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The greenhouse gas emissions reduction co-benefit of end-of-life electric vehicle battery treatment strategies

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Abstract
Vehicle electrification stands as a pivotal catalyst for effecting a low-carbon transition within the transportation sector. End-of-life (EoL) battery treatment, which is mainly aimed at facilitating material recycling, provides considerable co-benefit in reducing greenhouse gas (GHG) emissions. This study assesses the life-cycle GHG emissions from battery production, and examines the impact of three EoL battery treatment strategies: second use, regeneration, and recycling. Prospective scenarios of GHG emissions from electric vehicle battery production in China are further provided. The results show that under the Business as Usual (BAU) scenario, GHG emissions peak at 36 million tons in 2030, with 18 million tons for LFP and 18 million tons for NCM, and decrease to 11 million tons in 2060, with 4 million tons for LFP and 7 million tons for NCM. GHG emissions have more reduction potential as the collection rate increases and the proportion of different strategies applied changes. In a scenario with improved collection rates, GHG emissions would be reduced by 21% in 2060 compared to BAU. In a prioritized regeneration scenario, GHG emissions can be reduced by 32% in 2060, with 64% of lithium resources being supplied by regenerated batteries. In a prioritized second use scenario, GHG emissions can be reduced by 104% in 2060, which involves replacing 27 kilotons of lithium input and mitigating 13 million tons of GHG emissions related to the energy storage system. In light of these findings, we advocate for policy recommendations aimed at fostering the advancement of EoL battery treatment technologies and expediting the transformation of battery manufacturing processes towards carbon neutrality.

Keywords: Vehicle power battery, life cycle assessment, recycling technology, greenhouse gas emission, metal material

INTRODUCTION

In recent years, China's automotive sector has undergone a profound low-carbon transformation, with the electric vehicle (EV) market experiencing rapid expansion, solidifying its position as the global leader in EV adoption. Notably, in 2022, China marked a significant milestone by selling an impressive 5.365 million EVs, maintaining its preeminent status as the leading market for 14 consecutive years[1]. This remarkable ascent can be attributed to the environmentally friendly nature of EVs, relying on electricity as a power source, which is inherently cleaner than conventional gasoline and diesel fuels[2,3]. However, it is imperative to recognize that there are still opportunities to further reduce greenhouse gas (GHG) emissions, especially during the production and recovery phase of EVs[4]. Extensive research underscores this aspect, revealing that in the manufacturing process of vehicles within the same class, EVs generate 13.8 tons of GHG emissions, slightly more than the 10.6 tons emitted by internal combustion engine vehicles, with 3.1 tons stemming from lithium-ion batteries (LIBs)[5]. Consequently, the pursuit of low-carbon solutions in the realm of automotive power batteries emerges as a pivotal and forward-looking imperative for the automotive industry.

The reclamation and recovery of End-of-life (EoL) batteries play a pivotal role in advancing carbon reduction efforts. In tandem with the rapid proliferation of EVs, the Chinese market has witnessed a substantial upswing in EV adoption and ownership, thereby underscoring the necessity for addressing the recycling of EoL vehicle power batteries[6]. According to both empirical data and forward-looking projections, the quantity of discarded vehicle power batteries in China reached 77,000 tons in 2020, with an anticipated escalation to 291,000 tons by 2024, reflecting an annual growth rate averaging approximately 41%[7]. This robust growth trajectory suggests that the annual volume of EoL batteries will remain considerable. Notably, scholarly research posits that LIB recovery can contribute to conserving 43% to 90% of natural resources while reducing GHG emissions[8].

Simultaneously, the increasing demand for EV power batteries has engendered a corresponding augmentation in the resources[9]. Presently, LIBs serve as the primary power source for EVs, encompassing variants like LFP employing $LiFePO_4$ as the cathode material, and NCM batteries characterized by diverse compositions of $Li(Ni_xCo_yMn_{1-x-y})O_2$ as the cathode material. The cathode production process has witnessed a substantial surge in the demand for essential metals, notably lithium, nickel, cobalt, and manganese. In 2019, the Chinese demand for these vital resources surged to 35,000 tons, 1.3 million tons, 70,000 tons, and 14.3 million tons, respectively[10]. China's reliance on imports for these resources is presently pronounced, with external dependencies in 2019 reaching 78.5% for lithium, 91.5% for nickel, 97.1% for cobalt, and 91.0% for manganese[10]. Concurrently, the looming specter of supply disruption resulting from geopolitical, economic, and commercial competition in source countries underscores the imperative of resource recycling to ensure the security of supply for critical metals within China's burgeoning automotive industry[11,12]. This strategic pursuit assumes paramount significance in the context of safeguarding China's automotive metal resources[13].

Currently, the predominant strategies for the recovery of power batteries encompass second use, regeneration, and metallurgical recycling, each yielding distinct outcomes in terms of extending the operational lifespan of power batteries and harnessing metal resources[14,15]. Second use pertains to batteries retired from EVs that retain approximately 80% State of Health (SoH), rendering them suitable for utilization in low-end mobile applications or energy storage system (ESS)[16-18]. When EoL batteries exhibit the requisite energy density performance to fulfill these application demands, they present superior environmental and resource synergies compared to the dedicated production of equivalent LIBs specifically tailored for such scenarios[19]. Reinhardt *et al.* (2019) underscored that the adoption of second use strategies could effectively mitigate the cost associated with LIB utilization, while simultaneously nurturing ancillary industries capable of addressing the prevailing unsustainable dynamics within the EV sector, thereby facilitating the realization of a closed-loop battery recycling ecosystem[20]. Furthermore, it is noteworthy that EoL batteries from ESS systems can still be recycled for their metals.

Regeneration technology offers a viable solution for addressing EoL battery cathodes with diminished activity. This process involves the restoration of their functionality, rendering them suitable for reuse in automotive power battery production. Referred to as physical recycling or direct recycling, regeneration involves the disassembly of EoL batteries, wherein the cathode is separated from the battery cell. This procedure enables the recovery of the aluminum shell and copper anode. Subsequently, the regenerated cathode active material can be integrated into the production of new LIBs, thereby facilitating a closed-loop resource utilization system. A study by Xu *et al.* (2020) presents that a paradigm-shift LIB recycling method based on defect-targeted healing can fully recover the composition, structure, and electrochemical performance of spent LFP cathodes with various degradation conditions to the same levels as that of the primary materials[21]. Such a direct recycling approach can significantly reduce energy usage and GHG emissions, leading to significant economic and environmental benefits compared with today's metallurgical recycling methods[21,22]. In the case of NCM battery cathode materials, Wang *et al.* (2020) conducted a comprehensive investigation into their regeneration process. Employing the ionothermal synthesis method for cathode regeneration, the researchers analyzed the performance of the regenerated materials[23]. A comparative analysis, featuring cyclic voltammetric curves and AC impedance spectra of fresh and regenerated materials, revealed that batteries incorporating the regenerated materials exhibited decreased charge transfer impedance. However, it is worth noting that the SoH of these batteries indicated a reduction of approximately 5% compared to their fresh counterparts[24].

Metallurgical recycling technology is a prominent and extensively utilized approach, categorized into two primary subtypes: pyrometallurgical and hydrometallurgical recycling. Pyrometallurgical recycling entails considering the EoL battery as a valuable ore source, rich in metal resources akin to those found in urban mining. This method involves the addition of specific substances, followed by roasting within a blast furnace, culminating in the gradual separation and purification of compounds such as lithium carbonate[25]. On the other hand, hydrometallurgical recycling encompasses the dissolution of the initially disassembled battery cell in a leaching agent[26-28]. Subsequently, a series of chemical processes is employed to extract high-grade battery compounds[29]. Previous research has underscored certain limitations associated with both pyrometallurgical and hydrometallurgical methods, notably in terms of material loss and the type of materials that can be effectively recovered[6]. Consequently, contemporary engineering practices often adopt a combined approach that integrates elements of both pyrometallurgical and hydrometallurgical recovery methods, capitalizing on the respective advantages of each technique. For instance, Kumar *et al.* (2022) conducted a comprehensive study on LFP waste recovery, achieving a 96.92% of recovery rate battery grade lithium carbonate[30]. Similarly, in a study by Chang *et al.* (2022), the recovery technology for NCM battery cathode materials was investigated, resulting in the successful preparation of battery grade lithium carbonate and NCM precursor, meeting stringent standards and serving for cathode materials[31].

More current research illustrates the possibility of further development of recycling technology. Several researchers have shown the possibility of using organic solvents or biomass solvents to leach batteries. Professor Nicholls' research team from Linnaeus University has investigated an environmentally friendly way that uses a liquid solvent made from substances extracted from urine and acetic acid to achieve efficient cobalt recovery[32]. In addition, there are other physical methods that can be used to separate and extract battery components. Xiao *et al*., in 2021, used a method of ultrasound-assisted leaching battery, which used a 110 W ultrasonic bath for extraction during the leaching process, and analyzed that the leaching time was shortened by more than 50% and the leaching rate of valuable metals was significantly improved under the condition of ultrasonic bath assistance[33].

Diverse recovery strategies necessitate varying resource inputs, including materials and energy, for the management of EoL batteries. Additionally, the reintegration of products into battery production processes diverges among these strategies, yielding distinct environmental and resource-related advantages. Overall, second use can extend the service life of the battery until its capacity is reduced to about 60% of the initial value, which helps to fully utilize the potential of the battery and resources at the use side. Compared with metallurgical recycling, regeneration can directly produce cathode materials with higher emissions and improve the utilization efficiency of materials, but there is a loss in energy density, resulting in a trade-off relationship. In light of the projected evolution of China's EV market spanning the period from 2020 to 2060, this scholarly investigation undertakes an evaluation of the GHG emissions associated with China's automotive power batteries, considering multiple scenarios of recovery strategies. Furthermore, it conducts a comprehensive analysis of the corresponding resource requisites and contributions to the sphere of energy storage.

Methodology and data

This study predominantly employs the Life Cycle Assessment (LCA) methodology as its primary analytical tool for the comprehensive evaluation of GHG emissions associated with various battery treatment strategies. LCA is a method to quantitatively analyze the potential environmental impact of a product during its entire life cycle[34,35]. This method has been widely used in related fields to identify environmental hotspots and guide research work[36].

System boundary

The system boundary has been meticulously delineated to encompass the entire life cycle of LFP and NCM batteries, delineated across three principal phases, as visually represented in Figure 1. These phases encompass the battery production, use, and collection and recovery stages, each characterized by specific activities:

(1) The Battery Production Phase: This initial phase encompasses the intricate processes involved in the production and preparation of LIB materials. Additionally, it incorporates the mining, refining, and manufacturing operations requisite for battery production[37].

(2) The Battery Use Phase: Commencing with the assembly of the battery and its integration into an EV, this phase extends through the entire operational life cycle of the EV, concluding with its retirement. It encompasses the dynamic behavior of the battery, characterized by numerous cycles of charging and discharging. Importantly, for the purposes of this study, it is noteworthy that the Battery Use Phase has not been integrated into the LCA analysis.

(3) The Battery Collection and Recovery Phase: This phase encompasses the comprehensive management of EoL batteries. It entails the collection of EoL batteries and their subsequent processing through diverse treatment methods. While transportation considerations fall beyond the scope of this analysis, it is imperative to note that certain EoL batteries may remain uncollected due to accidents or other factors. Within this phase, EoL batteries are directed towards various treatment destinations. Batteries undergoing

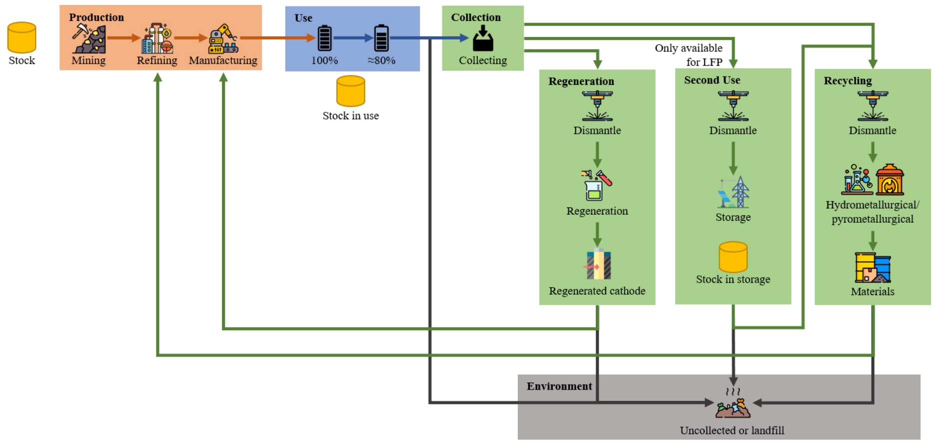

Figure 1. System boundary of LIBs. Regeneration and recycling technologies are available for both LFP and NCM batteries, but second use technology is only used for LFP batteries.

regeneration yield cathode active materials that are subsequently integrated into the battery production phase. Those earmarked for second use are subjected to disassembly, reassembly, and transport to energy storage facilities, where they serve for a defined period before being retired. Subsequently, these retired batteries join the stream of metallurgical recycling alongside EoL vehicle batteries. The metallurgical recycling process involves the extraction of battery components employing a combination of pyrometallurgical and hydrometallurgical techniques. The resulting compounds are then integrated into the refining stage of the battery production phase, thus concluding the battery's life cycle in a sustainable and environmentally conscious manner.

Assumptions

In this study, the life cycle is assumed in the following way. The production phase includes mining, refining, and manufacturing[38]. During the use phase, the battery is served in the vehicle and retired when the battery capacity drops to 80% of the initial value.

In the recovery phase, a recovery company collects, transports, and executes the treatment strategies. This study assumed the collection rate of EoL batteries in the whole society every year and the situation of applying three strategies, respectively named five different scenarios, outlined as follows:

(1) Scenario BAU (Business as Usual): In this scenario, the collection rate is projected to experience gradual increments up until 2040, after which it will plateau. Concurrently, the utilization of second use and regeneration technologies is expected to remain limited.

(2) Scenario COL (Enhanced Collection): Relative to Scenario BAU, this scenario envisions a substantial improvement in the collection rate, culminating in a peak rate of 90% by 2040, which is maintained thereafter. The application of second use and regeneration technologies is anticipated to see modest increments compared to the BAU scenario.

(3) Scenario BAL (Balanced Development): Building upon Scenario COL, this scenario forecasts a more equitable development of second use and regeneration technologies, maintaining a balanced approach.

(4) Scenario REG (Regeneration Priority): In contrast to Scenario COL, Scenario REG accentuates the prominence of regeneration technologies, with second use being implemented more sparingly.

(5) Scenario B2U (Second Use Priority): Diverging from Scenario COL, this scenario prioritizes second use strategies while constraining the application of regeneration technologies.

It is pertinent to note that, notably, this study does not consider the second use of NCM batteries, thus categorizing their second use rates in each scenario as metallurgical recycling. The graphical representation of the implementation levels of these strategies under each scenario is visually presented in Figure 2 for clarity.

Data sources

In this study, the dataset utilized for analysis was categorized into three distinct segments: battery production data, battery recovery data, and macro-industry data. The battery production data primarily relied on information extracted from the GREET model databases, encompassing comprehensive details pertaining to battery component manufacturing and the production of associated materials[40,41]. Battery recovery data were extracted from the GREET model databases, as shown in Supplementary Table 1A and B. The macro-industry data, pivotal for contextualizing our analysis, drew upon contemporary industry realities and encompassed projections and assumptions about future trends. This encompassed information gleaned from additional literature sources and government-provided datasets. Detailed specifics regarding the dataset employed will be elucidated in subsequent sections of this paper.

Battery production

The material composition data for various LIBs are sourced from the GREET model developed by Argonne National Laboratory, as meticulously detailed in Supplementary Table 2. The energy density for the LFP battery, as per the model, is specified at 174 Wh/kg. Furthermore, the GREET model provides energy density values for several NCM variants: NCM333 at 215 Wh/kg, NCM532 at 225 Wh/kg, NCM622 at 241 Wh/kg, and NCM811 at 248 Wh/kg[40,41]. Notably, the production phase of these batteries encompasses a comprehensive sequence of activities, including mining, refining, and manufacturing. Subsequently, these materials culminate in the assembly of battery cells, which are then further integrated into battery packs for practical use in EV propulsion systems.

Battery recovery

(1) Regeneration

In the regeneration phase, the EoL battery undergoes a series of meticulously structured steps involving dismantling, regeneration and reassembly to yield a regenerated battery. During the dismantling stage, the battery pack is disassembled into its constituent battery cells, whereupon the battery cell undergoes further deconstruction to extract the cathode material. This dismantling process is primarily reliant on the energy consumption of specialized instruments, without necessitating any additional material inputs, while also permitting the subsequent reuse of the aluminum shell within the context of subsequent battery assembly. Subsequently, the cathode material is subject to a restorative treatment involving the addition of lithium carbonate and a high-temperature melting process conducted within a CO_2 gas-protected environment[42]. This results in the partial restoration of the cathode material's activity. This regenerated cathode material is then integrated with freshly manufactured components to form a new battery pack. Notably, this assembly process incurs energy consumption and material inputs that align with the component composition and

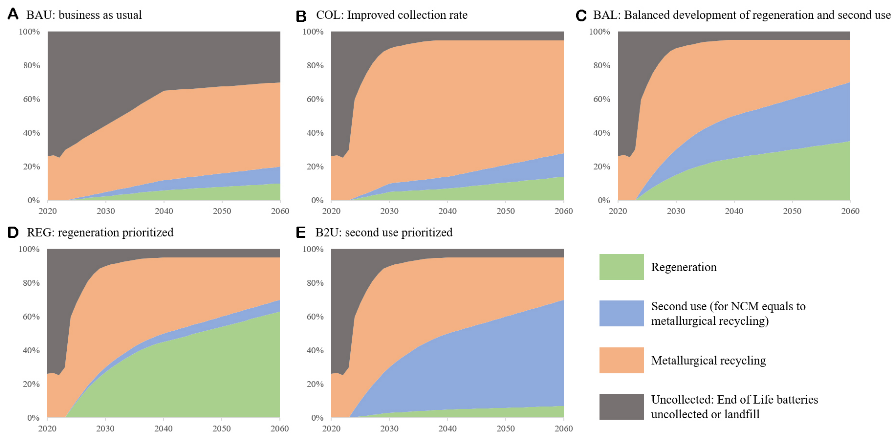

Figure 2. The rate of different recovery strategies under scenarios of (A) BAU, (B) COL, (C) BAL, (D) REG, and (E) B2U, the data before 2023 is based on the reality of the industry[39], and the data after 2023 is based on assumptions.

ratios characteristic of the battery production phase, all of which are quantified through the utilization of the GREET model, as shown in Supplementary Table 1C and D.

(2) Second use

In this investigation, the holistic operational paradigm of second-use application directs the integration of retired batteries into an ESS. Within the ESS framework, LFP batteries are allocated for the storage of electricity generated from renewable sources, such as wind, hydro, and solar, thereby serving as a critical tool to ameliorate voltage fluctuations caused by fluctuations in electricity demand. The entire process encompasses battery disassembly, transportation, structural modifications, and eventual integration into the electrical grid infrastructure. When the SoH of a battery diminishes to 60%, it is systematically disengaged from the ESS and earmarked for metallurgical recycling. This second use application operates on the assumption that it effectively extends the service life of the batteries. The empirical data underpinning this analysis originate from a large-scale energy storage battery project located in Hebei Province, China[43]. This dataset furnishes critical insights into energy consumption patterns and the material inputs required for the comprehensive second use process, as shown in Supplementary Table 1E.

Notably, when accounting for the substitution effect engendered by second use, this study concentrates exclusively on the offsetting of battery charge and discharge activities. This focus arises from the recognition that the design capacity of ESS units typically surpasses the peak storage capacity demanded by practical operational scenarios. Certainly, the industry development prospects also show the potential for the application of sodium-ion batteries and zinc batteries in ESS, and the substitution effect of second use may also be applied to them. Calculations of LFP batteries are used in this study, and other possibilities will be discussed in Section "Limitations and discussion". Consequently, through meticulous calculations, it is ascertained that the cumulative charge and discharge activities of a retired 1 kWh LFP battery within the ESS are comparable to those of a newly manufactured 0.438 kWh LFP battery of commensurate quality. This outcome substantiates the assertion that second use application for LFP batteries yields a substantial 43.8% reduction in the production requirements for new LFP batteries relative to their total capacity demands.

Macro-industry

This research endeavors to provide prognostications concerning the forthcoming yearly production and sales figures for LFP batteries and NCM batteries within the Chinese context. With respect to future commodity consumptions, China's LIB demands and degradation are extracted from the Transport Impact Model (TIM) developed by China Automotive Energy Research Center of Tsinghua University[44-46]. By taking into account factors such as growth of Gross Domestic Production, elasticity of vehicle sales, EV penetration and technological development, TIM was able to forecast annual sales and degradation of various batteries in 2020-2060. The graphical representation of these forecasted trends is visually elucidated in Supplementary Figures 1 and 2.

In light of these prognostications, it is anticipated that the production of power batteries will exhibit sustained growth in the foreseeable future, culminating in a zenith around the year 2045. Subsequently, a gradual tapering off of production volumes will ensue, leading to the establishment of a stable market equilibrium. In tandem with this trajectory, the obsolescence of power batteries is expected to rise incrementally, albeit with a discernible time lag vis-à-vis production dynamics, ultimately converging towards a plateau by the year 2060.

In the assessment of GHG emissions factors, this study predominantly draws upon data originating from the 2006 report of the United Nations Intergovernmental Panel on Climate Change[47], a recognized authoritative source in the field of climate science. Additionally, the study incorporates emission factors specific to energy usage in EVs. These meticulously selected and rigorously validated factors assume a pivotal role as foundational references, enabling the comprehensive evaluation of the environmental implications pertaining to GHG emissions throughout the analytical processes under investigation, as shown in Supplementary Table 3 and Supplementary Figure 3.

RESULTS AND DISCUSSIONS

LCA result

In accordance with distinct cathode materials and their respective sources, an exhaustive analysis of GHG emissions emanating from the production of various categories of LIBs was meticulously conducted and subsequently categorized by their constituent components, as visually represented in Figure 3. Specifically, for LFP batteries, the utilization of primary resources was found to be associated with the generation of 72.6 kg CO_2 eq./kWh of GHG emissions. However, employing recycling resources yielded a noteworthy reduction of GHG emissions by 6.8%, while the utilization of regenerated resources exhibited a more substantial reduction of 21.4%. Similarly, for NCM batteries, the deployment of primary resources was determined to yield GHG emissions ranging from 92.2 to 102.2 kg CO_2 eq./kWh. In contrast, the incorporation of recycling resources resulted in a GHG emissions reduction spanning from 18.8% to 23.6%, whereas the utilization of regenerated resources yielded a markedly greater reduction of GHG emissions, falling within the range of 42.9% to 48.0%.

In the context of LFP batteries, the production of 1 kWh of LFP battery utilizing primary resources yields noteworthy GHG emissions. Specifically, the cathode material production results in 9.7 kg of GHG emissions, while other materials, predominantly aluminum and copper, contribute 21.4 kg of GHG emissions. Moreover, the battery assembly process consumes a substantial 262.1 kWh of electricity and generates 41.5 kg of GHG emissions. However, the incorporation of recovery strategies proves to be effective in mitigating these emissions by enabling the recovery of lithium carbonate and aluminum materials from EoL batteries. This resource recycling substantially reduces the demand for cathode active materials and aluminum, resulting in a reduction of 3.0 kg and 12.3 kg of GHG emissions, respectively.

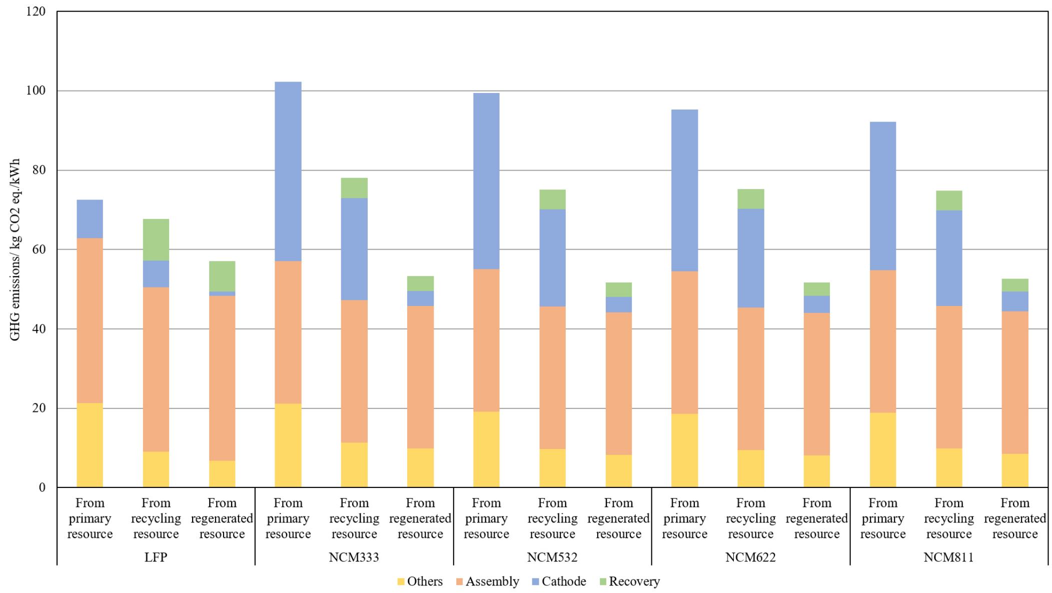

Figure 3. The GHG emissions of LFP and NCM production by using materials from different resources.

Furthermore, the adoption of regeneration technologies further enhances GHG emissions reduction by facilitating the recovery of copper and aluminum from EoL batteries, with a minor addition of lithium carbonate to obtain cathode active materials.

Shifting focus to NCM batteries, particularly exemplified by the NCM811 variant, the production of 1.0 kWh of such batteries from primary resources carries significant environmental implications. Specifically, cathode material production accounts for 37.4 kg of emissions, primarily attributed to cobalt sulfate and nickel sulfate production, while other materials, notably aluminum and copper, contribute 18.9 kg of GHG emissions. Furthermore, the assembly process for the battery materials consumes 226.7 kWh of electricity and results in 35.9 kg of GHG emissions. In a contrastingly positive light, recycling efforts exhibit substantial potential for emission reduction by recovering lithium carbonate, nickel sulfate, cobalt sulfate, and manganese sulfate from EoL battery cathodes, as well as copper and aluminum from the anode and shell. These recovered materials can be reintegrated into new battery production, thereby mitigating emissions by 13.2 kg CO_2 from cathode materials and 9.1 kg from other materials. Moreover, regeneration techniques prove to be particularly advantageous for high-emission NCM cathodes by effectively recovering copper and aluminum from EoL batteries and incorporating a limited quantity of lithium carbonate to yield positive active materials, thus amplifying emission reduction benefits.

Prediction of battery industry

Demand for materials

In the production of LIB, a substantial quantity of raw materials, including lithium, nickel, cobalt, and manganese, is necessitated. The implementation of diverse recovery strategies presents an effective means by which to curtail the demand for primary resources. Within the context of this study, an examination was conducted to assess the sources of supply for lithium, nickel, cobalt, and manganese materials across various scenarios, as visually represented in Figure 4.

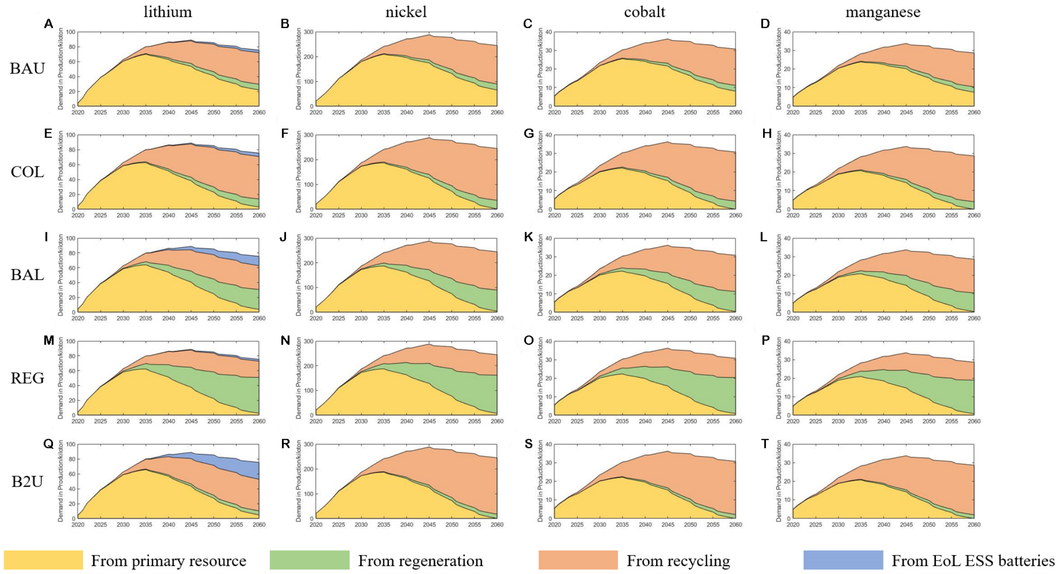

Figure 4. The demand for lithium, nickel, cobalt, and manganese resources from different sources under various scenarios.

In various scenarios, the demand for each metal exhibits an initial ascent until the year 2035, after which it demonstrates a gradual decline, coinciding with the maturation of recovery application. In the BAU scenario, the demand for primary lithium resources will peak in 2035 at 70 kilotons, accounting for 87% of the total demand in that year. However, total lithium demand will peak at 89 kilotons in 2045. After that, with the development of the recycling industry and strategies, the demand continued to decrease. By 2060, total lithium demand is expected to be reduced to 75 kilotons, and sources will change significantly: only 29% is expected to come from primary sources, while 56% will be supplied through recycling processes. Similarly, the peak demand for nickel, cobalt, and manganese in 2045 was 288, 36, and 34 kilotons, respectively, and is expected to decrease slightly to 244, 31, and 29 kilotons by 2060. It is worth noting that the primary resource demands have decreased significantly, from 84%~87% in 2035 to 26%~27% in 2060, respectively.

In the context of the COL scenario, characterized by elevated collection rates and concurrent technological advancements, there is a noteworthy reduction in the demand ratio of primary resources. By 2060, a mere 4% of lithium resources necessitate procurement from primary sources, while 14% emanate from regeneration, 76% from recycling, and 6% from EoL ESS batteries. Furthermore, primary resource contributions for nickel, cobalt, and manganese are at 0%~1%, which can be almost completely provided by recycled resources. In stark contrast, regeneration operations account for about 14% of these resources, while recycling significantly dominates, constituting about 85% of nickel, cobalt, and manganese resources. This predominance of recycling resources is primarily attributed to the enhanced collection rates coupled with the relatively restrained development of regeneration and second use avenues.

In the BAL scenario, rapid advancements are foreseen in the deployment of regeneration and second-use technologies. By the year 2060, it is anticipated that 5% of lithium resources will be derived from primary sources, marginally higher than in the COL scenario. Regeneration will account for 36% of lithium resources, while recycling will contribute 43%, and EoL second-use batteries will constitute 17%. For nickel, cobalt, and manganese resources, primary sources will provide about 1%, with regeneration responsible for about 35% of these resources and recycling supplying about 64%. The advent of regeneration technology has effectively bolstered the proportion of regenerated resources and concurrently played a pivotal role in reducing GHG emissions. However, it is worth noting that the increased emphasis on second-use technologies delays the recycling of batteries, which are repurposed several years later. Consequently, the demand for primary resources exhibits a slight increase compared to the COL scenario.

In the REG scenario, regeneration technology takes precedence, with the majority of EoL batteries undergoing regeneration processes. By 2060, only 3% of lithium resources will need to originate from primary sources, a reduction compared to the BAL scenario. Regeneration will contribute 64% of lithium resources. Nickel, cobalt, and manganese resources sourced from primary reserves will account for 3%, respectively, while regeneration will provide about 63%.

Lastly, under the B2U scenario, second use technology receives prioritized utilization, with most EoL LFP batteries being repurposed for ESS. In contrast, NCM batteries are predominantly earmarked for recycling upon retirement, as their suitability for second use is limited. By 2060, a mere 7% of lithium resources will necessitate primary sourcing. The primary resource demand of nickel, cobalt, and manganese metals is totally 0%. This is attributable to the fact that the recycling of NCM batteries can sufficiently meet resource demands, especially in terms of cobalt and manganese resources, yielding an additional 91 tons and 89 tons of stock in 2060.

From a resource supply perspective, all three strategies demonstrate the capacity to facilitate the collection and reutilization of valuable metal resources present in EoL batteries. Notably, the second use strategy effectively extends the operational lifespan of EoL batteries, thereby postponing the utilization of metal resources contained within them. Conversely, regeneration and recycling strategies promptly recover and reintegrate these metal resources into the supply chain. It is imperative to acknowledge that due to the inherently lower energy density of regenerated batteries compared to their primary counterparts, the efficiency of metal resource utilization is somewhat diminished. Consequently, metallurgical recycling emerges as a strategy associated with a heightened resource substitution benefit. Consequently, a higher recycling rate and an elevated regeneration rate correspondingly translate to reduced reliance on primary resources. In the context of lithium, the scenario denoted as REG exhibits the most conservative demand for primary resources, followed by BAL and B2U scenarios, with recycling and regeneration rates diminishing accordingly. In contrast, for nickel, cobalt, and manganese, the B2U scenario presents the lowest demand for primary resources, succeeded by BAL and REG scenarios, with recycling rates decreasing and regeneration rates ascending incrementally. Therefore, from the vantage point of resource reutilization, metallurgical recycling technology assumes a more efficacious role in resource reuse, bearing profound implications for the mitigation of primary resource demand.

Production emissions from different resource

As per the computational analysis conducted within this study, discernable disparities in GHG emissions emerge in the production processes of LFP batteries and NCM batteries across diverse scenarios. These variations are graphically depicted in Figure 5. Furthermore, it is noteworthy that the choice of metal resources in the manufacturing of batteries imparts distinct GHG emission profiles, thereby contributing to varying overall emission levels.

In the case of LFP batteries, GHG emissions exhibit a peak in the year 2030, followed by a consistent decline, accompanied by a gradual decrease in the proportion of GHGs stemming from batteries produced by primary resources. Across various scenarios, GHG emissions associated with LFP batteries in 2030 remain relatively stable, ranging from approximately 17 million tons, with primary resources accounting for approximately 95% of these emissions. However, by 2060, this proportion diminishes significantly to merely

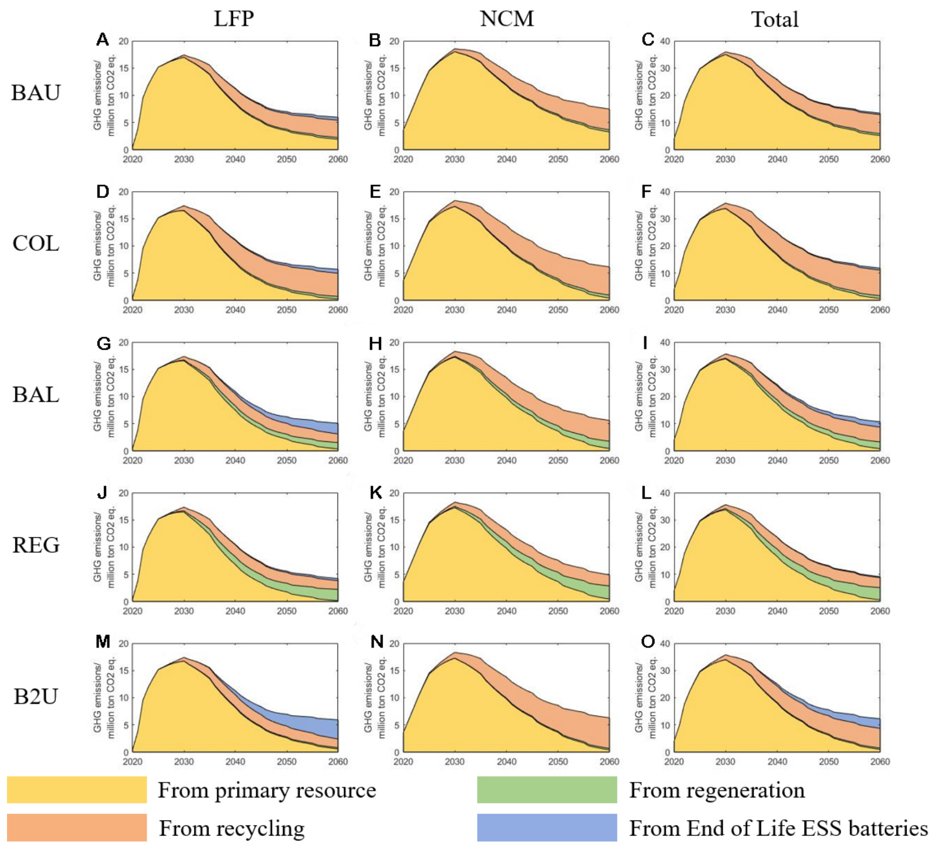

Figure 5. The GHG emissions of LFP and NCM batteries under various scenarios, according to the different sources of metal resources, are described separately.

2 million tons with the BAU scenario, representing a mere 32% of total emissions for that year. BAU is the scenario with the highest emission and proportion of primary resources among the various scenarios. Conversely, the REG scenario, which represents the lowest emissions, registers primary resource-induced emissions of 170 kilotons in 2060, corresponding to 4% of that year's total emissions. In summary, it is evident that scenarios prioritizing regeneration exhibit a lower proportion of GHG emissions originating from primary resources. Additionally, the B2U scenario reports 600 kilotons (10%) emanating from primary resources in 2060. It is worth noting that although second use does not yield substantial environmental benefits in battery production, it offers noteworthy substitution effects in ESS, thereby reducing battery demand - a facet to be explored in Section "Substitution on ESS".

In the case of NCM batteries, GHG emissions exhibit a notable peak in the same year 2030, followed by a consistent downward trajectory. Concurrently, the proportion of GHG emissions stemming from primary resources experiences a gradual decline over this period. To elucidate the variances across distinct scenarios, we examine the GHG emissions of NCM batteries in 2030, which remain relatively stable, ranging between approximately 19 million tons. Under different scenarios, the proportion of primary resource emission is about 95%~98%, and there is little difference among them. By 2060, under the BAU scenario, this proportion experiences a dramatic reduction to 3 million tons, accounting for 44% of the total emissions for that year, which represents the highest emissions. Conversely, in the B2U scenario characterized by a high recycling rate, 40 kilotons are attributed to primary resources in 2060, constituting 7% of the year's total emissions.

In summary, akin to the findings presented in Section "Demand for materials" regarding resource demand, metallurgical recycling stands out as the strategy with the lowest proportion of GHG emissions originating from primary resources. However, it is noteworthy that in the high recycling rate scenario B2U, the proportion of emissions attributable to primary resources is correspondingly the lowest, despite an increased reliance on primary resources. This phenomenon can be attributed to the substantial carbon reduction benefits associated with the regeneration of NCM batteries, resulting in a paradox where greater primary resource use is offset by lower total carbon emissions.

Substitution on ESS

In multiple hypothetical scenarios, the utilization of second use strategies entails the provision of EoL LFP batteries to ESS. The calculation of potential benefits accruing to ESS through second use is predicated on a specific conversion factor, where 1 kWh of EoL batteries is capable of substituting 0.438 kWh of new batteries. The quantification of these benefits is graphically illustrated in Figure 6, shedding light on the potential advantages realized by ESS through the incorporation of EoL LFP batteries in various operational scenarios.

In the BAU scenario, it is projected that by 2060, a total of 47 GWh of EoL LFP batteries will undergo a process of disassembly, reassembly, and grid integration for use in ESS. Concurrently, 40 GWh of batteries will be retired from the ESS. Within the ESS, an impressive 304 GWh of LFP batteries currently in service will trace their origin to EoL vehicle batteries. Under this strategic approach, the year 2060 anticipates a reduction of 21 GWh in the production of LFP batteries designated for ESS deployment, resulting in a saving of approximately 4 kilotons of lithium resources and mitigating a total of 2 million tons of GHG emissions.

Moreover, the contribution of LFP batteries to ESS in various scenarios exhibits noteworthy disparities. Of particular significance is the scenario denoted as B2U, which yields the highest level of substitution benefits. In this context, an impressive 297 GWh of EoL LFP batteries will be integrated into the ESS for service in 2060, while 260 GWh of batteries will be retired. Remarkably, within the ESS, an estimated 2 TWh of the LFP batteries in active service will originate from EoL vehicle batteries. This scenario envisages a substantial reduction of 129 GWh in the production of LFP batteries designated for ESS application, leading to the conservation of approximately 27 kilotons of lithium resources and the mitigation of a total of 13 million tons of GHG emissions in the same year.

For comparative purposes, it is noteworthy that the GHG emissions averted in 2060 across scenarios BAU, COL, BAL, REG, and B2U amount to 2, 3, 7, 1, and 13 million tons, respectively. It is essential to emphasize that while second use may not be the optimal recycling strategy in terms of metal resource recovery, its efficacy in GHG emissions reduction is conspicuously pronounced. In addition, the amount of batteries that can be provided to the ESS does not mean the application, and the demand for the ESS may not match the growth amount of EoL batteries. If the demand is less than the amount of EoL batteries, then we need to encourage the possibility of more renewable energy development, more second use situations of application and forced conversion to other treatment strategies. On the contrary, if the demand is ambitiously developed, the investment of more second use will also bring considerable effects.

Emissions of battery industry

To facilitate a comprehensive comparison of GHG emissions associated with LFP battery and NCM battery production across diverse scenarios, this investigation meticulously delineated the GHG emission profiles within the industry, as graphically illustrated in Figure 7. The quantification of both total GHG emissions

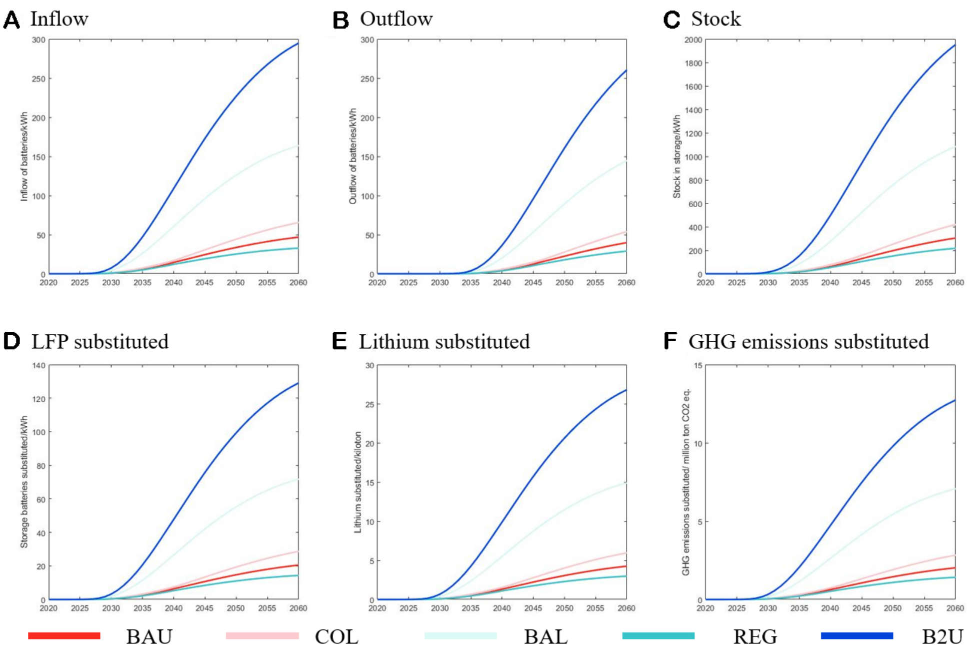

Figure 6. The scale of second use and the substitution benefits, (A) inflow, (B) outflow and (C) stock of LFP batteries from second use of EoL LFP batteries, (D) the production of LFP batteries, (E) the lithium resources and (F) the GHG emissions substituted by second use in each year.

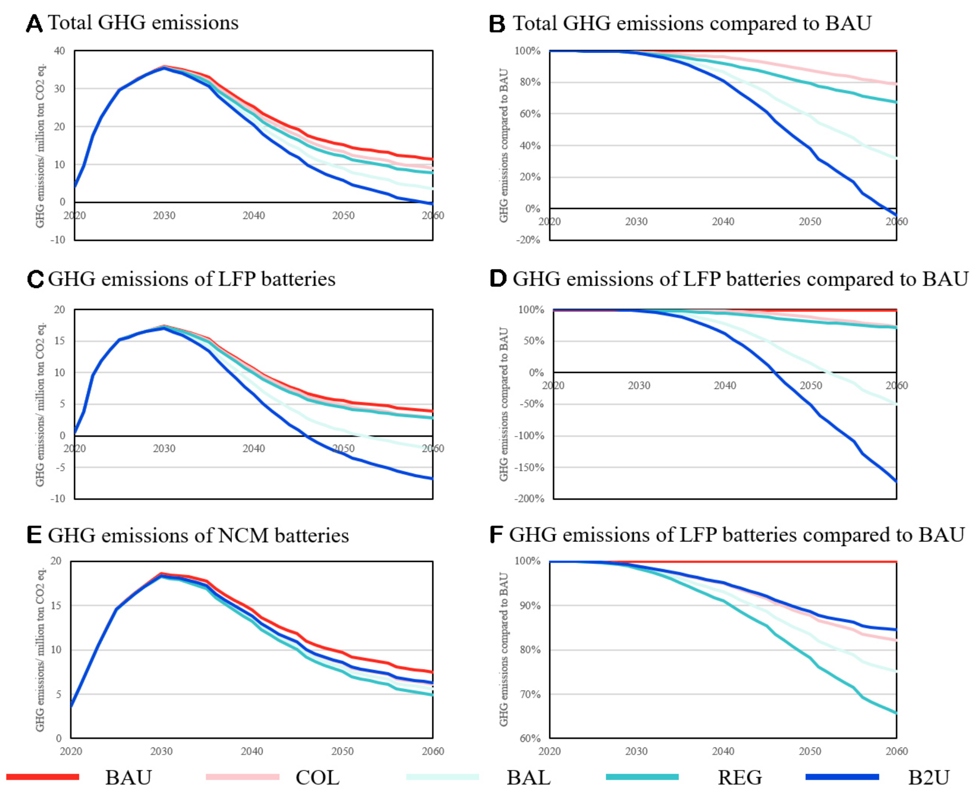

Figure 7. The GHG emissions of (A) total industry, (C) LFP batteries and (E) NCM batteries, and the proportion compared to scenario BAU of GHG emissions of (B) total industry, (D) LFP batteries and (F) NCM batteries.

and those attributed specifically to LFP batteries incorporated the GHG substitution effect attributable to second use practices, as expounded upon in Section "Substitution on ESS".

In the BAU scenario, it is projected that the cumulative GHG emissions from China's automotive battery industry in the year 2060 will amount to 11 million tons, with LFP batteries contributing 4 million tons and NCM batteries accounting for 7 million tons of this total. By utilizing the emissions level under the BAU scenario as the baseline reference, the GHG emissions of the battery industry exhibit varying degrees of reduction across alternative scenarios. Specifically, concerning LFP batteries, the COL, BAL, REG, and B2U scenarios result in GHG emission reductions of 27%, 150%, 19%, and an impressive 272% by 2060, respectively. Notably, the preeminence of the second-use strategy yields more substantial emission reductions, and concurrently, its application exerts a notable substitution effect on ESS, thereby ameliorating emissions considerably. In the case of NCM batteries, the COL, BAL, REG, and B2U scenarios contribute to GHG emission reductions of 18%, 25%, 34%, and 15% by 2060, respectively. The pronounced reduction attributed to the regeneration technology can be attributed to its low emissions during cathode material production, which significantly bolsters carbon mitigation for NCM batteries. When considering the industry as a whole, the COL, BAL, REG, and B2U scenarios collectively reduce carbon emissions by 21%, 68%, 2%, and an impressive 104% by 2060, with particular note that, under the B2U scenario, the industry is slated to attain carbon neutrality by the year 2058.

Limitations and discussion

There are some limitations in this study. Some parameters and assumptions may affect the results. This section introduces this and attempts to discuss how these factors affect the results of the study.

In the battery LCA, the data and methods used will significantly affect the results. The Life Cycle Inventory (LCI) firmly influences the creditability of the results. In the production phase, the development of battery technology may change the content of the LCI and the energy consumption of the production process, and this change may occur on a yearly basis. Vehicle power batteries have been developing in the direction of safer, more energy-saving, and higher energy density, which may lead to higher energy consumption in the production phase, but energy requirements can be reduced in the use phase. Therefore, the impact of the development of production technology needs to be accounted for by more detailed LCA.

In the recovery phase, the development of technology will also affect the material and energy consumption in the process. With the development of cleaner technologies, it is possible to further reduce the energy consumption of recycling processes and optimize input materials. The current advanced research proves the possibility of making a breakthrough in this respect. Given that future advancements in recycling technology are possible, there exists a likelihood of underestimating the GHG reduction potential within the future industry.

From the perspective of industrial development, this study assumes that LIBs will still have a dominant position in the future development of EVs, which is based on the current development of the EV market. With the different possibilities of future automotive power sources, the forecast of the power battery industry may be affected. The cathode material with a higher proportion of nickel in NCM, the emergence of lithium batteries with new chemical systems, and the application and popularization of sodium batteries, fuel cells or solid-state lithium batteries - all these factors will have an impact, which conflicts with the basic assumptions of this study. If other types of batteries become viable for ESS, this will reduce the demand for LIBs in the industry, thus affecting the flow of EoL batteries. Storage stations using sodium-ion batteries will only be replaced with the corresponding newly produced batteries, while storage stations with second use will have a more concentrated battery supply, and their emission level need to be compared by detailed and further calculations.

The limitations of this study also exist in that there are still other technical routes other than recycling that may affect the environmental resource benefits of power batteries, and many external factors will also affect each parameter of the study. In terms of low-carbon technology routes, potential technological routes such as grid cleanliness, vehicle lightweight, and low-carbon industrial production can also provide important support for the low-carbon development of the automotive industry. Among the possible externalities studied, the monetary impact is particularly strong. Vehicle recycling, as a market activity, is strongly influenced by profitability. For example, in recent years, the price fluctuation of lithium has brought challenges to the supply of resources. In the case of a rapid increase in the price of metal resources, enterprises will be more inclined to reduce the echelon utilization and increase the way of repair and recycling to achieve the rapid closed-loop utilization of resources. Batteries using other chemical systems in the energy storage system may affect the feasibility of echelon utilization of lithium batteries from the technical level and increase the corresponding cost.

CONCLUSION

This research is primarily dedicated to comprehensive research of treatment strategies pertaining to vehicle power batteries, with a specific emphasis on the rigorous evaluation of their associated GHG emissions and key materials demands. Employing a methodological framework rooted in LCA, this study meticulously assesses the GHG emissions stemming from the production of LFP and NCM batteries, discovering the difference in resource demands across various technologies. Moreover, within the purview of this study, meticulously designed scenarios are leveraged to provide prognostic insights into the forthcoming trajectories of China's power battery industry, thereby enriching our understanding of its environmental impact and sustainability outlook.

Through an assessment that includes the calculation of GHG emissions associated with battery production across various resource inputs, this study examines the application scenarios of different strategies and arrives at several noteworthy conclusions. Firstly, with regard to metal resource recovery, metallurgical recycling emerges as the most efficacious option, significantly mitigating the annual requirement for primary metal resources and thereby ameliorating concerns related to metal supply. Secondly, in order to reduce GHG emissions, the regeneration demonstrates notable effectiveness in curtailing GHG emissions stemming from battery production. This is achieved by adopting advanced, low-carbon technologies in the manufacture of cathode materials, which represents an important role in the GHG emissions during the production of batteries. Finally, although the second use may not directly manifest in diminished resource supply pressures or GHG emissions reductions, its capacity to extend the service life of batteries and replace alternative low-end application scenarios positions it as a highly advantageous approach. In the process of second use, the energy storage industry can achieve effective GHG emission reduction, but this effect is largely restricted by the development volume of the energy storage industry. Consequently, it emerges as a pivotal instrument for carbon reduction within the battery industry landscape.

Based on the development of the battery industry and the corresponding GHG emission projections, the study determines the realizability of the emission peak target by 2030. This optimistic trend is substantiated by the confluence of judiciously devised treatment methodologies, an escalating transition towards cleaner energy sources, and the relentless improvement of recovery technologies. Given these salient factors and according to the result, it becomes evident that the ambitious objective of carbon neutrality by the year 2060 stands as a plausible and attainable goal.

In order to ensure that the strategies can achieve the planning of China's environmental strategy and further optimize the realization process, this study offers a set of policy recommendations at the national level pertaining to the recuperation of vehicle power batteries:

1. Establish a unified industry standard: In order to provide the basis for battery recovery, it is necessary to establish a unified industry battery dismantling specification or battery configuration standard, so that recycling manufacturers can be equipped with mass processing dismantling equipment to expand the application of second use and regeneration.

2. Encourage the construction of the recovery industry: promote the rapid improvement of battery processing capacity by giving economic subsidies and establishing sustainable development policies. Even in the business-as-usual scenario, increased collecting rates and enhanced processing capacity can bring considerable environmental benefits.

3. Promote the development of the energy storage industry: Through the transformation of the energy structure, improve the construction of renewable energy generation facilities such as photovoltaic power and wind power, increase the volume of the energy storage industry and the demand for energy storage batteries, so as to ensure that EoL vehicle batteries can fully realize the second use. This can lead to the best decarbonation benefits for the entire industry.

4. Strengthen battery technology research: Promote the research progress of regeneration technology and accelerate the application into industry, so as to achieve co-benefits of energy and environment. Encourage intensive research into technologies related to battery production and recycling to achieve decarbonation in the process through research into processes that consume less energy and material.

By the diligent implementation of these recommendations, policymakers can establish an enabling environment conducive to the sustainable and ecologically responsible recycling of vehicle power batteries.

DECLARATIONS

Authors' contributions

Conceived the study: Hao H

Contributed equally to the development of the methodology, the data analysis and interpretation, and the writing and reviewing of the manuscript: Dou H, Hao H

Availability of data and materials

Confirmation that all data supporting your conclusions is fully presented within the article itself.

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Conflicts of interest

Hao H is a Associate Editor of the journal *Carbon Footprints*, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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