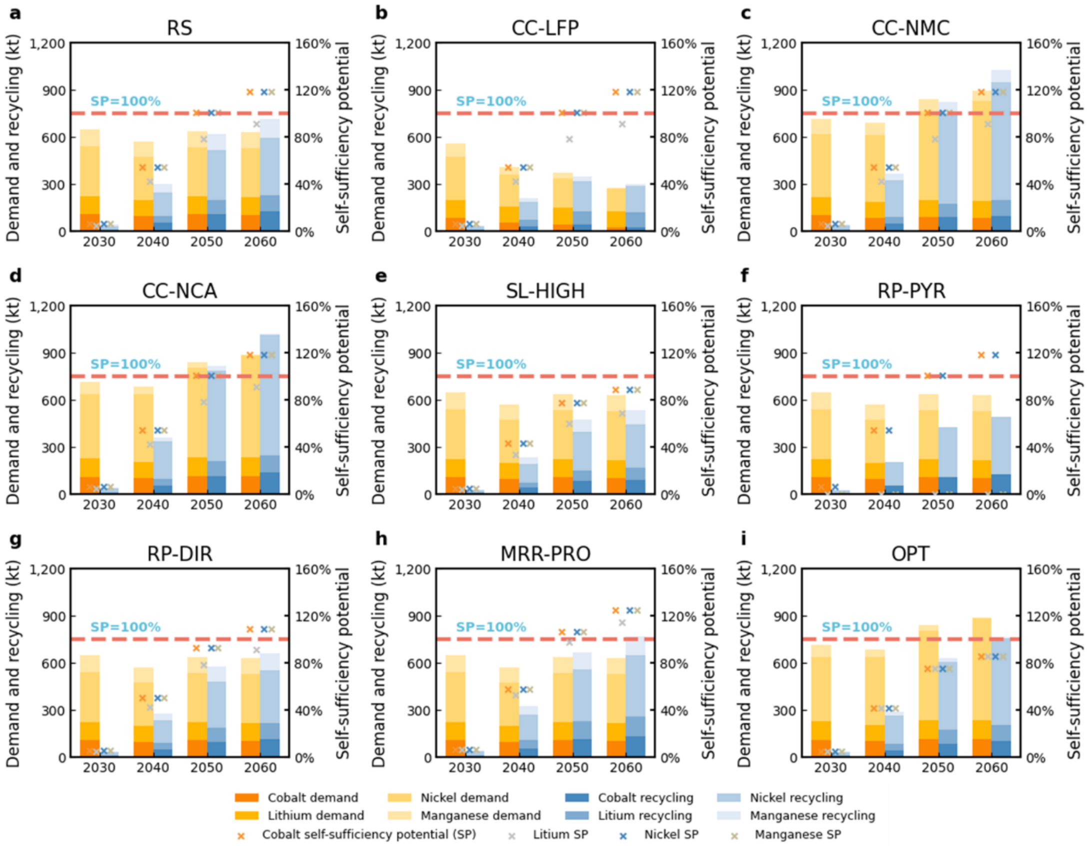
Supplementary Figure 2. Battery recycling roadmap. The grey area represents the battery cascading utilization process. *Abbreviations:* EV, electric vehicle; RR, battery replaced by early failure; NR, direct recycling by normal failure; ER, recycling from the echelon; SOH, battery state of health.



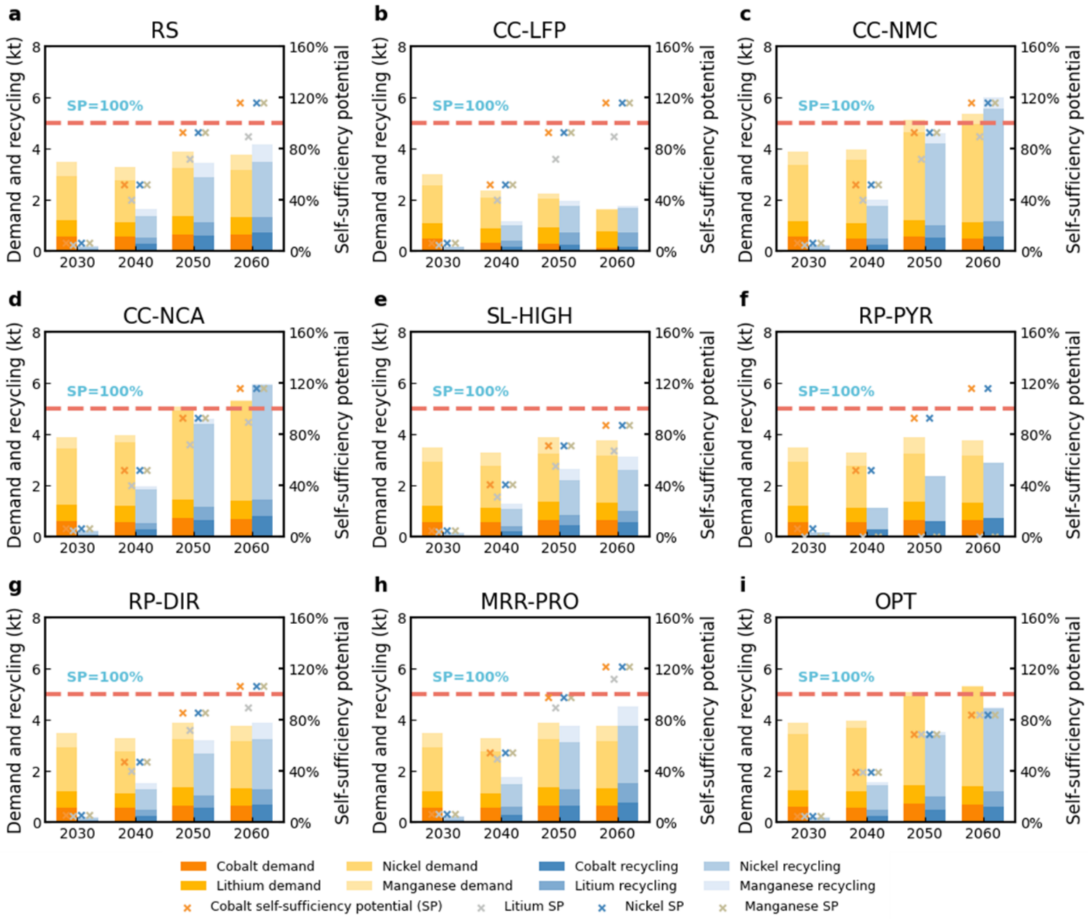
Supplementary Figure 3. Critical material flow roadmap. *Abbreviations*: EVs, electric vehicles; LIBs, lithium-ion batteries; Car BEV compact battery electric car, Car PHEV, compact plug-in hybrid electric car; Large Car BEV, battery electric large car and sport utility vehicle; Large Car PHEV, plug-in hybrid electric large car and sport utility vehicle; Mini Car BEV, mini-sized battery electric car; Mini Car PHEV, mini-sized plug-in hybrid electric car; NCA, nickel cobalt aluminum; LFP, lithium iron phosphate; NMC, Nickel Manganese Cobalt.



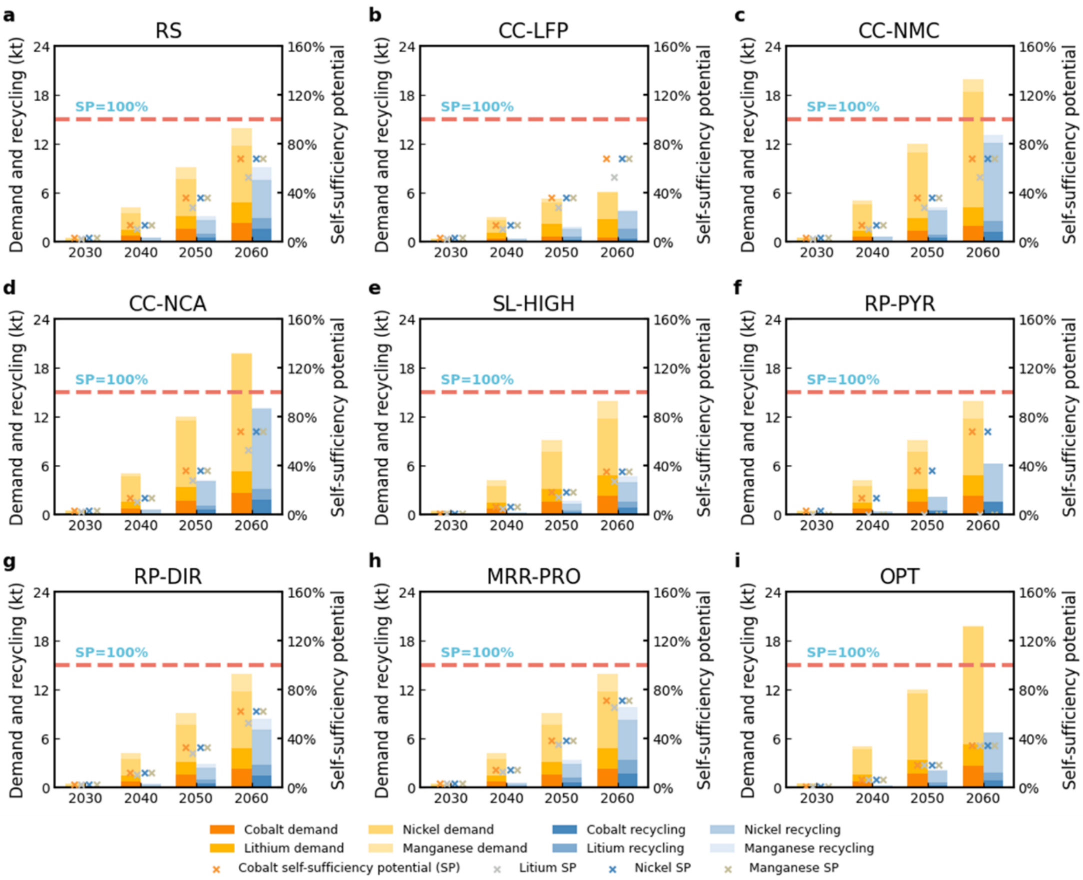
Supplementary Figure 4. Demand, recycling, and self-sufficiency potential of critical materials with compact car. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



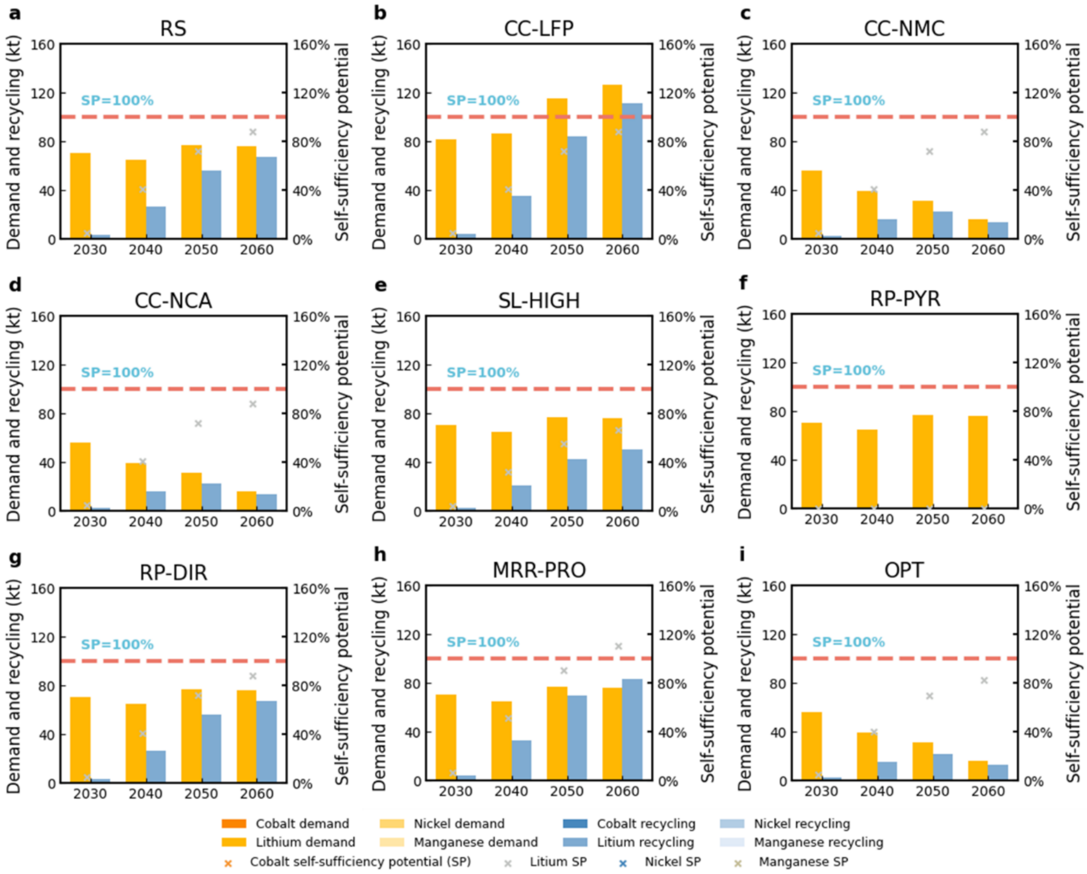
Supplementary Figure 5. Demand, recycling, and self-sufficiency potential of critical materials with large car and sport utility vehicle. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



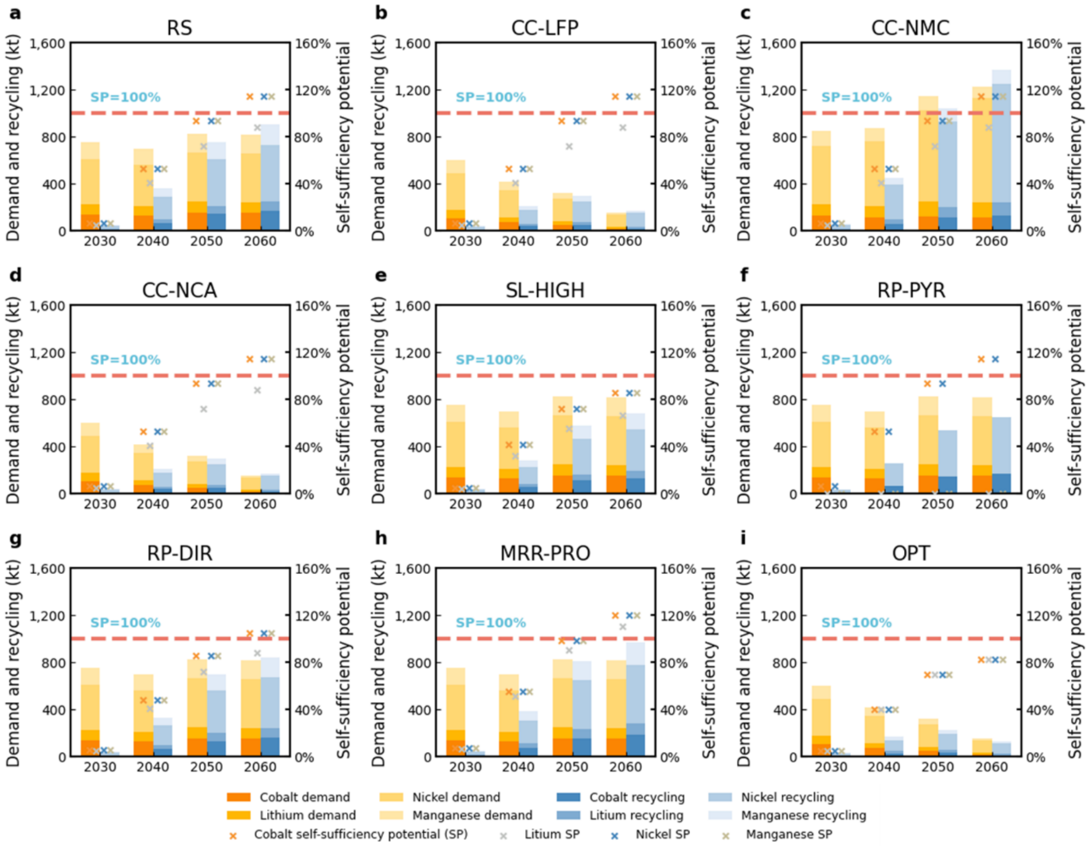
Supplementary Figure 6. Demand, recycling, and self-sufficiency potential of critical materials with mini-sized car. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



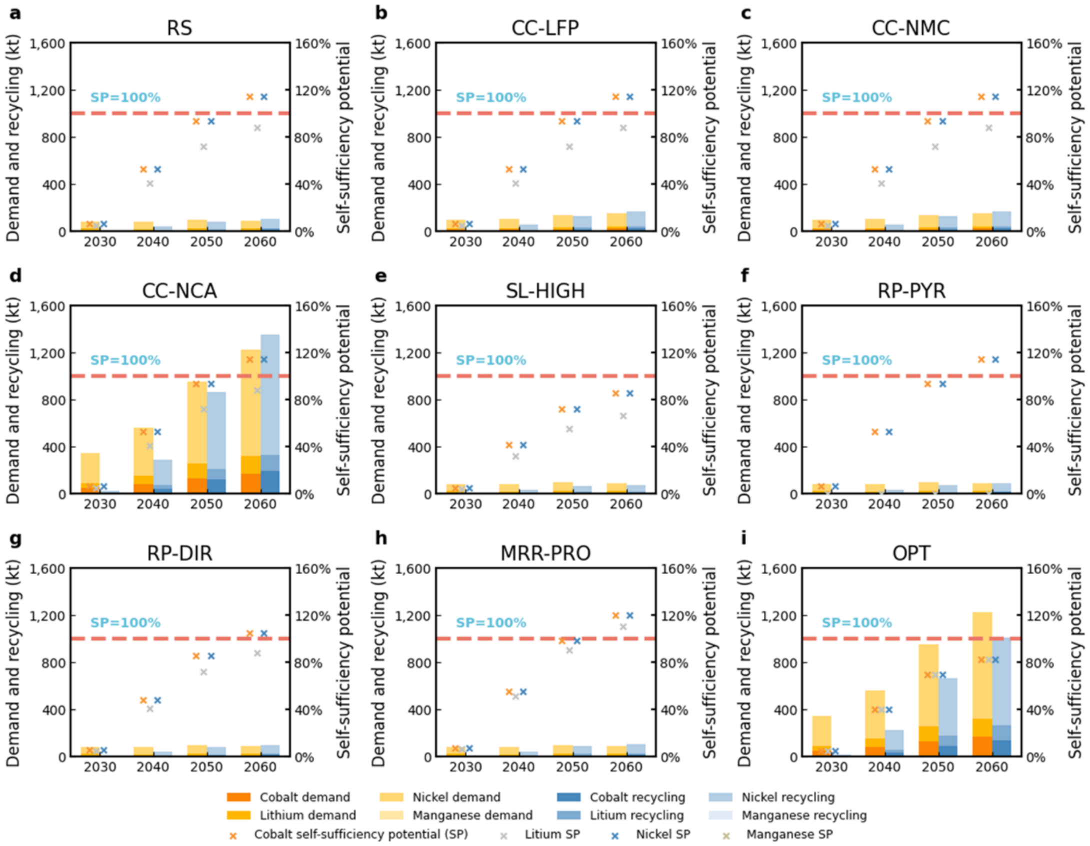
Supplementary Figure 7. Demand, recycling, and self-sufficiency potential of critical materials with truck. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



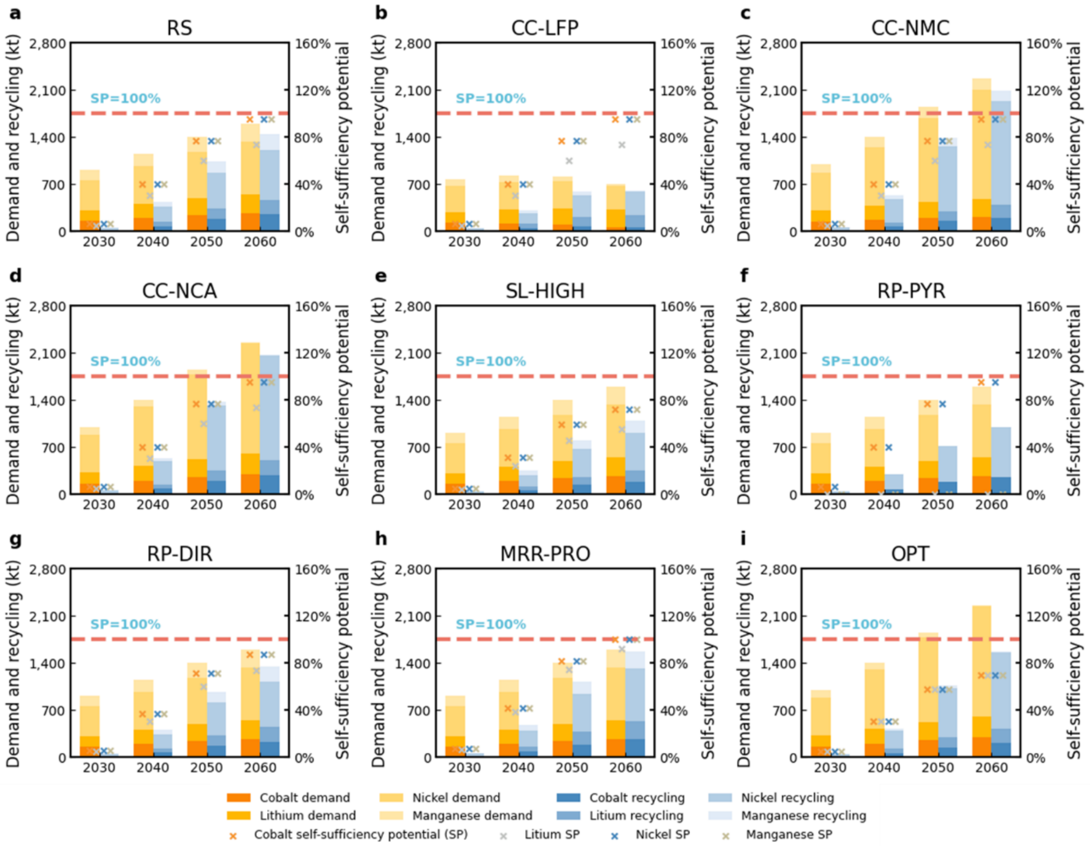
Supplementary Figure 8. Demand, recycling, and self-sufficiency potential of critical materials with LFP cathode. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



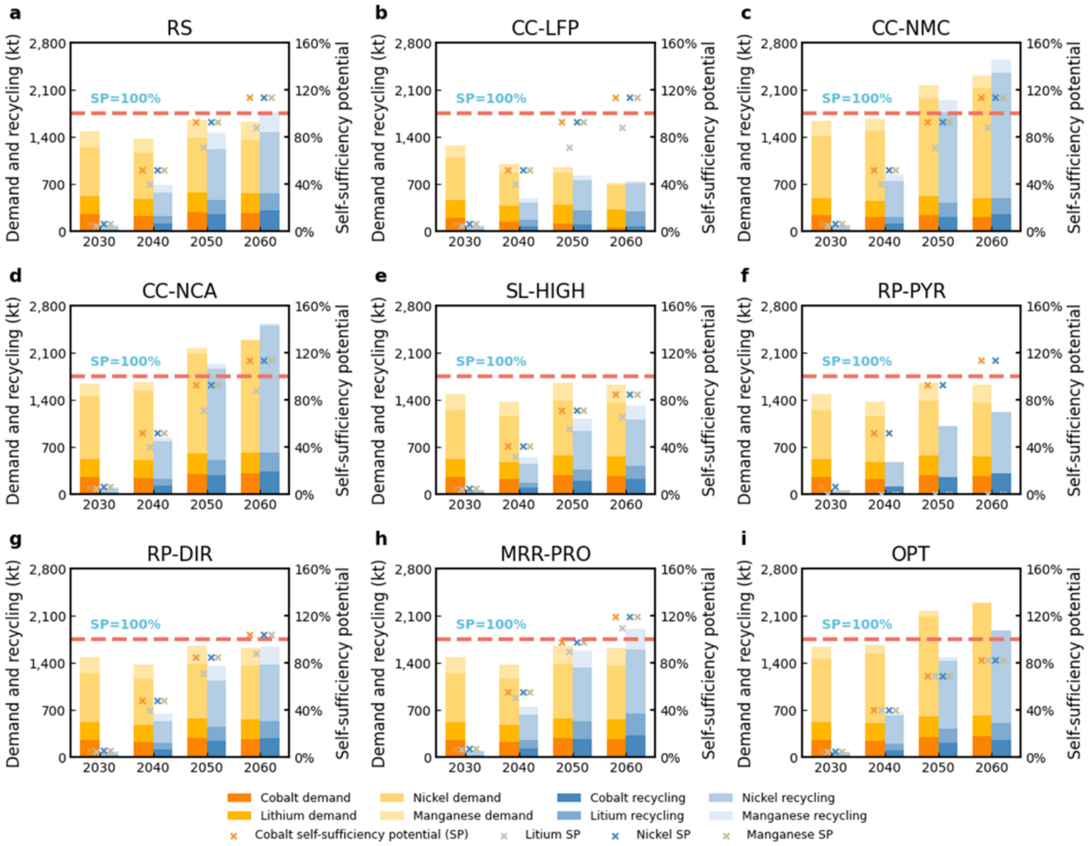
Supplementary Figure 9. Demand, recycling, and self-sufficiency potential of critical materials with NMC cathode. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



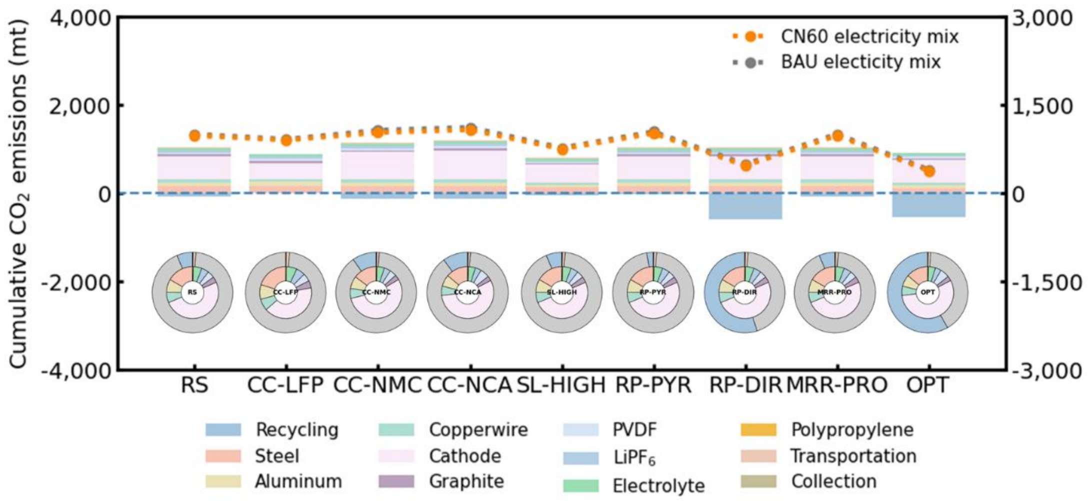
Supplementary Figure 10. Demand, recycling, and self-sufficiency potential of critical materials with NCA cathode. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



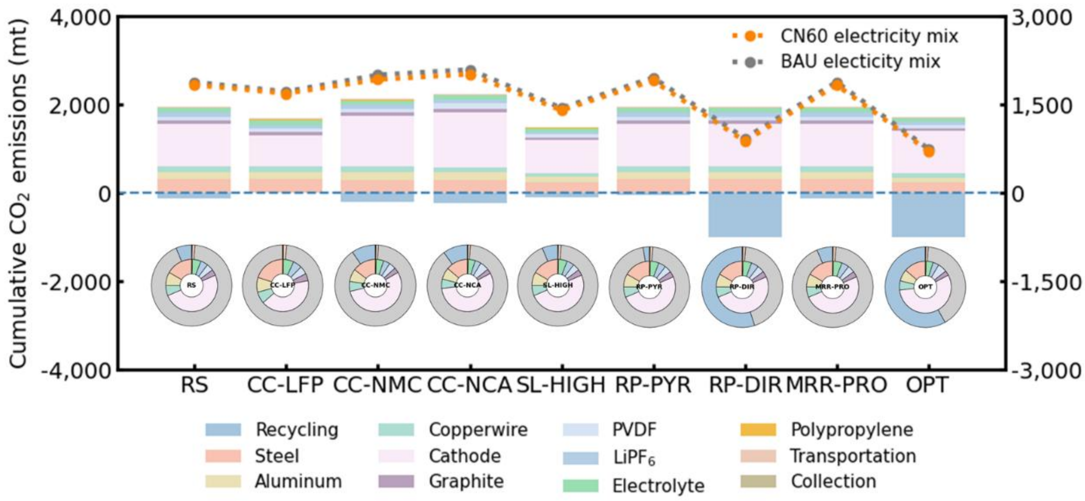
Supplementary Figure 11. Demand, recycling, and self-sufficiency potential of critical materials considering the EV uncertainty. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



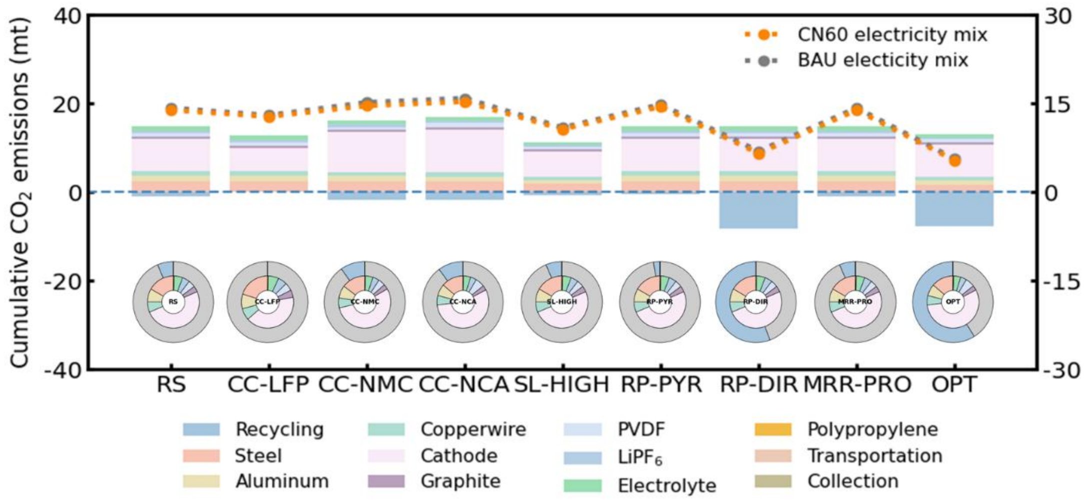
Supplementary Figure 12. Demand, recycling, and self-sufficiency potential of critical materials considering the battery capacity and density. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



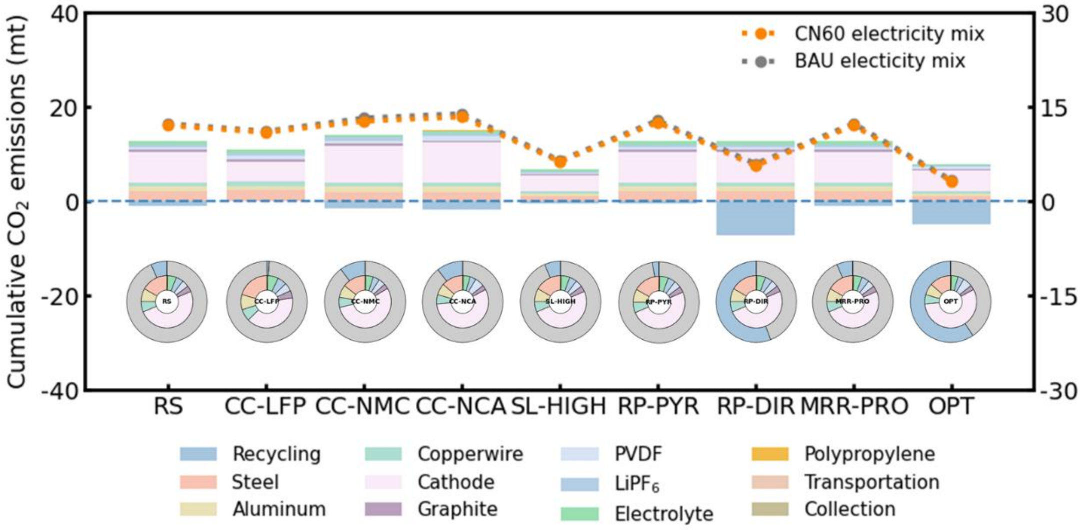
Supplementary Figure 13. Life-cycle CO_2 emission with compact car. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



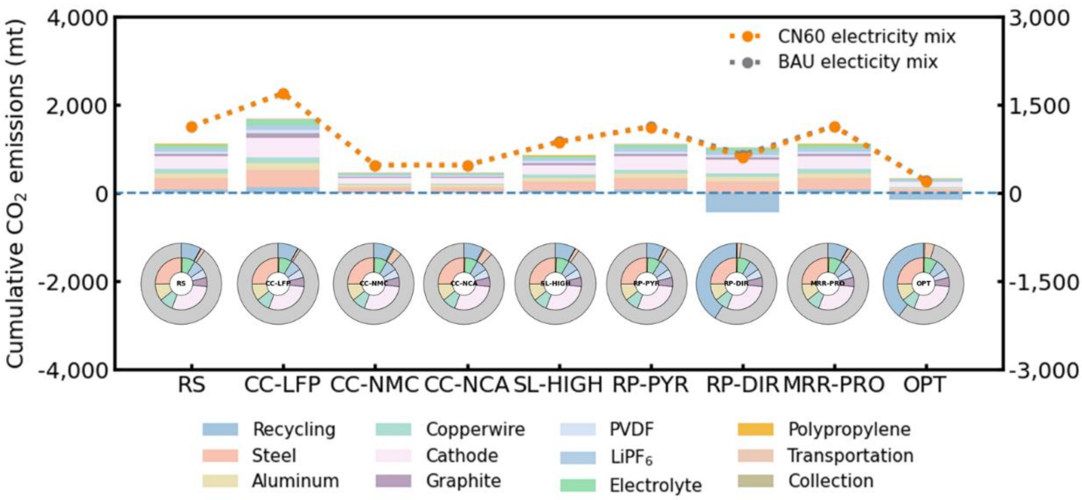
Supplementary Figure 14. Life-cycle CO_2 emission with large car and sport utility vehicle. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



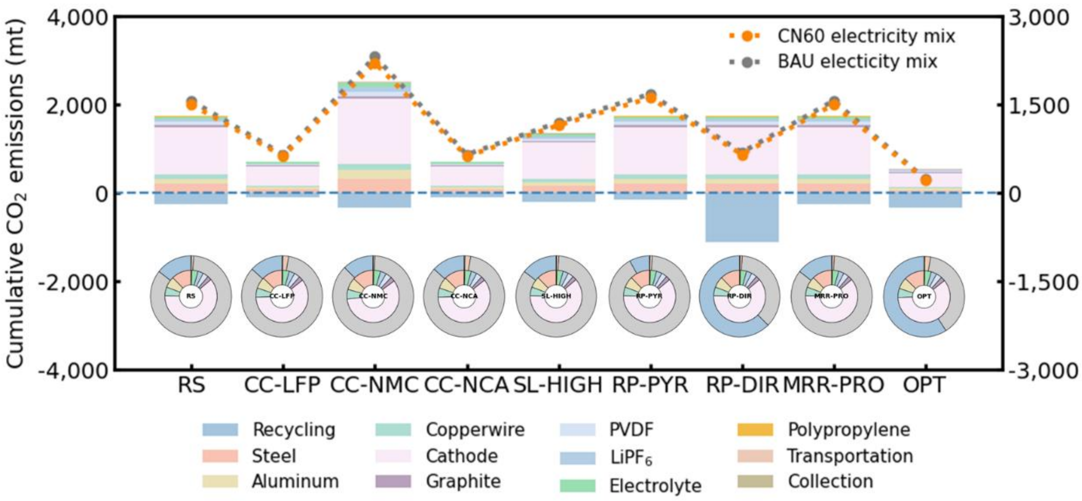
Supplementary Figure 15. Life-cycle CO_2 emission with mini-sized car. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



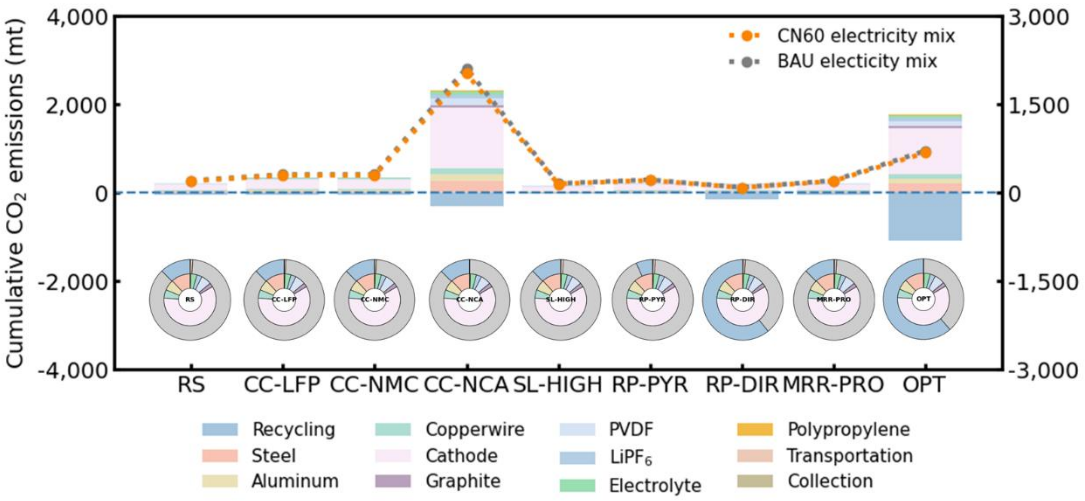
Supplementary Figure 16. Life-cycle CO_2 emission with truck. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



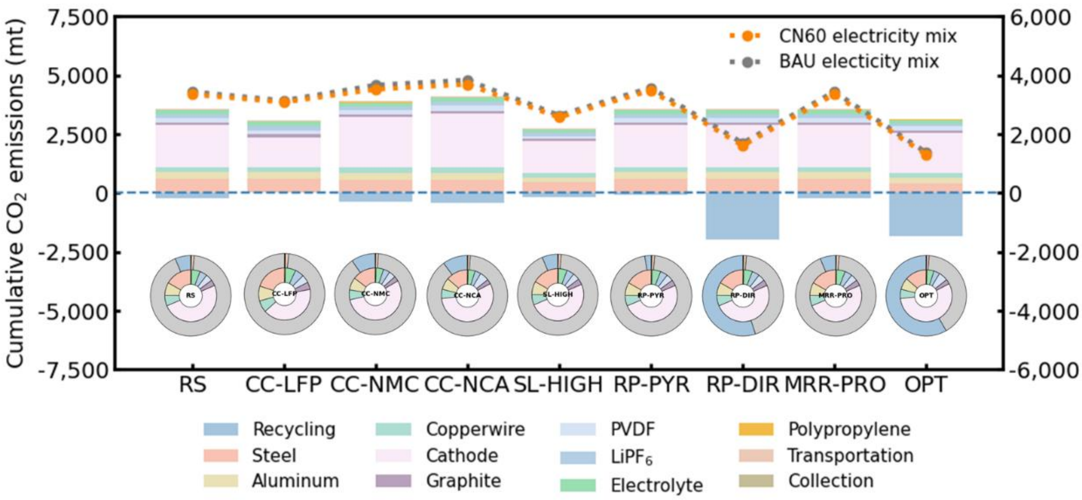
Supplementary Figure 17. Life-cycle CO_2 emission with LFP cathode. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



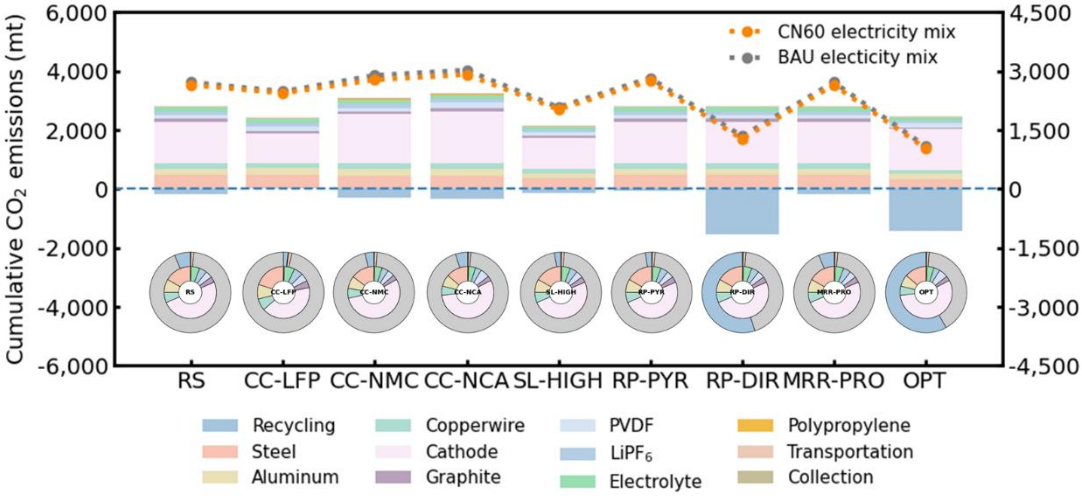
Supplementary Figure 18. Life-cycle CO_2 emission with NMC cathode. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



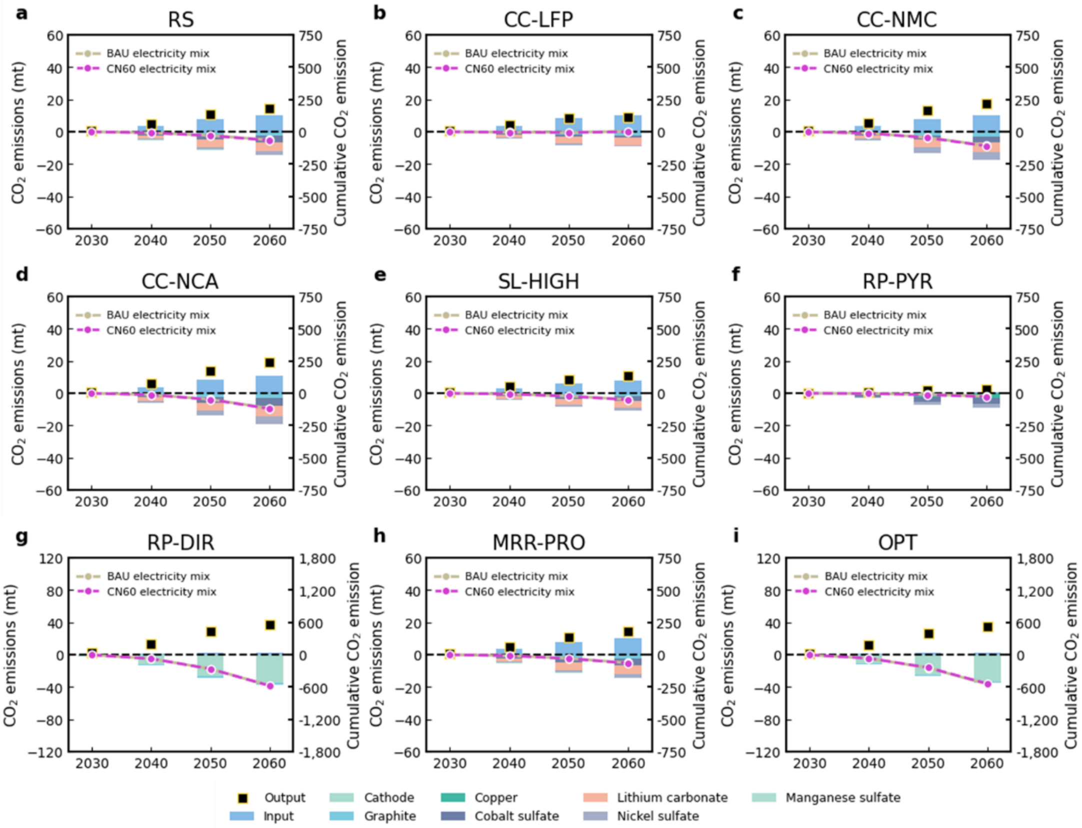
Supplementary Figure 19. Life-cycle CO_2 emission with NCA cathode. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



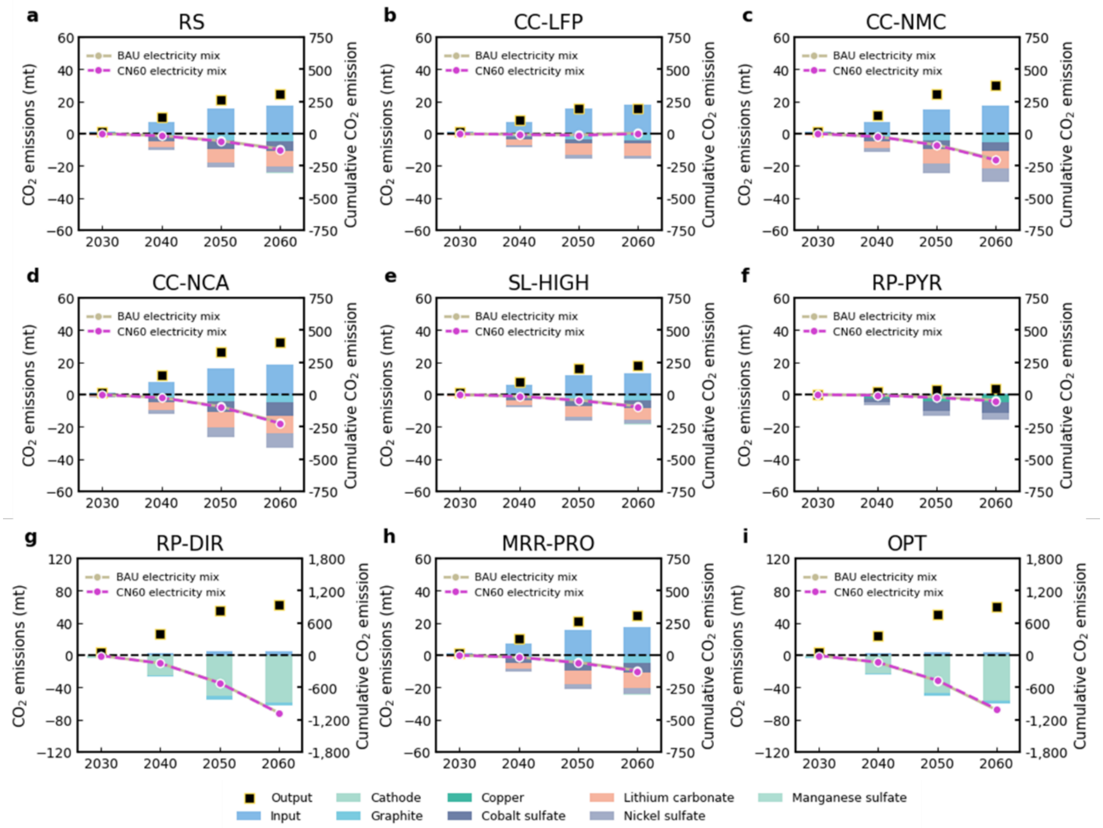
Supplementary Figure 20. Life-cycle CO_2 emission considering the EV uncertainty. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



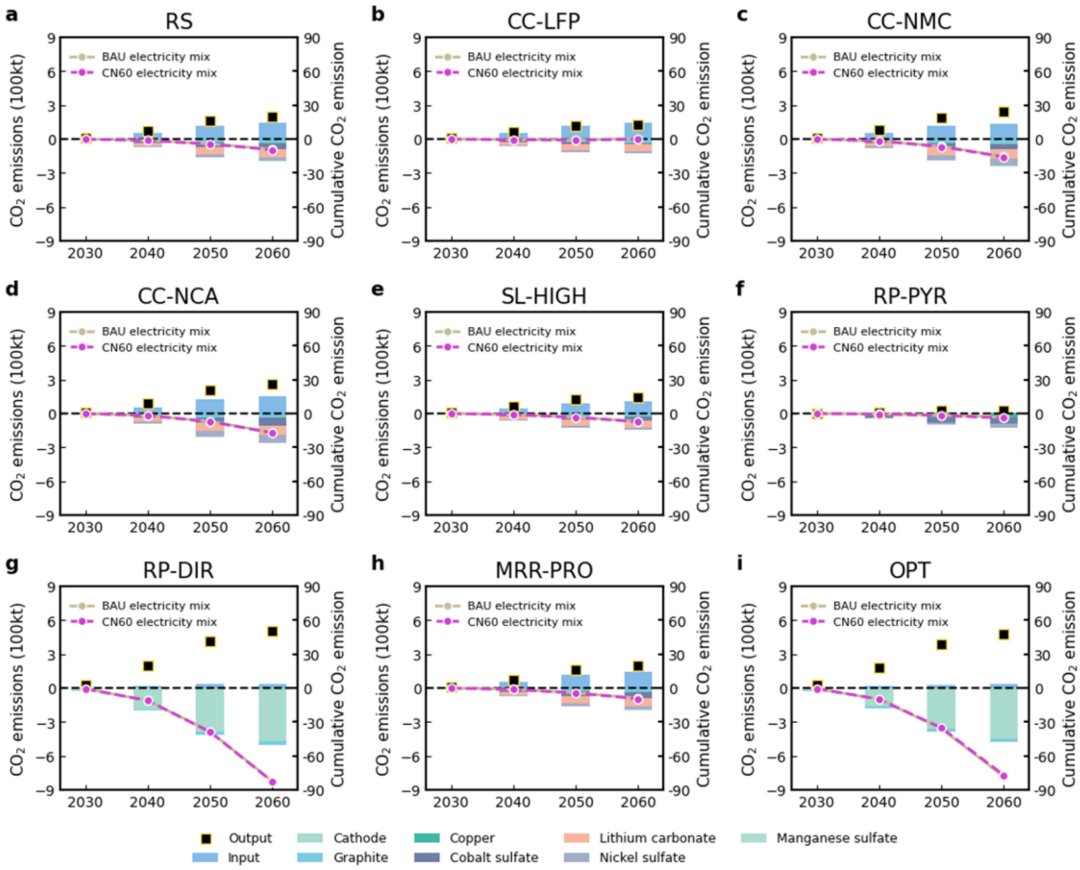
Supplementary Figure 21. Life-cycle CO_2 emission considering the battery capacity and density. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



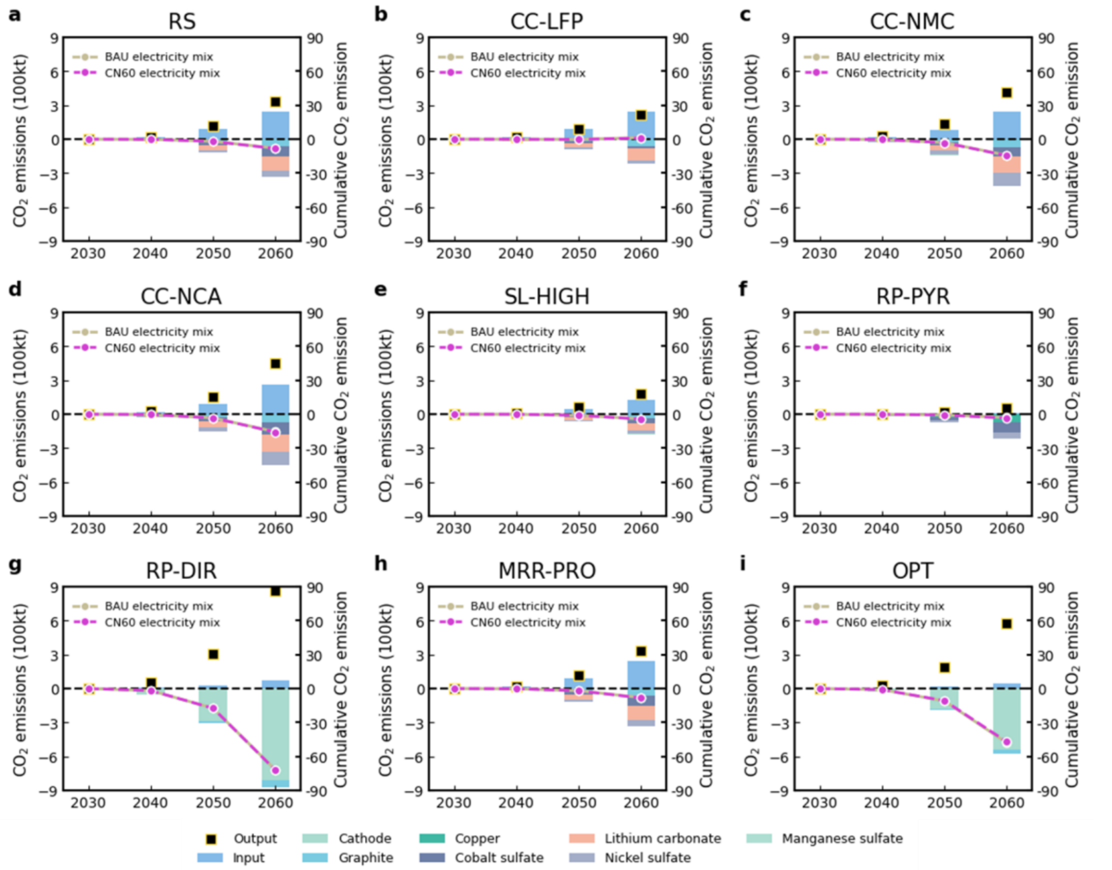
Supplementary Figure 22. Recycling CO_2 emission with compact car. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



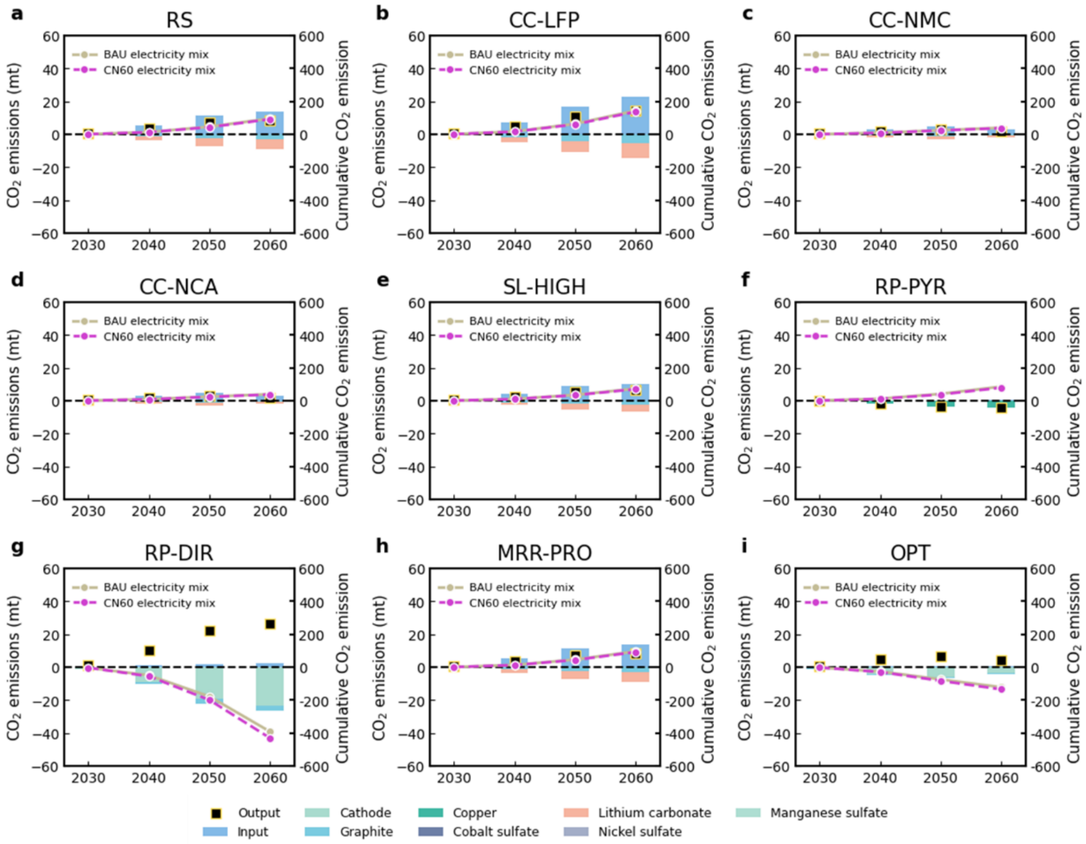
Supplementary Figure 23. Recycling CO_2 emission with large car and sport utility vehicle. **(a)** RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



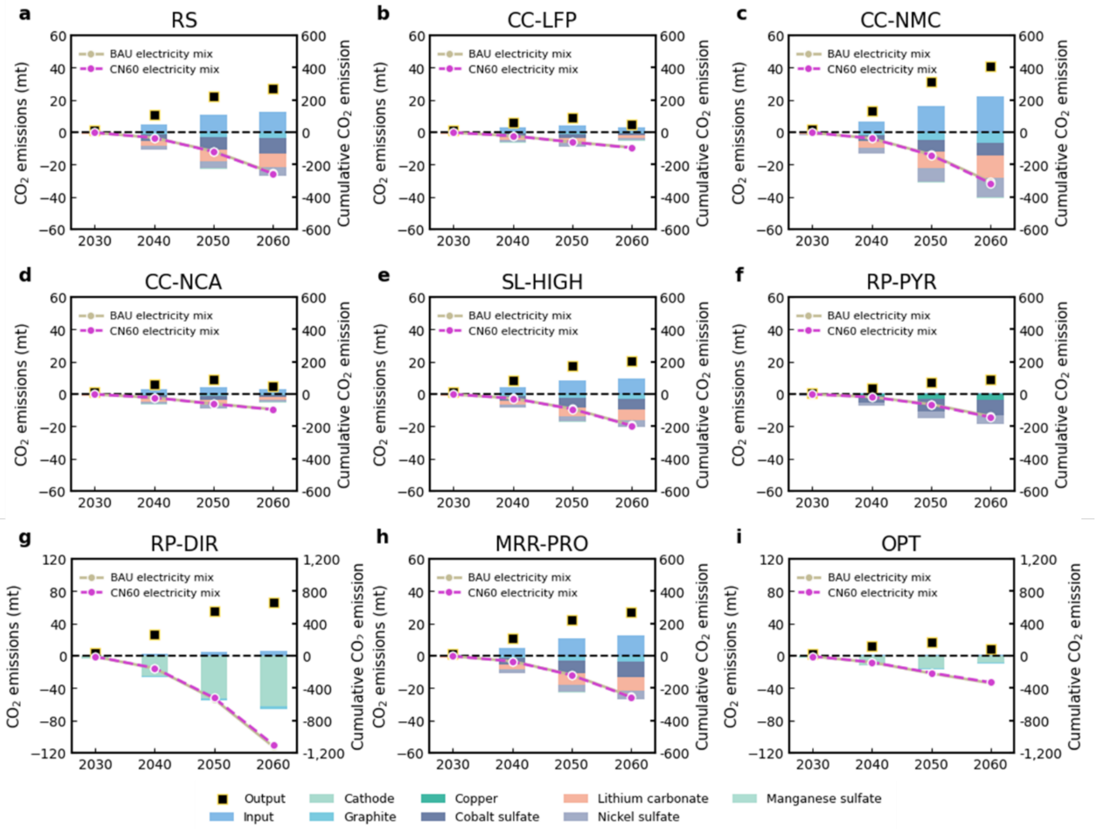
Supplementary Figure 24. Recycling CO_2 emission with mini-sized car. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



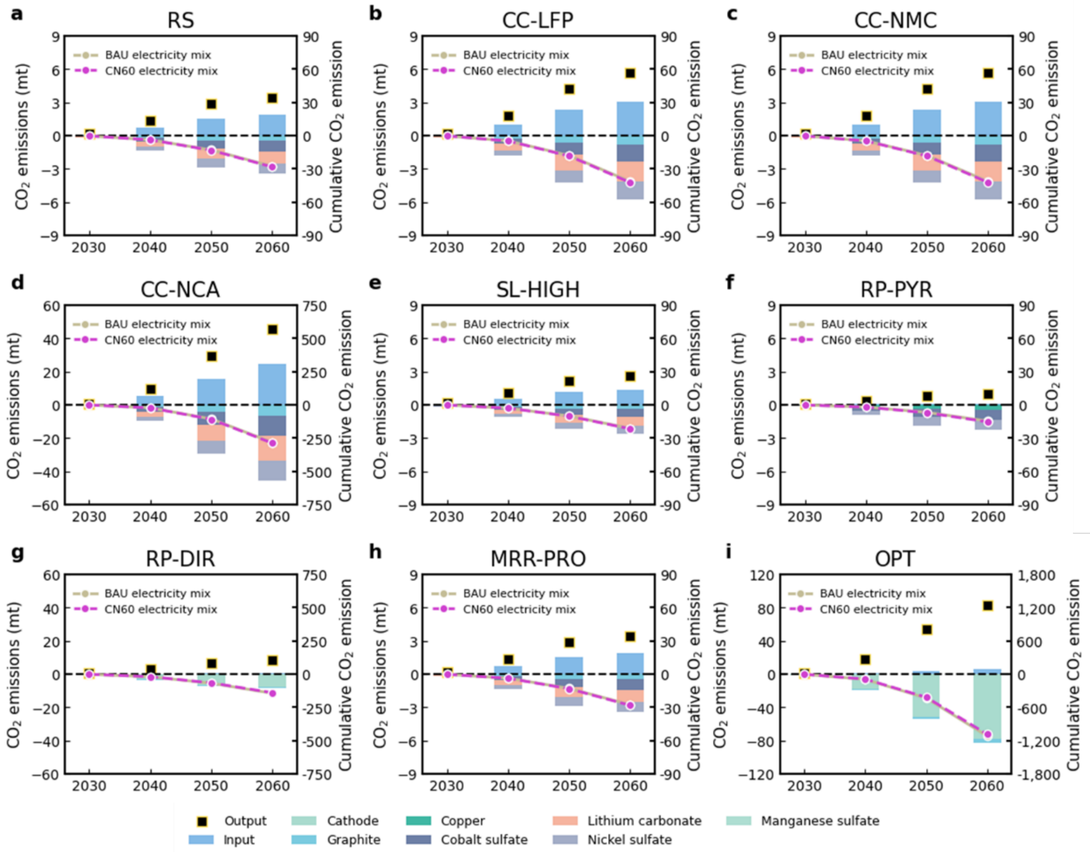
Supplementary Figure 25. Recycling CO2 emission with truck. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



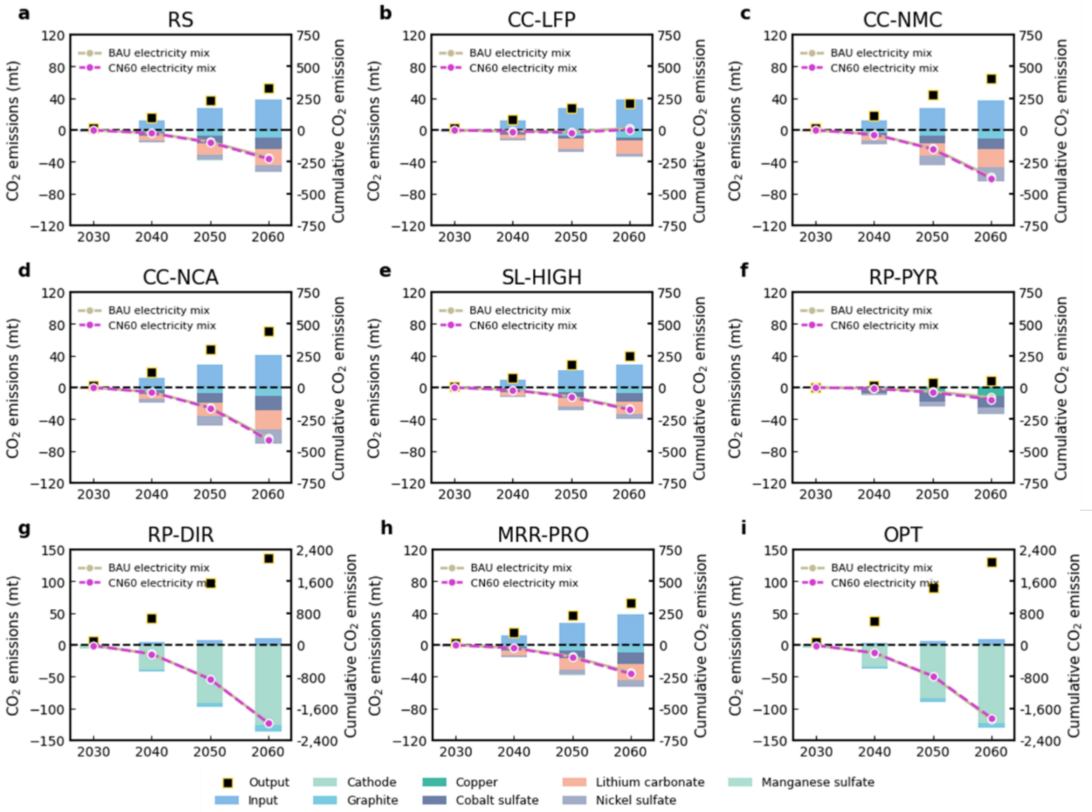
Supplementary Figure 26. Recycling CO_2 emission with LFP cathode. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



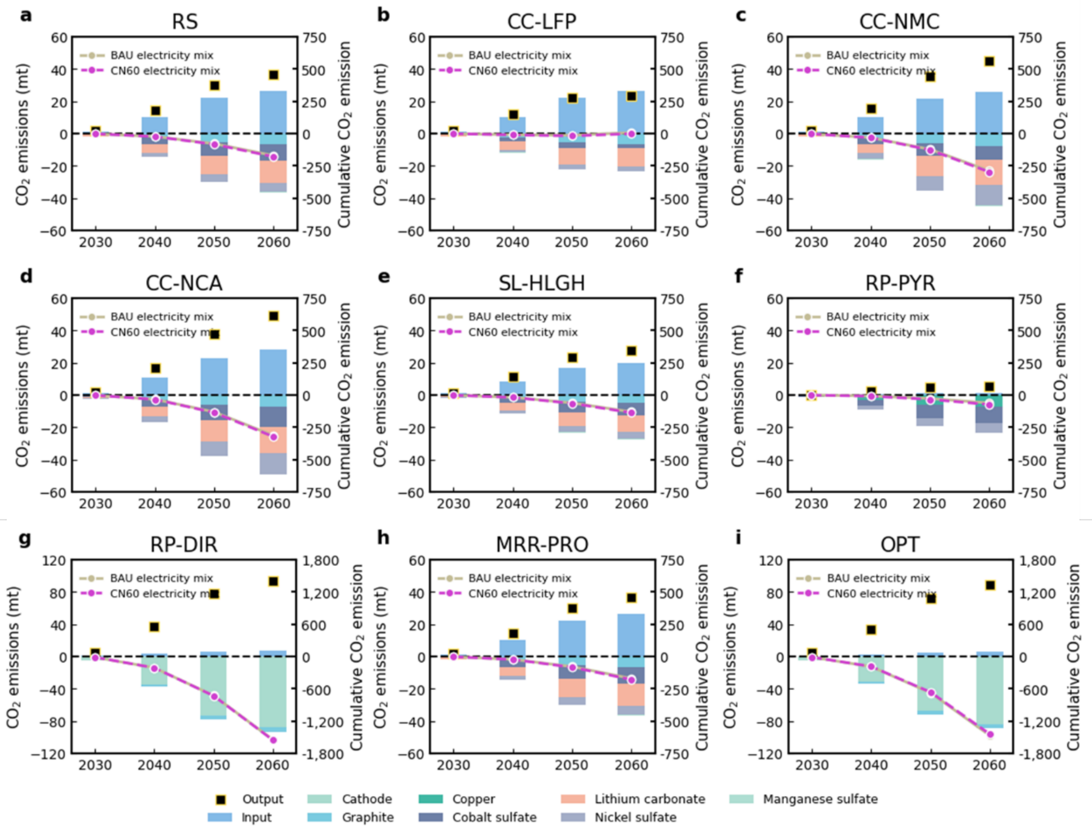
Supplementary Figure 27. Recycling CO_2 emission with NMC cathode. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



Supplementary Figure 28. Recycling CO_2 emission with NCA cathode. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



Supplementary Figure 29. Recycling CO_2 emission considering the EV uncertainty. **(a)** RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.



Supplementary Figure 30. Recycling CO_2 emission considering the battery capacity and density. (a) RS scenario. **(b)** CC-LFP scenario. **(c)** CC-NMC scenario. **(d)** CC-NCA scenario. **(e)** SL-HIGH scenario. **(f)** RP-PYR scenario. **(g)** RP-DIR scenario. **(h)** MRR-PRO scenario. **(i)** OPT scenario. *Abbreviations:* CN60 electricity mix refers to the China's carbon neutrality electricity mix; BAU electricity mix refers to China's baseline electricity mix. RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The figure is plotted under medium battery collection rate.

Strategy	Policy option	Critical material self-sufficiency potential	Carbon emission mitigation	Cost effectiveness
RS	Current battery and recycling technology	✓	⊖	⊗
CC-LFP	Developing cobalt-free battery technology	✓	⊖	⊗
CC-NMC	Cathode chemistry tends to low-cobalt and high-nickel equipment	✓	⊗	⊖
CC-NCA	Cutting-edge battery technology with low-cobalt and manganese-free equipment	✓	⊗	⊖
SL-HIGH	Extending battery lifespan technology	⊗	✓	⊗
RP-PYR	Mature pyrometallurgical recycling process	⊗	⊗	⊗
RP-DIR	High-end direct cathode recycling	✓	✓	✓
MRR-PRO	Advancement of recycling infrastructure	✓	⊖	⊖
OPT	The best technology evolution	⊗	✓	✓

Supplementary Figure 31. Comprehensive assessment of LIB recycling strategies. A check mark indicates strong performance for a given battery recycling strategy on that specific indicator, a minus sign denotes moderate performance, and a cross represents poor performance. *Abbreviations:* RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology and critical material rate develop according to current tendency. CC-LFP, CC-NMC and CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the batteries are adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO refers to the progressive critical material recycling rate. And the OPT scenario denotes the optimal battery technology and recycling technology transition.

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