

*Original Research*

# The Electric Vehicles' Recycling Process to Carbon Neutrality Mission in China Tends to Be Negative: Depending on the Technology Transition

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## Abstract

While electric vehicles are widely used, the number of waste lithium-ion batteries is increasing. The recycling and reproduction of materials with high environmental load is the key to the sustainable development of the electric vehicle power battery industry. This study conducted the life cycle assessment of CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub> emissions in the recycling stage of electric vehicles in the Beijing-Tianjin-Hebei region of China. The relevant conclusions are: electric energy makes a great contribution to pollutant emission. When taking 1 kg as functional unit, the emissions of SO<sub>2</sub> and NO<sub>x</sub> in the recovery process of lithium iron phosphate (LFP) power battery are lower than those of Lithium nickel manganese cobalt oxide (NMC) battery, while CO<sub>2</sub> and PM<sub>2.5</sub> are opposite. When taking 1 kWh as the functional unit, NMC power battery has better recovery and emission reduction effect than LFP, because it has higher mass and energy density. In particular, the recovery of active materials plays a significant role in NMC battery emission reduction. For CO<sub>2</sub>, recycling does not bring better effects on emission reduction. To achieve carbon neutrality, the recycling process must be optimized. However, for PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>x</sub>, recycling can in turn help reduce emissions in the production process, and the value is more obvious.

**Keywords:** electric vehicles, life cycle assessment, recycling, emission reduction benefits

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## Introduction

About three-quarters of the world's greenhouse gases are produced by road vehicles [1]. As the world's largest emitter of carbon dioxide, Chinese government has pledged to reduce its emissions [2]. In the past ten years, with the support of government policies and technological progress, the electric vehicle (EV) industry has developed rapidly [3-5]. The International Energy Agency (IEA) predicts that by 2030, the global electric vehicle inventory will exceed 130 million [6]. Compared with traditional internal combustion engine fuel vehicles, electric vehicles have the advantage of "zero emission" on the road, which can greatly reduce the CO<sub>2</sub> emission during the driving process [7-10]. In addition to CO<sub>2</sub>, the pollution emissions of PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>x</sub> are closely related to human health and air quality [11], and have become an issue of increasing concern.

The capability of fast charging rate, high energy density, high specific energy extended cycle life, low maintenance requirement are advantages of Li-ion batteries [12,13]. As a result, the demand for lithium-ion batteries has risen sharply in the world [14]. A large number of waste batteries have accumulated [15]. At the same time, waste accumulation and resource consumption are rising sharply [16-18]. According to data from the China Automotive Technology and Research Center, by 2025, the cumulative number of scrapped power batteries in China will reach 780,000 tons (about 116 GWh) [19]. Lithium-ion battery recycling is essential and is becoming the cornerstone of sustainable electric mobility [20,21], attracting widespread concern [22].

The model of Abdelbaky, proves that the inventory and scrap volume of lithium-ion batteries in the EU will increase significantly with the development of electric vehicles in 2040, and emphasizes the importance of achieving closed-loop recycling of lithium resources [23]. The life cycle assessment (LCA) of power batteries in China mostly focuses on the acquisition and use of raw materials, and there are few LCA studies on the scrap recycling of power batteries, or extremely simple models are used to simplify calculations [24]. Xue et al. [25] established a scrapping model to test the recycling potential of EVs. Song [26] analyzed the environmental impact of related industries using LFP power batteries as an example, and emphasized the importance of recycling. It can be seen that battery recycling can reduce emissions by reducing material input [27], which is vital to the environmentally friendly development of the power battery industry.

To this end, we used LCA, a method of assessing the energy consumption and environmental impact of a product, process or service from raw material collection to production, transportation, use and final disposal [28,29]. Not limited to CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub>, which directly harm human health and air quality,

are also included in this evaluation system. To explore the effect of recycling copper, aluminum, LFP and NMC active materials on emission reduction in the secondary production process of electric vehicle power batteries.

## Material and Methods

### Research Object

In this study, model was conducted in a professional environmental assessment software (Simapro). Based on the LCA method, the mainstream LFP and NMC power batteries in the market are taken as the research objects. The system boundary is the recovery stage of electric vehicle power batteries, and the overall research objective is the emission reduction level of CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub> by the recycled materials. To achieve this goal, the following steps are carried out. Firstly, the emission of the recovery technology is compared and analyzed, and its emission contribution is explored. Secondly, it analyzes whether the recycled material can achieve emission reduction. Finally, the contribution of recycled substances to emission reduction is studied. The selected functional unit (FU) is 1 kg and 1kWh. The two functional units are selected to introduce the parameter of mass energy density and explore the influence of the mass energy density on the CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub> emissions in the recovery stage of NMC and LFP power batteries. The mass energy density of the LFP power battery in this study is 88 Wh/kg, and that of the NMC power battery is 150 Wh/kg.

The materials recovered in this paper are copper, aluminum, active materials of LFP and NMC. The recycled materials are put into the battery production process instead of the primary materials. The emissions of the above materials prepared are calculated according to the list, which is the emission reduction of the recycled materials. Input the materials and energy needed for recycling into the software, and calculate the emission levels of CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub> of the two, which is the emission of the recovery technology. The difference between the two is the emission reduction level of power battery in the recycling stage.

In the recycling process, because the current domestic power battery recycling industry is relatively incomplete, the recycling list used in this study is based on a large amount of literature research.

### Analysis of Recovery Method

LFP power batteries do not contain nickel, cobalt, manganese and other precious metals. The method of thermometallurgy is mainly to recover materials such as lithium, phosphorus and iron, and it has low added value of recycling [30]. The list used in this

study comes from the research of Wang Zhuopu at Tsinghua University [31], which includes traditional hydrometallurgy technology and full-component physical recycling technology.

For the NMC power battery, its active materials contain a lot of precious metals, especially cobalt material which greatly pollutes the soil, so it is necessary to recover NMC active materials. In this study, the recycling list of NMC power battery comes from the directional cycle process of waste power battery provided by Xie Yinghao et al. [32]. This method combines the advantages of traditional hydrometallurgy and thermometallurgy and improves their respective deficiencies. For example, the traditional hydrometallurgy cannot effectively recover aluminum and needs to consume more alkali.

As for the choice of recovery process, this research tends to choose the process of aluminum, copper and active materials. Electrolyte recovery has high technical requirements, and currently there are few companies that recover electrolytes in China. Diaphragm is a polymer material, it will be aging after a period of use, and the recycling value is not great. If the negative electrode is used for a long time, the structure will change, and it cannot be used directly after recycling. Moreover, the price of graphite is not high, and the economic value of recycling is not large [33].

## Results and Discussion

### Emissions and Contributions of the Recovery Process

Recycling and reproducing materials with high environmental load are crucial for the sustainable development of the electric vehicle power battery industry. The  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$ , and  $\text{NO}_x$  emissions during the recovery process of the LFP and NMC power batteries with 1 kg and 1 kWh functional units are shown in Fig. 1(a-d).

As shown in Fig. 1(a-d), when 1 kg is taken as the functional unit, compared with the LFP power battery, the emission changes of the NMC battery in  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$ , and  $\text{NO}_x$  are -2.41%, -6.26%, 54.57%, and 0.24%, respectively. That is, the emissions of  $\text{CO}_2$  and  $\text{PM}_{2.5}$  in the NMC power battery recovery process are lower than the emissions of LFP power battery, while the  $\text{SO}_2$  and  $\text{NO}_x$  emissions are higher than the emissions in LFP power battery recovery process.

When using 1 kWh as the functional unit, the emissions of  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  in the recovery process of NMC power batteries are lower than those during the recovery process of LFP power batteries. It is worth noting that the change in emissions gap is greater than that taking 1 kg functional unit. Compared

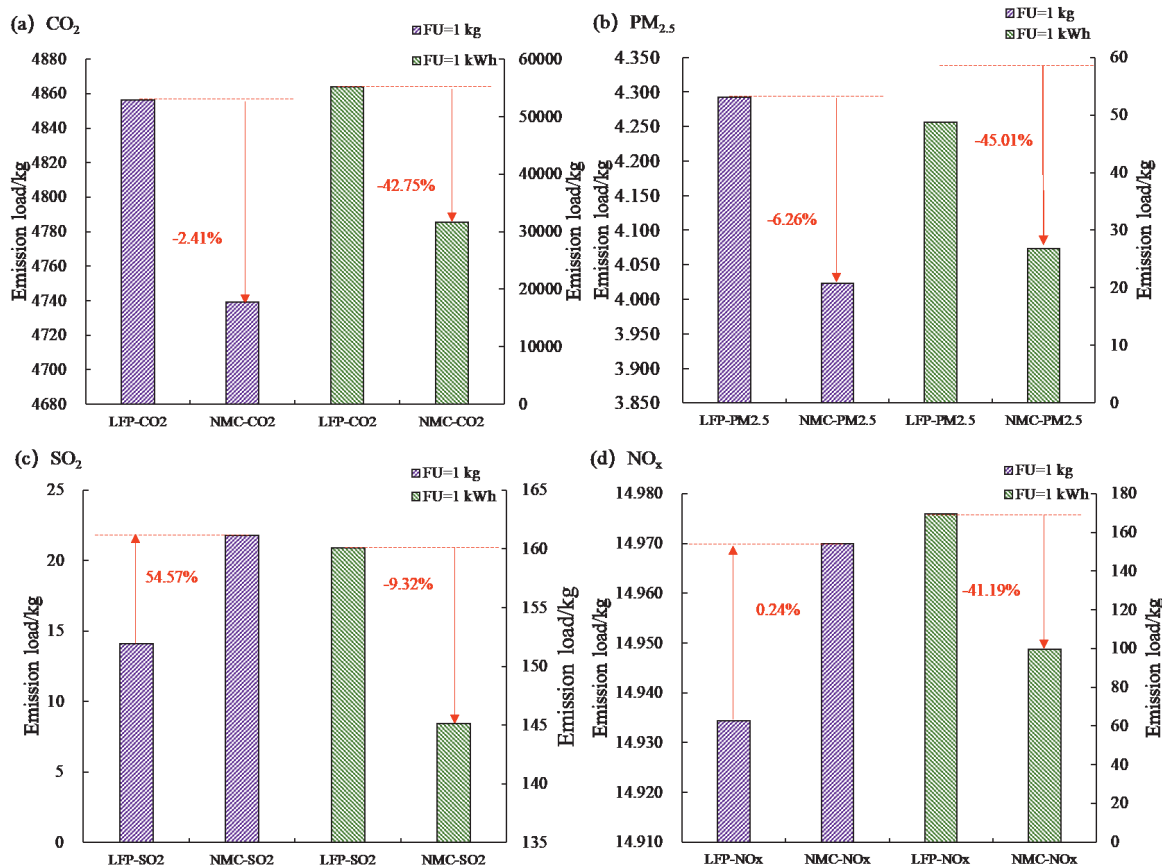


Fig. 1. (a)-(d) Emissions of two types of power batteries in recycling processes.

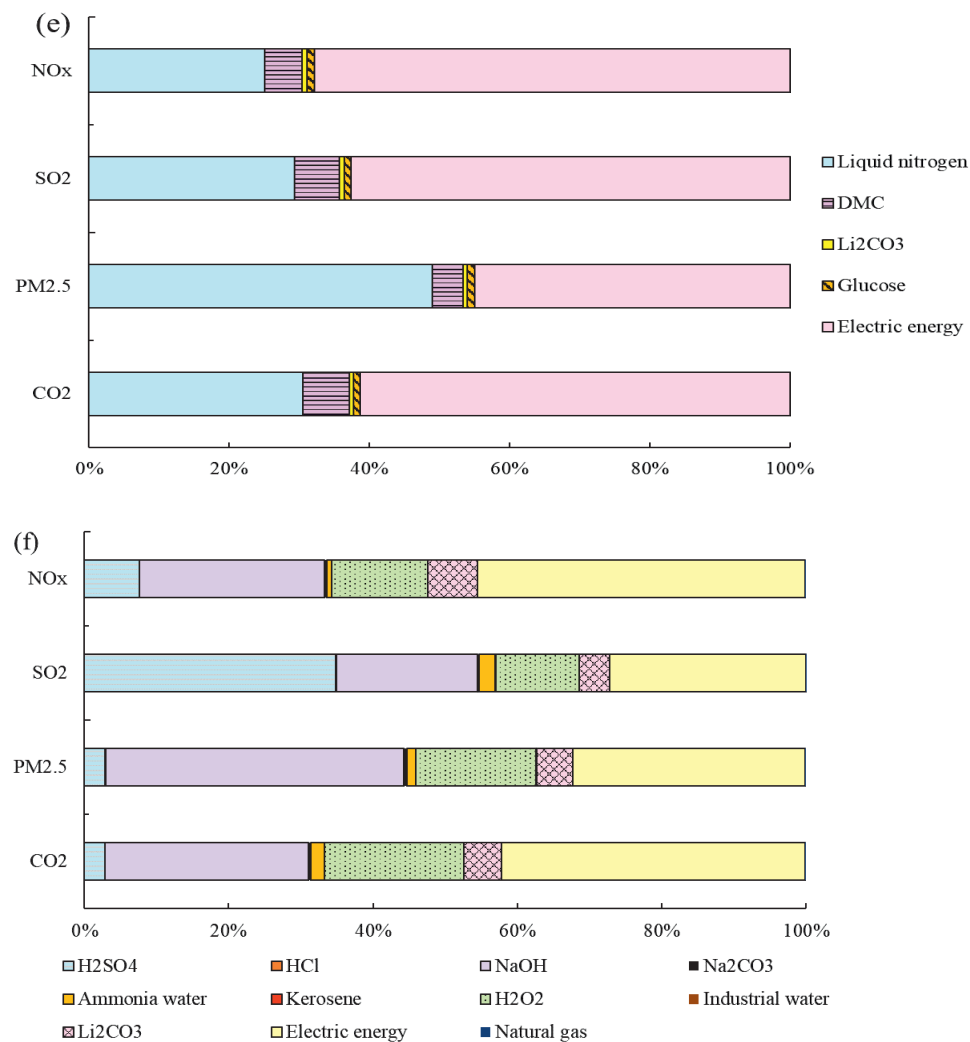


Fig. 1. (e) Emission contribution of each component in LFP recovery process; (f) Emission contribution of each component in NMC recovery process.

with the LFP power battery recycling process, the emission changes of NMC batteries in  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  are -42.75%, -45.01%, -9.32% and -41.19%, respectively. It shows that mass energy density can not only affect the environmental load caused by the consumption of raw materials per unit mass, but also affect the recycling stage. It is a very important parameter in the LCA evaluation of power batteries.

The corresponding environmental impacts for each material and energy input in the recovery process are shown in Fig. 1(e, f). Fig. 1(e) shows the emission ratio of each link in the recovery process of LFP power battery. It can be seen that among the four types of emissions, the input of electrical energy and the use of liquid nitrogen are the main contributing sources of  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emissions in the recovery process. The cleanliness of the power affects the pollutant emission caused by the input of electric energy in the power battery recovery process. In addition, improving the use efficiency of liquid nitrogen can effectively

reduce the  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$ , and  $\text{NO}_x$  emissions in the LFP power battery recovery process.

As shown in Fig. 1(f), in the NMC power battery recovery process, the use of electric energy, sodium hydroxide and hydrogen peroxide have a greater contribution to  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emissions. Consistent with the LFP power battery recycling process, the input of electricity is still the main source of  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emissions. For the use of sodium hydroxide and hydrogen peroxide, it should be used as efficiently as possible to avoid waste. This requires reasonable calculations in the specific operation process, linking the usage with the recovery efficiency, and pursuing a higher recovery rate with the least reagent consumption. Finally, it is worth noting that in  $\text{SO}_2$  emissions, the contribution of sulfuric acid has increased significantly, and it accounts for the highest proportion of all reagents and energy inputs, reaching 34.86%. However, in  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ , and  $\text{NO}_x$  emissions, the use of sulfuric acid is only 2.83%, 2.84% and 7.60%. This is most likely to be related to the sulfuric acid

production process. A cleaner sulfuric acid production process will directly reduce the  $\text{SO}_2$  emissions in the NMC recovery process, such as increasing the yield of industrially prepared sulfuric acid and equipping with high-efficiency sulfur absorption devices.

### Emission Reduction of Recycled Substances

The  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emissions by producing aluminum sheet, copper sheet, LFP active materials and NMC active materials at a time are too high, so it is necessary to recycle them effectively. As shown in Fig. 2, the emissions generated by the battery process are inconsistent with the emissions reduced by adding recycled materials to secondary production. For  $\text{CO}_2$ , the emission of the recycling process itself is greater than the emissions reduced by using recycled materials. But for  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$ , the emissions of the recycling process itself are lower than the emission reduction of recycled materials, and its value is more obvious. For example, in the LFP power battery recycling process, the  $\text{SO}_2$  produced by the process itself is 14 g, while the recovered copper sheets, aluminum sheets, and LFP active materials can reduce the emissions from secondary production by 44 g, which is a three-fold gap.

Therefore, the environmental advantages of effective recovery of power batteries are mainly reflected in the emissions of  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$ . To achieve carbon neutrality, current recycling processes may not be able to support it. It needs to be done at the source, that is, improve the extraction technology of raw materials and the manufacturing technology of battery parts; In addition, the recycling technology should be

optimized. It is necessary to start with two aspects: effective use of reagents and improvement of power cleanliness, and improvements in these two aspects will continue to increase the efficiency of  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emission reduction.

### Contributions of Recycled Materials on Reducing Emissions

The  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emissions of LFP power battery after the recycling of copper, aluminum and LFP active materials are shown in Fig. 3. As shown in Fig. 3(a-d), for different emissions, the recovery importance of copper, aluminum and LFP active material is not in the same order. Among them, recycled aluminum has excellent performance in reducing emissions of  $\text{CO}_2$ ,  $\text{PM}_{2.5}$  and  $\text{NO}_x$ . It shows that in the primary production process of LFP power batteries, the aluminum foil used for the current collector and the production of all-aluminum battery shells have a large burden of  $\text{CO}_2$ ,  $\text{PM}_{2.5}$  and  $\text{NO}_x$  emissions, which can be reduced by recycling aluminum.

The second is the recycling of copper, which accounts for a significant reduction in  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emissions. Especially in terms of  $\text{SO}_2$  emissions, copper recycling accounts for 64.91%, and the emission reduction value reaches 0.029 kg, which far exceeds the 26.24% of aluminum foil recycling. The copper sheet used as the negative current collector has obvious  $\text{SO}_2$  emission preference in the primary production process, which is largely related to the smelting of sulfide ore. So, reducing the upstream emissions of copper production or increasing the recovery rate are both conducive to reducing the  $\text{SO}_2$  emissions of the whole life cycle of the LFP power battery.

It is worth mentioning that, for LFP power batteries, the emission reduction value of recycling active materials is not as good as that of aluminum and copper. This is mainly because there are no precious metal elements like NMC active materials in the elements that make up LFP active materials. Another possible reason is that LFP power batteries have excessive demand for aluminum and copper resources, such as copper resources in the battery casing and circuit board, resulting in an insignificant emission reduction ratio of LFP active material recycling.

As shown in Fig. 3(e-h), the importance of copper, aluminum and NMC active substance recycling and emission reduction is inconsistent with that of LFP power battery. The recycled NMC active materials have excellent performance in  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and  $\text{NO}_x$  emission reductions. It is not only much higher than the proportion of LFP active materials in power battery recycling and emission reduction, but also the environmental benefit of NMC recycling is significantly higher than that of LFP active materials in specific quantities. This is because NMC active materials contain nickel, cobalt, manganese, and lithium materials, all of which have a high environmental load. In addition,

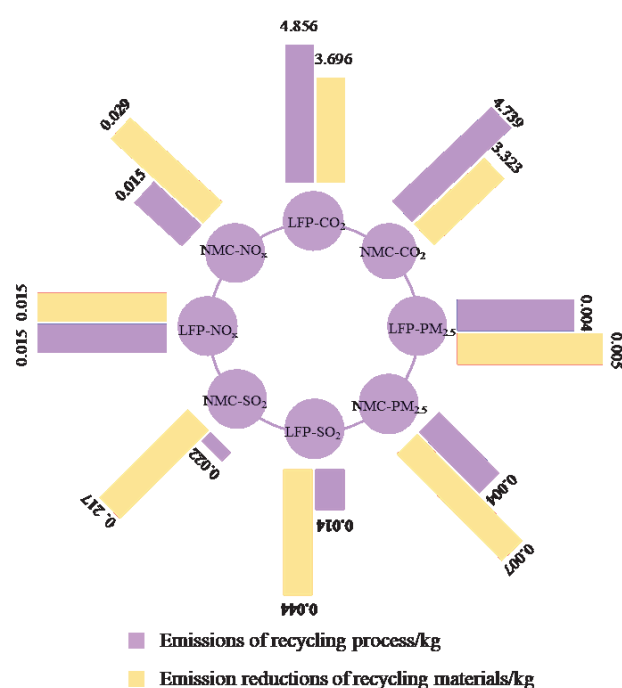


Fig. 2. The emission reduction of recycled substances.



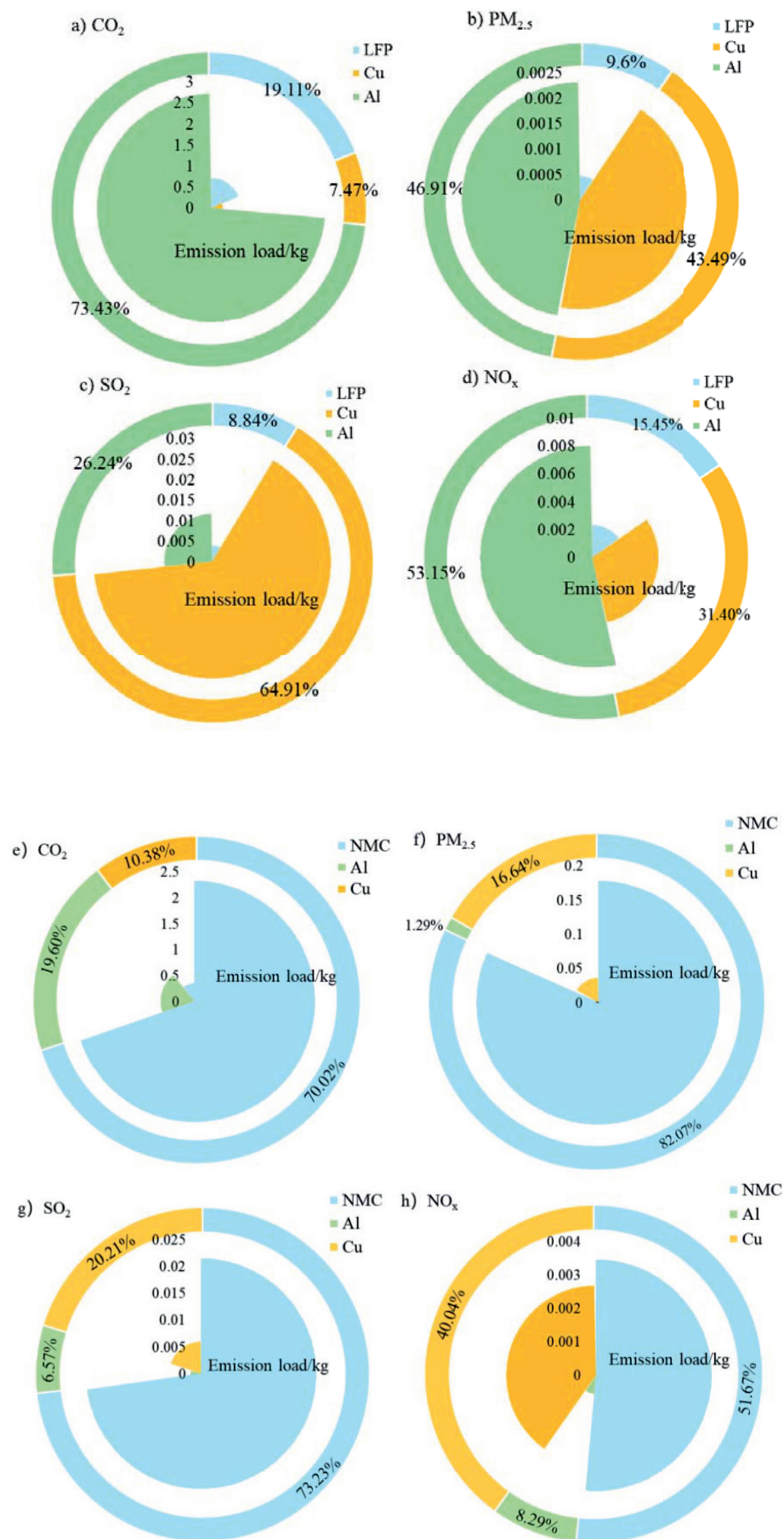


Fig. 3. The proportion of LFP and NMC active materials, aluminum and copper emission reduction in recycling process.

the preparation process of NMC precursor requires high energy and resource consumption. The effective recycling of NMC active materials after the battery is scrapped can not only prevent the cobalt element from entering the land and rivers and polluting the environment when it is directly landfilled. At the same time, it can also significantly reduce the input of NMC active materials in the secondary production process of power batteries, and avoid excessive CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>x</sub> emissions caused by the consumption of raw materials.

## Conclusions

Power batteries have different mass and energy densities due to their different types, which in turn will affect the material input in the recycling process. That is, the higher the mass energy density, the less the material and energy input per kWh. When taking 1 kg as the functional unit, the CO<sub>2</sub> and PM<sub>2.5</sub> emissions during the recovery process of LFP power batteries are higher than those of the NMC power battery recovery process, while the emissions of SO<sub>2</sub> and NO<sub>x</sub> are contrary. When taking 1 kWh as the functional unit, the CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub> emissions of NMC power battery recovery process are lower than those of LFP power battery recovery process.

The main sources of CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>x</sub> emissions in the the two types of power batteries recycling process come from the input of electric energy. In the recovery process of LFP power battery, the use of liquid nitrogen contributes significantly to the emission of CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub>. In the recycling process of NMC power battery, the use of sodium hydroxide and hydrogen peroxide contribute significantly to the discharge of four pollutants. In addition, the use of sulfuric acid will have the greatest contribution to SO<sub>2</sub> emissions in the NMC power battery recovery process. In the recovery process, the reagents with high emission load should be efficiently utilized and recovered.

Recycled materials for reproduction can reduce the input of raw materials in the battery production process, so that resources can be fully and effectively utilized, reducing waste. But it is worth noting, for CO<sub>2</sub>, recycling does not bring better effect on emission reduction. If we want to achieve carbon neutrality for EVs, on the one hand, we need to reduce emissions from the source, that is, optimize the process from cradle to gate; on the other hand, the recycling technology needs to be innovated, such as improving the efficiency of chemical reagents and the cleanliness of electricity in recycling processes to reduce the carbon emissions. However, for PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>x</sub>, recycling can in turn help reduce emissions in the production process, and the value of reducing emissions is more obvious.

For different emissions, the importance of the recovery of copper, aluminum and LFP active material is not consistent. Among them, recycled aluminum

performs well of CO<sub>2</sub>, PM<sub>2.5</sub>, and NO<sub>x</sub> emission reductions in LFP primary production. The recycling of copper greatly reduces the emission of PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub>, especially in SO<sub>2</sub>. Moreover, the emissions reduction value of recycling LFP active materials is not as good as that of aluminum and copper. The recycled NMC active materials performed well in the emission reduction of CO<sub>2</sub>, PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>x</sub>. Not only is it much higher than the ratio of LFP active materials recycling and emission reduction, in terms of specific magnitude, the environmental benefits of NMC recycling are also significantly higher than LFP.

From the perspectives of clean production and circular economy, it is extremely important for the effective recycling of LFP and NMC power batteries after they are scrapped, and it will also benefit the sustainable development of electric vehicles.

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## Conflict of Interest

The authors declare no conflict of interest.

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