Preliminary Exploration on the Calculation of Carbon Footprint for Automotive Power Batteries

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Abstract. In recent years, global warming has intensified, prompting countries worldwide to promote electric vehicles (EVs) as a sustainable alternative to traditional fuel-powered cars. This shift aims to accelerate transportation electrification, reduce greenhouse gas emissions, and achieve carbon neutrality goals. However, while the adoption of new energy vehicles is crucial for environmental protection, accurately assessing the carbon emissions generated throughout the entire lifecycle of automotive batteries remains a significant challenge. This paper explores the carbon footprint calculation of EV power batteries, analyzing current evaluation methodologies, key influencing factors, and potential improvements. Existing research highlights discrepancies in emissions measurement due to variations in battery production, usage, and recycling processes. Factors such as raw material extraction, manufacturing energy sources, and end-of-life disposal significantly impact overall emissions. Additionally, this study discusses future development directions, including advancements in battery technology, standardization of carbon accounting frameworks, and policy recommendations to enhance sustainability. By addressing these challenges, the transition to electric mobility can achieve its full environmental potential.

Keywords: Carbon Footprint; Automotive Power Batteries; Life Cycle Assessment (LCA); Circular Footprint Formula (CFF); Cut-off Method (CUT-OFF).

1. Introduction

1.1. Research Background and Significance

The challenge posed by global warming to human societal development has significantly promoted political consensus and major actions globally in response to climate change. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) stated that to achieve net-zero greenhouse gas (GHG) emissions by mid-century, global warming must be limited to within 1.5 degrees Celsius. Consequently, countries have accelerated their carbon reduction efforts. As shown in Fig.1, on September 22, 2020, President announced China's goal of peaking carbon emissions by 2030 and achieving carbon neutrality before 2060 at the United Nations General Assembly; the U.S. introduced the Green New Deal, aiming for net-zero carbon emissions by 2050; the European Union declared a reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990 levels, with a target of net-zero emissions by 2050. By the end of 2020, nearly 10 million EVs had been launched into the global market. Under these circumstances, it is crucial to study, define, calculate, and control the carbon emissions of automotive power batteries throughout their lifecycle.

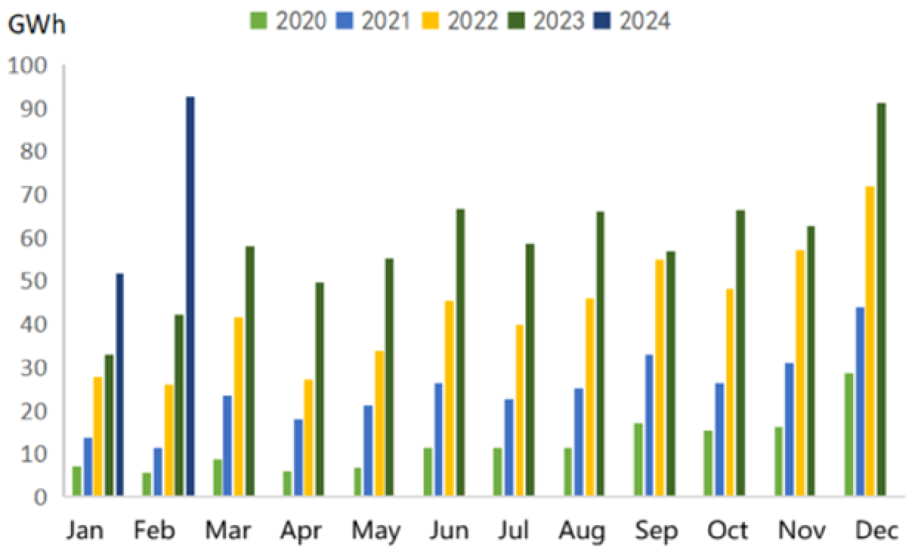

Fig 1. Global Power Battery industry installed capacity.

1.2. Current Research and Related Strategy Development

In many countries and regions, manufacturers and sellers must comply with relevant laws and regulations to disclose the carbon footprint information of their products. For instance, the EU mandates displaying carbon emissions on product labels, Japan has implemented a carbon footprint certification system, and China has established a carbon emission reporting system. On February 2, 2024, the National Development and Reform Commission, National Bureau of Statistics, and National Energy Administration of China jointly issued a notice titled 'On Strengthening the Synergy between Green Power Certificates and Energy Saving and Carbon Reduction Policies to Vigorously Promote Non-Fossil Energy Consumption,' which proposes studying and calculating the adjusted grid emission factors after deducting green certificates for different application scenarios. This proposal sends a positive policy signal for future international recognition of green certificates and their inclusion in battery carbon footprint calculations. The document also emphasizes promoting international recognition of green certificates and aligning carbon emission calculation methods of large international institutions with green certificates. However, there is still no sufficiently clear, unified, and simplified regulatory framework for carbon footprint measurement internationally. For example, according to the latest draft industry standard 'Carbon Footprint of Road Vehicle Products - Product Category Rules - Traction Batteries' of the People's Republic of China, the basic principles for calculating the carbon footprint of vehicle products should in accordance with ISO 14067 and GB/T 'Requirements and Guidelines for Quantifying the Carbon Footprint of Products' to include a lifecycle perspective, relative methods and functional units or declaration units, repetitive methods, the priority of scientific methods, relevance, completeness, consistency, accuracy, transparency, and avoidance of redundant calculations.

1.3. Method for assessing the carbon footprint of automotive power batteries

Lifecycle assessment of automotive power batteries: Life Cycle Assessment (LCA) is a method used to evaluate the environmental impact of products, processes, or activities throughout their entire life cycle. The LCA of automotive battery packs refers to the calculation method of the entire (or partial) "cradle-to-grave" process of automotive battery pack products, from acquiring raw materials through production, usage, until disposal (or recycling). Cradle-to-gate refers to calculating the carbon footprint of a product up to the point it leaves the factory. Cradle-to-grave involves calculating the carbon footprint of a product from its creation until it reaches the consumer, is eventually discarded, and recycled. When calculating the carbon footprint of a product, one can choose various system boundaries for quantification, such as cradle-to-gate, cradle-to-grave, gate-to-grave, or even grave-to-grave (Fig. 2). Currently, numerous studies employ this method to assess environmental pollution and greenhouse gas emissions associated with various battery technologies, focusing primarily on the following areas:

(1) Comparison of carbon emissions and environmental indicators between lithium-ion batteries and other types of batteries;

(2) Comparison of carbon emissions and environmental indicators among different material systems of lithium-ion batteries;

(3) Analysis of carbon emissions and environmental impacts at different stages of lithium-ion batteries.

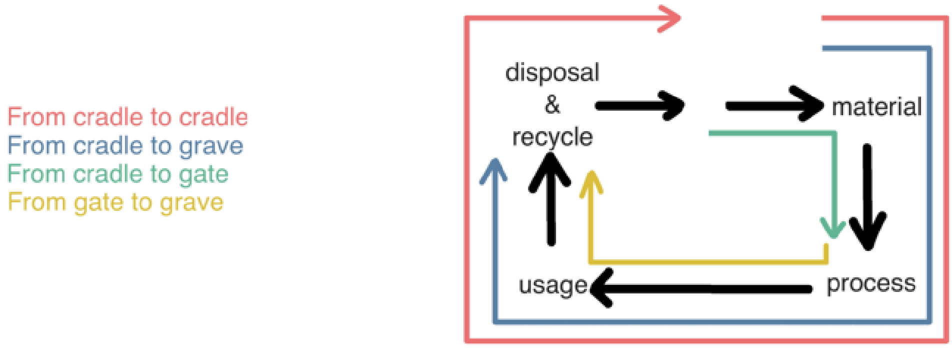

Fig 2. System boundaries and life cycle phases.

1.4. Calculation of the carbon footprint of automotive power batteries

Calculation boundaries

The selection of the accounting boundary for power battery should align with the objectives of the carbon footprint study and clearly explain the criteria used to establish the accounting boundary, such as selection criteria.

(1) When the objective of the power battery carbon footprint study is to communicate carbon footprint information among individual products of the same technological route, the cutoff method (CUT-OFF) should be used. For the disposal and recycling processes generated during all lifecycle stages of power batteries, the CUT-OFF method should be used for modeling. During the stage of factory sales of power battery products, if it is necessary to communicate carbon footprint information among individual batteries produced by different organizations with the same material system and technological route, and future usage and disposal/recycling emissions have not yet occurred and primary data cannot be provided, the CUT-OFF method can be used to calculate only the carbon emissions that have already occurred from cradle to gate. Additionally, based on factors such as the rated energy, cycle life, energy efficiency, and weight ratio of the battery in the vehicle, potential self-energy loss and energy loss allocated to the battery during future usage can be calculated. The results can be used by organizations to improve supply chain carbon footprint performance or by consumers to choose more low-carbon power battery products based on carbon footprint information. The results based on the CUT-OFF method for individual power batteries of different technological routes cannot be compared.

(2) When the objective of the power battery carbon footprint study is to compare the lifecycle carbon footprint performance of power batteries with different technological routes or to investigate whether the carbon footprint shifts across different lifecycle stages of power battery products, the cyclic footprint formula (CFF) should be used. For the disposal and recycling processes generated during all lifecycle stages of power batteries, the CFF should be used for modeling. Power batteries include various material systems and technological routes such as lithium iron phosphate batteries, nickel cobalt manganese oxide batteries, lithium titanate batteries, sodium-ion batteries, and nickel-metal hydride batteries. Products with different material systems and technological routes have different total and proportional carbon footprints at each lifecycle stage. If it is necessary to compare the carbon footprint differences between technological routes, a full lifecycle approach should be adopted, systematically considering the carbon emissions of all lifecycle stages for each technological

route, especially taking into account whether recycled materials can be used, disposal methods, recyclability, and recycling efficiency, which affect carbon emission allocation. This research method can be used by relevant decision-makers to select lower-carbon product technological routes but is not suitable for communicating carbon footprint information among individual power battery products.

Different research objectives correspond to different accounting boundaries, and the application scenarios of the research results also vary, as illustrated in Fig. 3.

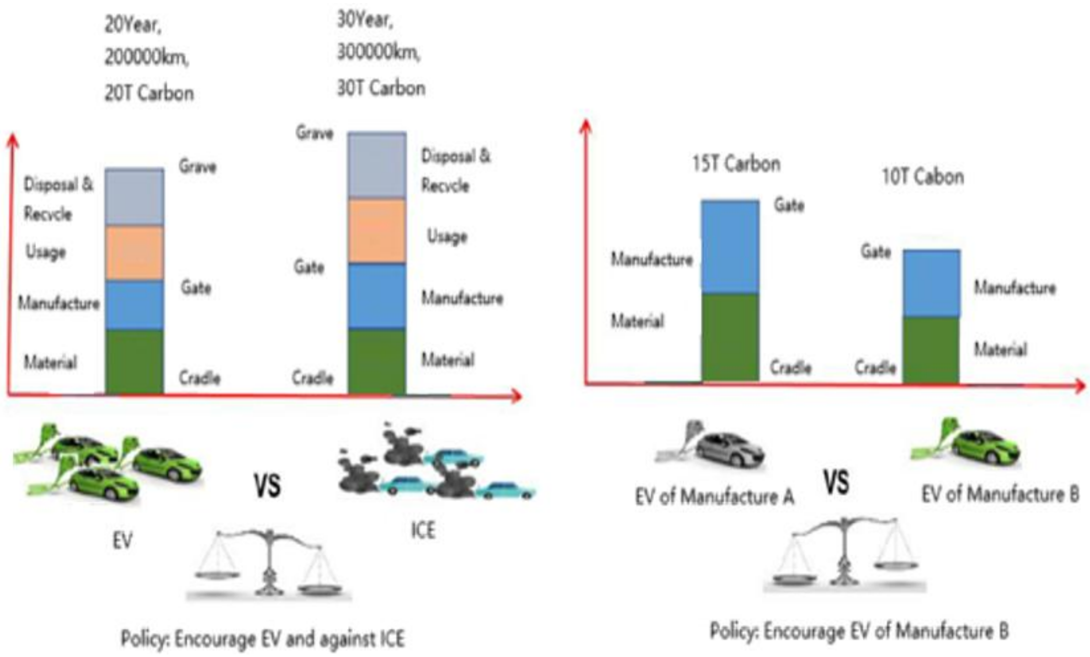

Fig 3. Different accounting boundaries and their corresponding application scenarios.

The research objective of the power battery carbon footprint is to use truncation method when communicating carbon footprint information between individual products of power batteries with the same technological route. The truncation method should be used for modeling the disposal and recycling processes that occur during all life cycle stages of the power battery.

The life cycle stages of the power battery product and the activities and processes involved are shown in Table 1[1,2].

Table 1. Life cycle stages of traction battery products, and activities and processes involved.

Life cycle stages		Brief description of the processes included	CUT-OFF	CFF
Material acquisition stage	Mining and refining of raw materials	The process ranging from raw material mining of positive and negative electrodes of traction batteries, electrolyte, diaphragm, shell, metal monomer and plastic particle, and to preparing metal salts into active materials	Required	Required
	Production of recycled materials	Production of recycled materials for traction batteries (including but not limited to recycled nickel, cobalt,lithium, aluminum, plastics, electrolytes.etc)	Required	Required
	Manufacturing of battery parts & components	Manufacturing of other chemicals (e.g. conductive agents, adhesives, electrolytes); assembly of current collectors, isolators, mechanical parts, housings and complex components such as electrical/electronic assemblies and BTMS components	(optional)	Required
	Packaging	Production of packaging materials at each stage in the acquisition of virgin materials and recycled materials for batteries	(optional)	Required

Battery production stage	Transportation	Transportation of various battery virgin materials and recycled materials from suppliers to customers	(optional)	Required
	Disposal and recycling	Material disposal and recycling process of each organization in the production process at material acquisition stage	Excluded	Required
	Cell/module manufacturing	Manufacturing of electrodes, assembly of battery cells and modules	Required	Required
	Battery system assembly	Assembling battery cells or modules into more integrated mechanical structures until a battery system is formed	Required	Required
	Packaging	Manufacturing of various packaging materials for parts & components finished products of batteries	(optional)	Required
	Transportation	Transportation process of various battery parts & components between suppliers and customers	(optional)	Required
	Disposal and recycling	Parts & components disposal and recycling process of various organizations in the production process at battery production stage	Excluded	Required
	Distribution	Process of transportation finished traction batteries to Original Equipment Manufacture (OEM) or battery swap stations or individual customers	(optional)	Required
	Installing the battery on the vehicle	OEMS install finished batteries in electric vehicles	(optional)	Required
	Battery's own energy loss	When the battery system operates within a specified cycle or load curve, it includes the electrical energy consumption caused by the energy loss caused by the battery itself such as its own internal resistance and BMS	Required	Required
Battery use stage	Vehicle energy consumption due to battery	Vehicle operation needs to overcome various resistances caused by the weight of the vehicle. The heavier the traction battery, the higher the proportion of energy consumption allocated to the battery	Required	Required
End-of-life stage	Repair/Replacement	Carbon emissions generated due to the maintenance and parts replacement processes if there are processes such as maintenance and parts replacement during the use of battery	(optional)	Required
	Transportation	Energy consumption of transportation tools caused by the transshipment of the battery due to maintenance and battery swap during the use of the battery	(optional)	Required
	Disposal and recycling	Parts & components disposal and recycling process during battery maintenance	Excluded	Required
	Scrapping and dismantling	Disassembling, collection, dismantling, residual energy detection, classification, crushing, land-filling, and organic matter incineration of batteries	Excluded	Required
	Packaging	Production of packaging materials for processes such as the transfer of retired batteries; reusable metal packaging materials (such as safety boxes) are excluded in the accounting	Excluded	Required
	Transportation	Energy consumption of vehicles and energy consumption of storage sites generated during the transportation and storage of decommissioned batteries	Excluded	Required
	Recycling	Reuse, re-manufacturing, cascade utilization, material recycling, and energy recovery of decommissioned traction batteries	Excluded	Required

1.5. The following provides a detailed introduction and discussion of these two calculation methods

Circular Footprint Formula (CFF): The Circular Footprint Formula is an indicator used to measure the environmental impact of individuals or organizations in their daily lives or business operations. It quantifies the size of the circular footprint formed by resource consumption and waste emissions in the environment. Its calculation method can be referenced by the following formula:

$$CE = (CE_{part} + CE_{production} + CE_{use} + CE_{Transport} + CM)/c \quad (1)$$

In the formula, CE-the carbon footprint of the power battery, measured in kilograms of carbon dioxide equivalent per kilowatt-hour ($kgCO_2e/kWh$); CE_{Part}-the carbon emissions from the manufacturing process of components, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$);

$CE_{production}$ - Carbon emissions during the battery production phase, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$); CE_{use} - Carbon emissions during the usage phase, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$); $CE_{Transport}$ - Carbon emissions during the transportation phase, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$); CM - Carbon emissions related to material production and end-of-life in the Circular Footprint Formula (CFF), measured in kilograms of carbon dioxide equivalent ($kgCO_2e$);c - Total energy provided by the power battery to the vehicle, measured in kilowatt-hours (kWh).

The specific calculation method of the circular footprint formula varies depending on the availability of data and the environmental aspects of concern. However, generally speaking, the circular footprint formula takes into account the following aspects:

1. Resource consumption: Circular footprint calculations typically cover the consumption of resources such as energy, water, soil, and minerals. This includes the processes of resource extraction, production, and use over a year or a specific period.

2. Waste emissions: The circular footprint formula also considers the generation and emission of waste, such as solid waste, wastewater, and exhaust gases. These wastes are generally considered to have adverse effects on the environment.

3. Environmental impact: The circular footprint formula also comprehensively considers the impact of the resource life cycle and waste treatment methods on ecosystems. For example, impacts on biodiversity, land use, and water resources.

By considering factors such as resource consumption and waste emissions, the circular footprint formula can provide individuals or organizations with an indicator to assess the degree of their negative impact on the environment. This helps to promote sustainable development and resource conservation practices, fostering environmental protection and reducing the ecological footprint.

It is important to note that the specific formulas and methods for calculating the circular footprint vary due to differences in research and practice. Therefore, when applying the circular footprint formula, adjustments and applications should be made according to specific situations and research purposes.

Cut-off method (CUT-OFF): The cut-off method (CUT-OFF) refers to the approach in life cycle assessment of products where only the environmental impacts and benefits of using recycled materials in new products are considered, without considering the environmental impacts and benefits of the disposal and recycling processes at different life cycle stages. The calculation method can be referenced by the following formula:

$$CE = (CE_{Materials} + CE_{part} + CE_{production} + CE_{use} + CE_{Transport})/c \quad (2)$$

In the formula, CE - Carbon footprint of the power battery, measured in kilograms of carbon dioxide equivalent per kilowatt-hour ($kgCO_2e/kWh$); $CE_{Materials}$ - Carbon emissions during the material production phase, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$); CE_{part} - Carbon emissions during the part processing process, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$); $CE_{production}$ - Carbon emissions during the battery production phase, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$); CEuse - Carbon emissions during the usage phase, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$);CETransport - Carbon emissions during the transportation phase, measured in kilograms of carbon dioxide equivalent ($kgCO_2e$); c - Rated energy provided by the power battery, measured in kilowatt-hours (kWh).

Below, a simulation calculation of a lithium iron phosphate automotive power battery is used as an example to illustrate the calculation results using the partial truncation method. It is noted that due to the unknown stage parameters, the definition of the main boundary is set as the point of sale upon factory release. [3]

Objective Evaluation

The objective of this study is to determine the 'cradle-to-sale' carbon footprint of a lithium iron phosphate (LFP) battery pack with a total weight of 113 kg, an energy density of 85 Wh/kg, a power density of 800 W/kg, an expected cycle life of 6,000 cycles, and a maximum depth of discharge (DoD) of 80%.

The potential audience for communicating these results includes two groups: internal management and other relevant personnel within the company, and external stakeholders such as downstream purchasers, local governments, and environmental non-governmental organizations.

2. System Boundaries

Functional Unit: One kilowatt-hour (kWh) of total energy provided by the battery over its lifetime, collected for data collection and statistical purposes in mass units. The system boundary for the LFP battery pack is illustrated in Fig. 4.

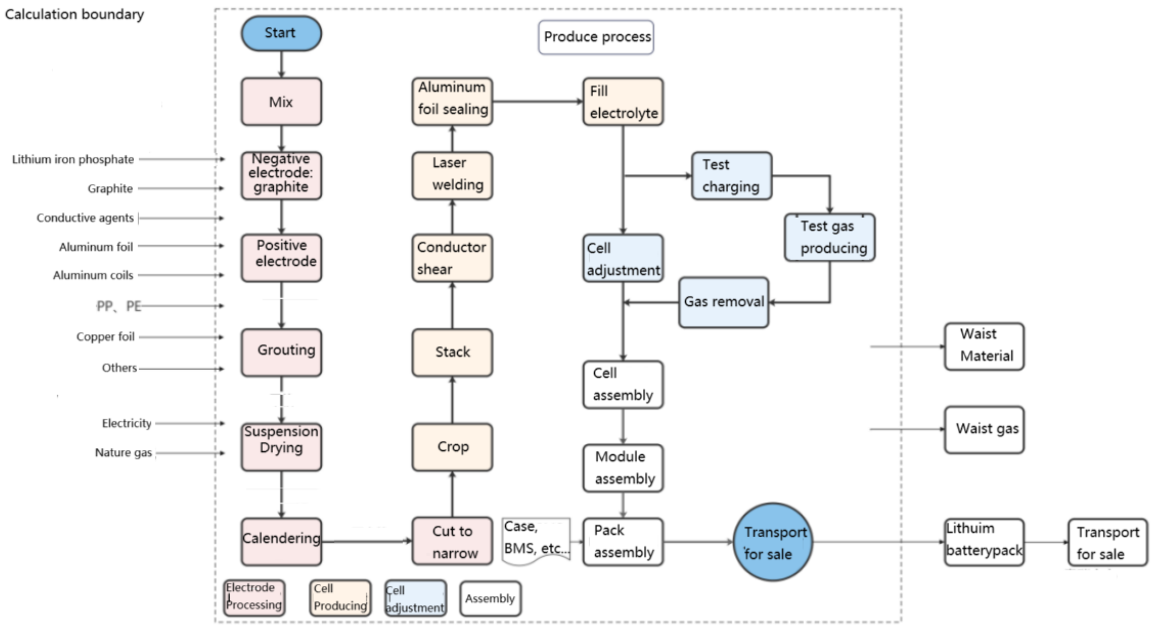

Fig 4. System boundary for the LFP battery pack.

3. Data requirements

Within system boundaries, guidelines for allocating proportions of material, resources, and energy consumption data that cannot be measured individually for multiple products, data selection rules and fundamental principles for data accuracy, representativeness, and consistency.

3.1. Life Cycle Inventory Analysis (LCI)

Life Cycle Inventory Analysis (LCI) involves studying the input and output processes of materials and energy within the scope of the research object system, and collecting corresponding data to quantify it. For example: How much of each material such as positive electrode, negative electrode, separator, electrolyte, casing, fasteners, etc., is required to produce 1 kg of LFP battery pack? How much electricity, natural gas, and other energy sources are consumed?

Based on the research objectives, this study focuses solely on the impact type of climate change, specifically converting greenhouse gas emissions throughout the product lifecycle into carbon dioxide equivalents (CO_2e) using the Global Warming Potential (GWP). The GWP is an environmental impact metric used to quantify the carbon footprint of products. Within the lifecycle boundary of LFP battery packs from 'cradle to sales,' the carbon footprint amounts to 72.40 $kgCO_2e/kWh$. An analysis of the contributions to the carbon footprint from the production and transportation of LFP battery raw materials, the energy consumption during product manufacturing, and the transportation during product sales is provided, as illustrated in Fig. 5.

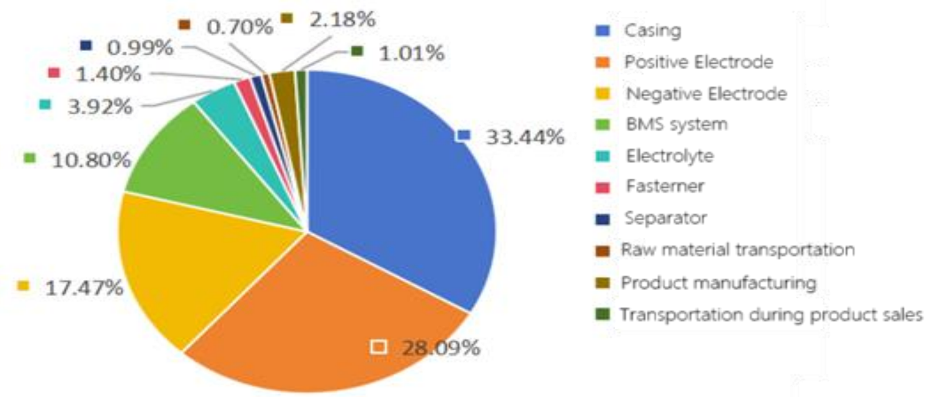

Fig 5. Contributions to the carbon footprint of LFP battery raw materials.

The study results indicate that the carbon emissions of LFP battery packs amount to 72.40 $kgCO_2e/kWh$. Among these, the highest carbon emissions occur during the production of the casing, followed by the production of the cathode, anode, and other stages. For lithium iron phosphate batteries, the carbon emissions from the casing, cathode, anode, and BMS system account for 33.44%, 28.09%, 17.47%, and 10.80% of the total emissions from 'cradle to sales,' respectively.

It is evident that clearly defining the purpose and application intentions of the research, determining the boundaries of the products and systems under study, and elaborating on the functional units, data requirements, and assumptions of the evaluation system are the first and most critical steps in implementing a product life cycle assessment.

Analysis of Factors Influencing the Carbon Footprint of Automotive Power Batteries:

To ensure the accuracy of the carbon footprint accounting for automotive power batteries and minimize errors, relevant factors affecting the carbon footprint of batteries should also be considered. Next, the potential impact of specific factors on accounting for the carbon footprint of automotive power batteries will be discussed from the differences in battery type and technology roadmap, as well as battery recycling and utilization.

3.2. Battery Type and Technology Roadmap

The impact of battery type on the carbon footprint calculation of automotive power batteries is mainly reflected in the following aspects.

The production of the positive electrode is the main source of carbon emissions during the battery manufacturing stage, accounting for a significant proportion of the total emissions in lithium-ion battery production. Different battery types, such as ternary lithium and lithium iron phosphate, have a significant impact on the carbon footprint. For the dominating impact of material sourcing over production location, with nickel and lithium identified as major contributors to the carbon footprint and its variance. [4] Ternary lithium batteries require metals such as cobalt and nickel, resulting in higher carbon emissions from mining, refining, and processing; lithium iron phosphate batteries have a lower upstream carbon footprint due to more accessible materials and relatively simplified processes.

The battery type determines the complexity of the production process. For example, ternary lithium batteries with high energy density may require more complex electrode coating and packaging technologies, leading to higher energy consumption and carbon emissions; new technologies such as solid-state batteries may also increase the carbon footprint during the manufacturing stage if they require high-temperature and high-pressure processes.

Power consumption is a key link in the production stage, and different processes have different sensitivities to the carbon emission factor of the power grid. When high-energy batteries are produced in areas dependent on high-carbon electricity, the carbon footprint will significantly increase.

Recycling methods vary depending on the battery type. Lithium iron phosphate batteries are chemically stable and more suitable for low-emission recycling technologies such as hydrometallurgy; ternary batteries contain precious metals and may require high-energy processes such as pyrometallurgy, increasing carbon emissions during the recycling stage.

According to the new regulations of the European Union, the declaration of the full life cycle carbon footprint of batteries, the differences in the recycling process directly affect the overall carbon footprint rating of different types of batteries. [5]

4. Conclusion

In summary, although formulas for accounting for the carbon footprint of automotive power batteries have been issued internationally, their use still has significant limitations. At the same time, multi-dimensional factors such as the selection of battery cathode materials, process energy consumption, and recycling technologies will affect the carbon footprint calculation. In the accounting process, a dynamic optimization should be carried out in conjunction with the full life cycle assessment method.

The People's Republic of China has approved the initiation of the national standard for "Greenhouse Gases-Quantification methods and requirements for carbon footprint of products — Traction batteries used in electric vehicles" as of December 31, 2024. Currently, it is open for public consultation, with an expected official implementation within 2026. Looking to the future, we hope to introduce a unified international carbon emission label, promote the improvement of the carbon footprint labeling system for road vehicles, and thus facilitate the development of accounting standards for automotive power batteries and the achievement of carbon neutrality and carbon peak goals.

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