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Integrated carbon responsibility allocation in the electric vehicle battery supply chain: a comprehensive approach to emission reduction

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Abstract

This study investigates the allocation of carbon responsibility within the entire supply chain, utilizing a comprehensive traceability framework. Using the electric vehicle battery industry as a case study, it examines the transfer and allocation of carbon responsibilities across upstream raw material production, the power battery industry, downstream industries, and end-users, resulting in a more equitable distribution of carbon responsibility. The electric vehicle battery industry bears only 6.6%-18.9% of its original carbon responsibility, with the remainder shared among related industries and consumers. Industries such as the computer, communication, and other electronic equipment manufacturing industry, the electrical machinery and equipment manufacturing industry (except the electric vehicle battery industry), the automobile product manufacturing industry, and the transport and storage industry bear a heavy carbon responsibility. Notably, the carbon responsibility of end-use categories such as exports and urban consumption is significantly higher, highlighting the substantial role of final consumers. The analysis demonstrates that a collaborative allocation strategy, integrating market-driven mechanisms, technological innovation, and policy support, can effectively drive emission reductions across the entire supply chain. This approach promotes equitable carbon reduction targets and fosters global cooperation for sustainable



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development.

Keywords: Carbon responsibility, electric vehicle battery industry, supply chain, emission reduction

INTRODUCTION

Global climate change is one of the most serious environmental problems today, and the intensification of climate change has promoted the international community to form a consensus on emission reduction. All governments and international organizations are committed to reducing greenhouse gas emissions, and the trend of global low-carbon transition is unstoppable^[1]. Assigning responsibility for carbon emissions is the basis and imperative for achieving national emission reduction targets. Through the allocation of carbon responsibility, it can clarify the obligations of the main body and encourage multi-party collaboration, which will play a leading role in the global low-carbon transition and promote the sustainable development of the systemic and whole industrial chain. Currently, responsibility is mainly focused on energy-intensive industries with high emissions. The production side (industry/companies) bears most of it, which emphasizes that high emitters bear more responsibility, while attention to the consumption side is relatively insufficient^[2].

Addressing climate change has become a global imperative, necessitating the promotion of green and low-carbon energy transitions. Driven by social needs and policies, industries such as electric vehicles, power batteries, and photovoltaics are becoming pivotal in low-carbon transitions. These technologies offer strategies for decarbonization and green development. Developed countries have reinforced carbon reduction responsibilities at the production end of the supply chain through green barriers and carbon tariff policies, such as the EU Carbon Border Adjustment Mechanism, the New Battery Act, and regulatory policies from the United States, South Korea, Germany, and Japan. If we only consider the production side, emerging low-carbon transition industries would bear all the carbon responsibility. However, these industries, while producing carbon emissions during production, significantly aid in reducing carbon emissions during the usage stage by providing low-carbon products. For example, electric vehicles offer substantial emission reduction benefits compared to fuel vehicles, and photovoltaic systems supply clean energy to many industries.

Production activities are driven by market demand, and as long as there is demand for commodities, carbon emissions will be generated. It is unreasonable to allocate carbon responsibility solely to the traditional production end. Instead, carbon responsibility should be allocated among stakeholders, including producers, consumers, and policymakers, to promote sustainable development.

Currently, traditional energy-intensive industries bear the primary carbon responsibility, guided by the producer principle. However, many studies indicate that carbon emissions responsibility should extend beyond producers to include all stakeholders, such as consumers, governments, and upstream and downstream industries^[3-6]. Existing research on emerging low-carbon transition industries focuses on their emission reduction potential and incentives^[7-14]. Research on stakeholders emphasizes their participation's importance in carbon reduction^[8,15,16].

While traditional producer responsibility principles remain crucial in emerging low-carbon transition industries, broader implications need consideration. For example, the EU Battery Act emphasizes battery manufacturers' responsibility^[17], overlooking consumer responsibility. Although these industries produce carbon emissions, they also create economic value for other industries, provide services to consumers, and

importantly, help others improve their emissions reduction capacity. Therefore, when assessing the carbon responsibility of emerging low-carbon transition industries, it is essential to consider not only the carbon emissions at the production level but also the economic and environmental impacts on other social stakeholders. This approach aims to balance the responsibilities and rights of various stakeholders.

As an important sub-sector supporting the electric vehicle industry, the power battery industry provides efficient and reliable energy storage solutions and opportunities for carbon emission reduction in electric vehicles^[18]. Ultimately, it enables low-carbon travel and transportation for end users^[19], playing a vital role in promoting low-carbon transformation and green development. However, power batteries account for 40% of the life-cycle carbon emissions of electric vehicles, presenting a major constraint to green development^[20]. Moreover, the carbon emissions of power batteries are predominantly concentrated in the supply chain, with each stage from raw material extraction to production facing significant challenges in achieving low-carbon outcomes^[20]. Industry carbon emissions are closely linked to the demand for its products, particularly in rapidly developing emerging industries such as the electric vehicle battery. Addressing current and future carbon emissions issues is critical. Clarifying the allocation of carbon responsibility will help accurately assess the pressure to reduce emissions, promote effective carbon reduction measures, and support the sustainable development of the entire industry.

This paper focuses on the electric vehicle battery industry as an emerging sub-sector case. It proposes a method for allocating carbon responsibility that integrates both the production and consumption sides. Compared with the existing research^[21,22], the method of this study pays more attention to the transfer of responsibility between the upstream and downstream of the industry in addition to considering the sharing of responsibility at the production and consumption ends. By considering the transfer of carbon responsibility from the upstream raw material mining stage to downstream stages, the study allocates the power battery industry's carbon responsibility to downstream industries and final consumers, forming a more comprehensive responsibility allocation system. This allocation mechanism emphasizes the entire industrial chain, accounting for the key responsibilities of both production and consumption. The aim is to distribute the burden of carbon emissions more equitably and encourage collective action across society to address climate change.

METHODS

Carbon responsibility transferring and allocation logic

The electric vehicle battery industry chain can be divided into upstream raw material production, midstream battery production and assembly, and downstream application stages. According to the approach proposed by Zhang *et al.*, based on the product carbon emission benchmark from the perspective of consumption, an enterprise's carbon responsibility is defined as the direct carbon emissions from the production process plus the indirect carbon emissions from purchased heat, electricity, raw materials, intermediate products, *etc.*, minus the embodied carbon emissions of sold products^[21]. Thus, for the electric vehicle battery industry, its carbon responsibility is equal to the carbon emissions from upstream raw material production and transportation, minus the embodied emissions in downstream applications. The model constructed by Gao *et al.* allocates the carbon responsibility of the electric vehicle battery industry to downstream industries and final consumers through the supply chain^[22].

Combining the above two types of carbon responsibility allocation logic, this study constructs an industrial allocation method based on both production-side and consumption-side perspectives. Firstly, the carbon responsibility of the electric vehicle battery industry includes its own production emissions and a portion of the upstream raw material production emissions. Secondly, following the model proposed by Gao *et al.*^[22],

these carbon responsibilities are transferred and distributed across the industries and end consumers, both directly and indirectly connected to them. This approach ultimately creates a method for transferring and allocating responsibility. The diagram is shown in [Figure 1](#).

To share carbon responsibility with various entities directly and indirectly related to the electric vehicle battery industry, understanding their supply chain relationships is crucial^[22,23]. However, obtaining real supply chain data is challenging. Based on the national input-output table, this study first separated the economic data of the industry from the battery product sector and then distributed its carbon responsibility among various industries in the supply chain. This approach relies on input-output tables to build, but avoids total reliance on granular supply chain data and enables faster responsibility allocation.

Through field research and expert discussions, the relationship between the electric vehicle battery industry and related sectors has been examined. As a result, all industries (153 product sectors) have been reclassified into 40 industries and three stages (see in the [Supplementary Table 1](#) for details). These stages are: Stage I: This includes only industries directly involved in battery production activities, referred to as the electric vehicle battery industry. Stage II: This stage encompasses industries related to processing, manufacturing, *etc.*, that are directly served by battery production activities. Stage III: This stage includes industries related to circulation, services, *etc.*, that are indirectly served by battery production activities. Each stage has corresponding final consumers. [Figure 2](#) illustrates the transfer and allocation of upstream and downstream responsibilities within the electric vehicle battery industry.

The allocation scenarios explored include:

Scenario I: No allocation scenario - Only the electric vehicle battery industry and corresponding final consumers are responsible for the carbon emissions associated with power battery production (Stage I).

Scenario II: Two-stage allocation scenario - In addition to the electric vehicle battery industry being responsible for the carbon emissions of battery production, the industries that the power battery production directly supports and serves (Stage II) also need to share the responsibility. The corresponding final consumers in both stages also share the responsibility.

Scenario III: Three-stage allocation scenario – Building on Scenario II, the industries that the power battery production indirectly supports and serves (Stage III) also need to share the responsibility. The corresponding final consumers in all three stages also share the responsibility.

Model algebra

In this study, carbon responsibility pertains exclusively to direct carbon emissions (i.e., direct greenhouse gas emissions). Therefore, the carbon responsibility allocation discussed in this paper specifically refers to the carbon emissions related to production for which the responsible entity should be accountable. It is important to highlight that, in this study, the electric vehicle battery industry is regarded as a pure producer, while other industries act as both producers and consumers. The end-use category, on the other hand, is regarded solely as a consumer.

Equation (1) gives the responsibility transfer from the upstream raw material production stage to the industry. Equations (2)-(7) detail the responsibility transfer from the industry to the downstream sectors.

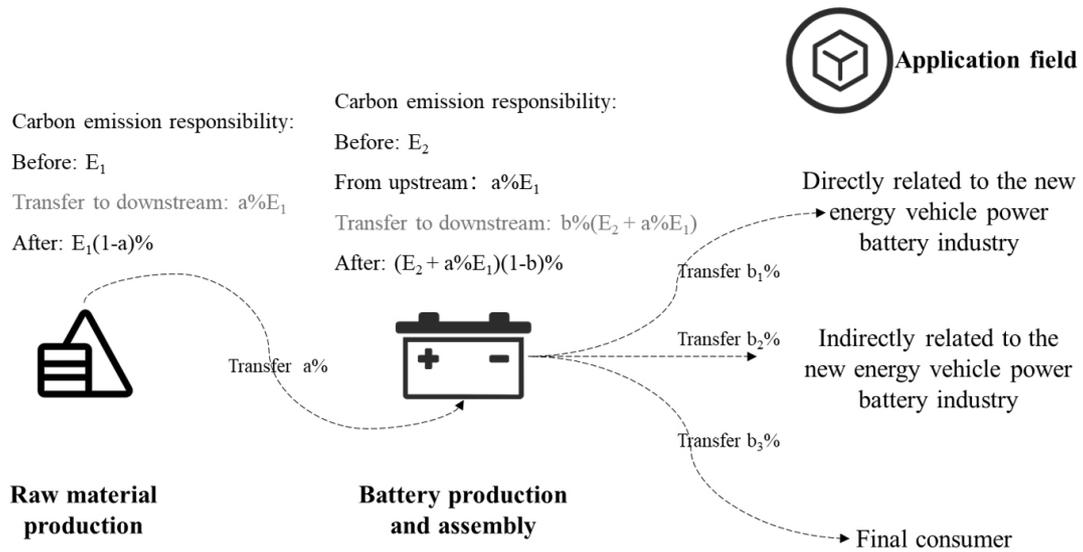


Figure 1. Schematic diagram of carbon responsibility allocation in the electric vehicle battery industry.

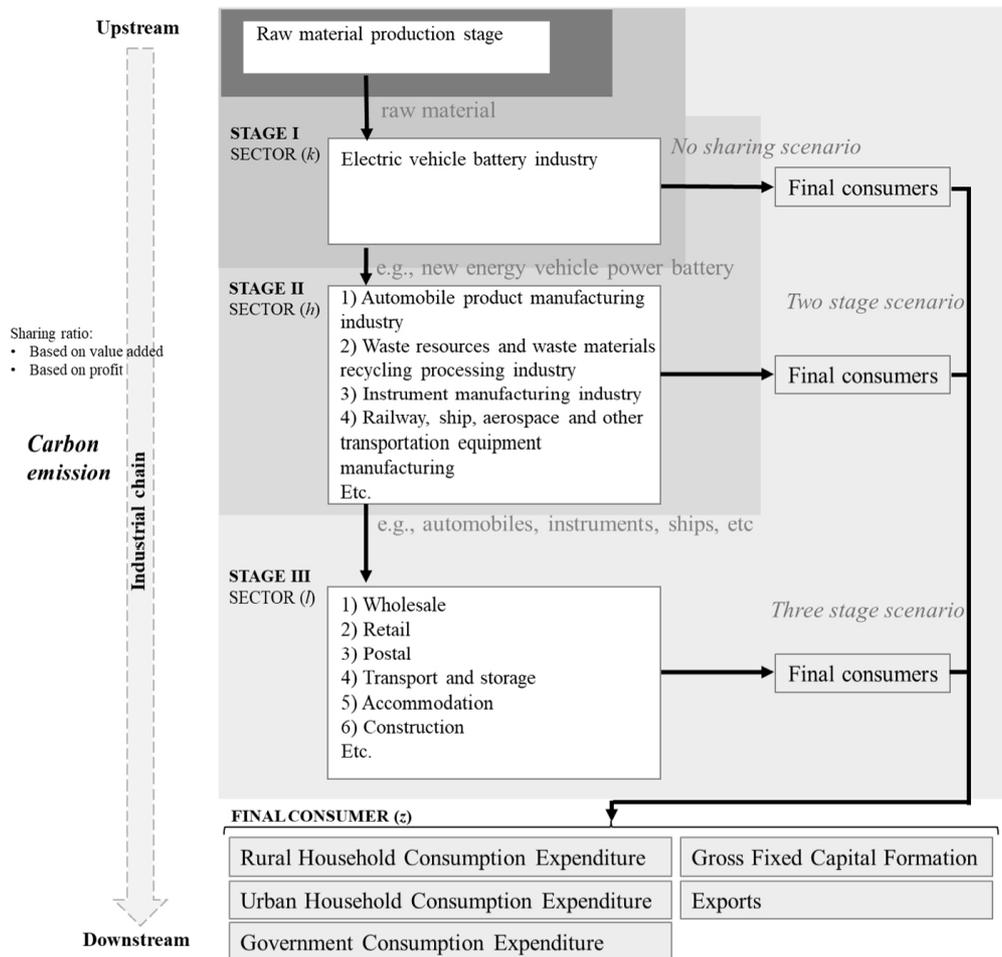


Figure 2. Responsibility allocation – upstream allocated with the electric vehicle battery industry, then reallocated with downstream.

$$E_{\text{carbon emission, from upstream}} = \gamma E_{\text{upstream}} \quad (1)$$

where k represents the electric vehicle battery industry, γ represents the responsibility allocation ratio from the upstream raw material production stage to industry k , E_{upstream} represents the upstream raw material production stage carbon emissions.

$$x_k = \begin{cases} \beta_k y_k + (1 - \beta_k) y_k + (1 - \alpha_k)(x_k - y_k) \\ \sum_h \alpha_{kh} \alpha_{kh} [\beta_h y_h + (1 - \beta_h) y_h + (1 - \alpha_h)(x_h - y_h)] \\ \sum_l \alpha_{kl} \alpha_{hl} \alpha_{kh} \alpha_{hl} [\beta_l y_l + (1 - \beta_l) y_l + (1 - \alpha_{ls})(x_l - y_l)] \\ \dots \end{cases} \quad (2)$$

where h and l represent other downstream industries and final consumers.

Two carbon emission allocation ratios (“ α ” and “ β ”) were used in the study^[22-24]. Different allocation ratios lead to varied outcomes in carbon responsibility sharing. In selecting these ratios, the paper primarily relies on previous studies^[22-24]. There are two allocation rules: one based on the ratio of value added to net output (hereinafter referred to as the “value added allocation rule”), derived from Equations (3) and (4), and another based on the share of profits in total annual revenue (hereinafter referred to as the “profit allocation rule”), derived from Equations (5) and (6). As Lenzen *et al.* noted^[24], arbitrary selection of allocation ratios should be avoided to prevent unfairness. Gao *et al.* pointed out that, while these two rules cannot ensure absolute fairness, they are both reasonable^[22]. The issue of carbon emissions reflects the challenge of transitioning to a green economy. Value added focuses on value creation and efficiency in the production process, whereas profit focuses on economic returns and market competition^[22]. Therefore, selecting value added and profit as allocation ratios is based on the input-output approach and aligns with the industry’s dual roles as both producer and consumer^[22].

$$1 - \alpha_{ij} = 1 - \beta_i = \frac{v_i}{x_i - T_{ii}} \quad (3)$$

where α_{ij} represents the share of carbon emissions transferred from industry i to industry j , so α_{ij} can be denoted as α_i . Therefore,

$$\alpha_i = \beta_i = 1 - \frac{v_i}{x_i - T_{ii}} \quad (4)$$

where v_i is the value added of industry i , $x_i - T_{ii}$ is the total output generated by the industry i minus intra-industry transactions, which describes the net output.

$$1 - \alpha_i = 1 - \beta_i = \frac{\text{Net GOS}_i}{x_i} \quad (5)$$

$$\alpha_i = \beta_i = 1 - \frac{\text{Net GOS}_i}{x_i} \quad (6)$$

Since the ultimate aim of the study is to determine the allocation of carbon emission responsibilities among industries, it is also necessary to multiply Equation (2) by the environmental factor Φ representing carbon emissions. Based on input-output theory, for the electric vehicle battery industry, set carbon emission environmental factor = (annual carbon emissions of electric vehicle battery industry + part of upstream carbon emissions)/the annual total output of electric vehicle battery industry.

Equation (7) provides the mathematical relationship between the commodity output of the electric vehicle battery industry and the total carbon emission responsibility of each stage directly and indirectly related to the industry:

$$X_{carbon\ emission, k} = \begin{cases} \Phi_k [\beta_k y_k + (1-\beta_k) y_k + (1-\alpha_k)(x_k - y_k)] \\ \sum_h \Phi_h \alpha_{kh} a_{kh} [\beta_h y_h + (1-\beta_h) y_h + (1-\alpha_h)(x_h - y_h)] \\ \sum_l \Phi_l \alpha_{kl} \alpha_{lh} a_{lh} a_{kl} [\beta_l y_l + (1-\beta_l) y_l + (1-\alpha_l)(x_l - y_l)] \\ \dots \end{cases} \quad (7)$$

Data sources

The input-output data for 2020 come from the National Bureau of Statistics website^[25]. The carbon emission data for the electric vehicle battery industry in 2020 are derived from the conversion and processing of relevant data, including the output of electric vehicle batteries in 2022^[26] and carbon emissions^[27] and the output of electric vehicle batteries in 2020^[28]. The carbon responsibility allocation rules based on value added and profit are obtained from the 2020 input-output table. To facilitate the discussion of the method constructed in this paper, it is assumed that 50% of the carbon emission responsibility of the raw material production stage is transferred to the battery production and assembly stage.

RESULTS AND DISCUSSION

As previously noted, industry carbon emissions are equated with industry carbon responsibility. Figures 3 and 4 compare the allocation results under different allocation rules, based on value added and profit, respectively, within Scenario II and Scenario III. The corresponding detailed data of the carbon responsibility allocation by industry and consumption category are shown in Table 1.

Based on value added allocation rule

Scenario I: If we do not consider the transferring of carbon responsibility from upstream to downstream, the responsibility for carbon emissions is fully borne by the electric vehicle battery industry. This aligns with the polluter pays principle, which is one manifestation of producer responsibility.

Scenario II: If the responsibility passes to the next stage, the electric vehicle battery industry's carbon responsibility decreases. Compared to Scenario I, the electric vehicle battery industry is only responsible for 18.9% of the emissions associated with battery production. The remaining responsibility is shared among downstream Stage II industries and the corresponding consumers in Stages I and II. As shown in Figure 4, under the value-added allocation rule, the computer, communication, and other electronic equipment manufacturing industry (0.696 million tons of CO₂eq) and the electric vehicle battery industry (0.694 million tons of CO₂eq) bear the most carbon responsibility. Other significant industries include electrical machinery and equipment manufacturing (excluding the electric vehicle battery industry), automobile product manufacturing, the transport and storage industry, and the railway, ship, and aerospace sectors. In the end-use category, exports carry the largest carbon responsibility, followed by gross fixed capital formation, urban household consumption expenditure, rural household consumption expenditure,

Table 1. The results of the carbon responsibility allocation by industry and consumption category under two sharing scenarios and two allocation rules

Industry	Carbon responsibility (10 ⁴ t CO ₂ eq)		Carbon responsibility (10 ⁴ t CO ₂ eq)	
	Scenario II: two-stage allocation scenario		Scenario III: three-stage allocation scenario	
	Based on value added allocation rule	Based on profit allocation rule	Based on value added allocation rule	Based on profit allocation rule
Electric vehicle battery industry	69.40	27.37	67.09	24.36
Computer, communication and other electronic equipment manufacturing	69.63	74.34	54.05	45.95
Electrical machinery and equipment manufacturing industry (except electric vehicle battery industry)	38.55	41.47	18.63	14.96
Automobile product manufacturing industry	19.37	18.64	15.04	10.42
Transport and storage industry	10.82	10.88	9.92	6.48
Railway, ship, aerospace and other transportation equipment manufacturing industry	8.91	7.95	6.09	3.28
Information transmission, software and information technology service	6.34	5.20	8.09	5.21
General equipment manufacturing industry	3.98	3.98	4.87	4.66
Special equipment manufacturing industry	2.64	2.36	3.37	2.75
Instruments manufacturing industry	1.79	2.07	2.10	2.62
Residential services, repairs and other service	1.68	1.27	2.34	1.25
Research and experimental development	1.54	0.15	2.00	0.20
Construction	1.50	0.53	3.84	1.41
Chemical fiber products, rubber and plastic products	1.23	1.36	0.92	0.96
Metal products, machinery and equipment repair services industry	0.93	1.00	0.56	0.42
Integrated technical service	0.93	0.97	2.77	3.39
Wholesale	0.92	0.90	1.91	1.99
Mining and Washing of Coal	0.89	1.05	0.80	0.65
Non-metallic mineral products industry	0.66	0.75	1.01	1.38
Retail	0.64	0.56	0.98	0.70
Postal	0.63	0.69	0.76	0.79
Chemical raw materials and chemical products industry	0.61	0.70	0.88	1.30
Smelting and pressing of metals industry	0.48	0.55	0.85	1.30
Metal Products Manufacturing Industry	0.48	0.52	0.61	0.77
Other manufacturing products industry	0.25	0.27	0.17	0.15
Electricity and heat production and supply industry	0.24	0.26	3.21	4.31
Business service industry	0.23	0.26	3.17	4.80
Extraction of Petroleum and Natural Gas	0.22	0.37	0.19	0.24
Gas and water production and supply industry	0.12	0.11	0.13	0.11
Education	0.09	0.01	0.30	0.05
Petroleum, coking and other fuel processing industry	0.09	0.10	0.31	0.62
Accommodation	0.07	0.08	0.11	0.16
Mining and processing of nonmetal ores	0.03	0.04	0.18	0.25
Mining and processing of metal ores	0.03	0.05	0.16	0.32
Finance, capital markets and insurance	0.01	0.01	0.35	0.67
Culture, sports and entertainment	0.01	0.00	0.06	0.06
Waste resources and waste materials recycling	0.00	0.00	0.02	0.03

processing industry				
Catering	0.00	0.00	0.15	0.26
Leasing industry	0.00	0.00	0.18	0.29
Other	4.43	3.38	7.29	5.48
Rural household consumption expenditure	5.63	7.94	6.77	10.89
Urban household consumption expenditure	17.38	25.39	21.69	36.59
Government consumption expenditure	1.28	2.84	2.19	6.09
Gross fixed capital formation	28.03	43.55	43.15	74.58
Inventory change	9.27	11.05	9.69	11.97
Export	93.10	120.46	106.65	149.08
Import	-38.41	-54.79	-48.91	-77.54
Total	366.66	366.66	366.66	366.66

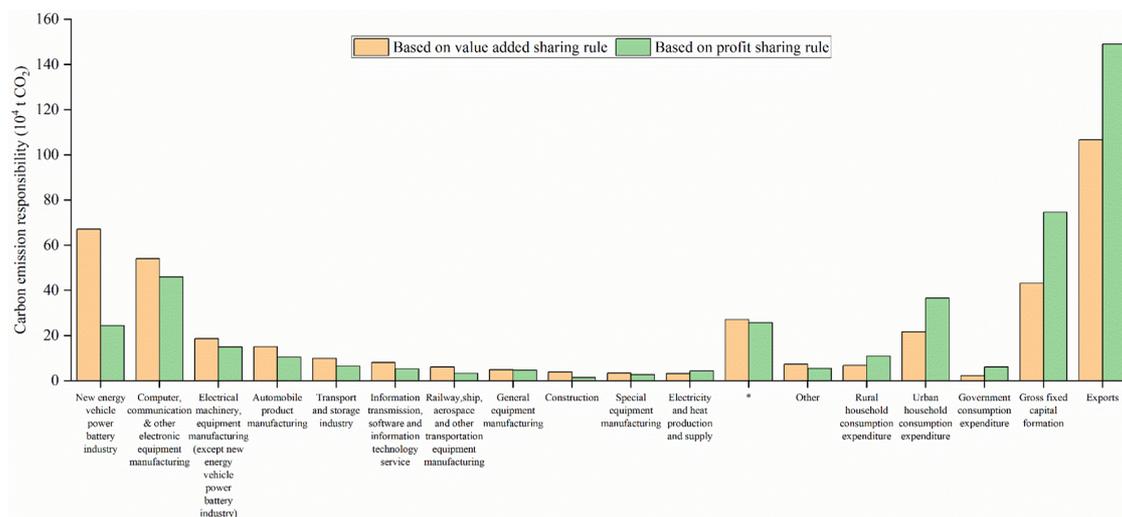


Figure 3. Allocation of carbon emissions of the electric vehicle battery industry among industries and final consumption categories in Scenario III (*represents the sum of sectors with minimal allocated results, see [Supplementary Figures 1 and 2](#) for details).

and government consumption expenditure. Notably, the carbon responsibility of exports is significantly higher than that of the electric vehicle battery industry and other sectors. A similar situation appears in Scenario III under the value-added allocation rule, likely due to the extensive overseas market of the power battery industry (see [Figures 3 and 4](#)). Gao *et al.* found that in the fishery industry, urban consumption carries the largest carbon responsibility under the value-added allocation rule, with the carbon responsibility of the fishery industry being much higher than that of all end-use categories^[22]. This suggests that different industry and product attributes can lead to significant differences in carbon responsibility allocation. In the end-use category, exports refer to products and services provided abroad; thus, overseas consumers need to be responsible for these carbon responsibilities, not domestic ones.

In addition, it should be noted that all industries are divided into three stages directly and indirectly related to the electric vehicle battery industry. The transport and storage industry and the information transmission, software, and information technology service industry belong to Stage III. Theoretically, in Scenario II, industries in Stage III do not share carbon responsibility. However, since the carbon responsibility sharing model is based on the input-output model, carbon responsibility allocation for the electric vehicle battery industry includes all industries.

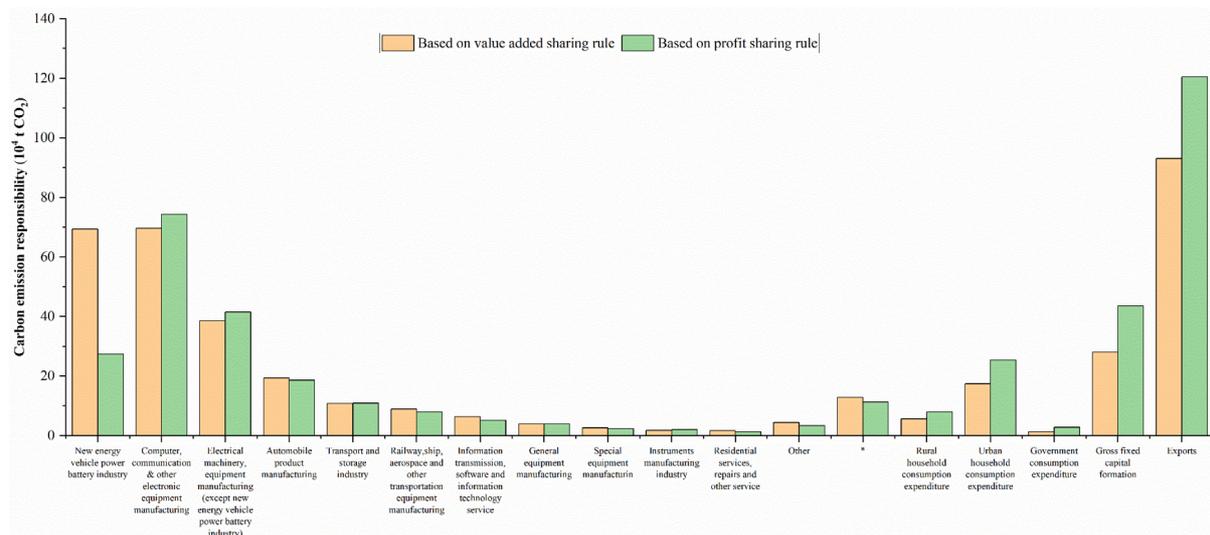


Figure 4. Allocation of carbon emissions of the electric vehicle battery industry among industries and final consumption categories in Scenario II (*represents the sum of sectors with minimal allocated results, see [Supplementary Figures 3 and 4](#) for details).

Scenario III: Building on Scenario II, further exploration is warranted to extend carbon responsibility to lower levels. Compared to Scenario II, the carbon responsibility of the electric vehicle battery industry is slightly reduced, bearing only about 18.3% of the responsibility from Scenario I. The rest is shared among downstream industries in Stages II and III, the electric vehicle battery industry, and the end consumers in Stages II and III. According to [Figure 3](#), under the value added allocation rule, the electric vehicle battery industry remains the primary bearer of carbon responsibility. Compared to Scenario II, its carbon responsibility decreases slightly (0.671 million tons of CO₂eq), followed by the computer, communications, and other electronic equipment manufacturing industry, whose carbon responsibility also declines (0.540 million tons of CO₂eq). Similar to Scenario II, numerous industries share the responsibility. These include the electrical machinery and equipment manufacturing industry (except the electric vehicle battery industry), the automobile product manufacturing industry, the transport and storage industry, the information transmission, software, and information technology service industry, and the railway, ship, aerospace, and other transportation equipment manufacturing industry. However, carbon responsibilities are reduced in these industries compared to Scenario II, except for the information transmission, software, and information technology service industries.

The carbon responsibility of each end-use category under Scenario III is higher than under Scenario II. This implies that final consumers will take on a greater share of the responsibility for the ongoing transfer and expansion of carbon responsibility. In both scenarios, among the consumption categories, exports bear the greatest responsibility, reflecting the rapid development of China's power battery industry and its significant role in the international market.

Based on profit allocation rule

Scenario I: Similar to the value added-based carbon responsibility allocation, if the carbon emissions generated by the electric vehicle battery industry from providing power battery products and services are not transferred to other downstream industries, the responsibility for these emissions is entirely borne by the electric vehicle battery industry.

Scenario II: As shown in Figure 4, under the profit-based allocation rule, if the carbon responsibility extends down one layer, the carbon responsibility borne by the electric vehicle battery industry is significantly reduced (only about 7.5% of the original responsibility compared to Scenario I). Consequently, this industry is no longer the primary bearer of carbon responsibility. The computer, communication, and other electronic equipment manufacturing industries have emerged as the largest drivers of carbon responsibility. Other major industries bearing carbon responsibilities include the electrical machinery and equipment manufacturing industry (except the electric vehicle battery industry), the automobile product manufacturing industry, the transport and storage industry, and the railway, ship, aerospace, and other transportation equipment manufacturing industry. For the end-use category, exports also represent the largest carbon responsibility category, with carbon responsibility more than four times that of the electric vehicle battery industry. The carbon responsibility of urban residents' consumption (0.254 million tons of CO₂e) is only slightly lower than that of the electric vehicle battery industry (0.274 million tons of CO₂e).

Scenario III: Similar to Scenario II, the electric vehicle battery industry is no longer the primary industry responsible for carbon emissions. In comparison to Scenario I, it only bears about 6.6% of the original responsibility. As shown in Figure 4, the computer, communication, and other electronic equipment manufacturing industry bears the highest carbon responsibility, which is 1.8 times that of the electric vehicle battery industry. This is followed by the electrical machinery and equipment manufacturing industry (except the electric vehicle battery industry), the automobile product manufacturing industry, and the transport and storage industry. Overall, industries generally share less carbon responsibility than in Scenario II. In comparison to Scenario II, the carbon responsibility of these five industries accounts for 61.8%, 89.0%, 36.1%, 55.9%, and 59.6% of the responsibility.

Exports also represent the largest carbon responsibility category, more than six times that of the electric vehicle battery industry. Each end-use category assumes a greater carbon responsibility compared to Scenario II. Additionally, the carbon responsibility of urban residents' consumption is slightly higher than the electric vehicle battery industry, about 1.5 times that of the latter.

To sum up, the carbon responsibility of the electric vehicle battery industry, based on different allocation scenarios and rules, will eventually be distributed among other industries and final consumers. Industries such as the computer, communication and other electronic equipment manufacturing industry, the electrical machinery and equipment manufacturing industry (except the electric vehicle battery industry), the automobile product manufacturing industry, and the transport and storage industry bear a heavy carbon responsibility, and the carbon responsibility of the end consumer cannot be ignored. This is mainly because the electric vehicle battery industry is highly dependent on upstream raw materials, so it is necessary to share the responsibility for carbon emissions from the upstream industry. Industries closely related to battery production, such as electronic equipment, electrical machinery, *etc.*, also need to bear a larger carbon responsibility. While the automotive products sector is related to the procurement of batteries and electronic equipment, its use-stage emissions may be transferred to the power sector. The electric vehicles as a strategic product, with the expansion of application scenarios, consumer demand to promote the expansion of battery production, at the same time, low-carbon preferences and sharing economy, and other factors also make consumers' carbon responsibility increase through the supply chain. In addition, the treatment and recycling of power batteries are important links in the whole life cycle, not only affecting the efficiency of the resource cycle, but also changing the distribution pattern of carbon responsibility. The recycling process reduces carbon emissions from upstream mining, but it also introduces new carbon responsibilities. According to this research method, the carbon responsibility of the power battery recycling industry is about 56.80-588.80 t CO₂e, which is consistent with the current situation that the recycling

industry needs to share less upstream carbon responsibility in the early stage of development. Based on the carbon responsibility allocation method in this paper, while reducing the carbon responsibility of the electric vehicle battery industry, other industries will emerge as new focal points for responsibility allocation. Furthermore, each industry can reallocate its carbon responsibility based on the model method in this paper, and there is a close relationship between each industry and consumers in the transferring and sharing of carbon responsibility. When each industry assumes carbon responsibility, its emission behavior not only affects its own responsibility allocation, but also may affect the responsibility of the upstream and downstream of the supply chain or the consumer side. Therefore, adopting this allocation method can promote fairness among industries and, to a certain extent, encourage all parties to take coordinated emission reduction measures and restrict the production behaviors of all parties, so as to achieve the overall emission reduction target.

Strategies for promoting emission reductions across all stages of the supply chain

In the approach proposed by this study, the electric vehicle battery industry shares part of the carbon responsibility from upstream raw material production, while downstream carbon responsibility is shared with directly or indirectly related industries and final consumers. The main entities bearing responsibility include the industry itself, other industries, resident consumers (urban and rural consumption expenditures), government (government consumption expenditures), overseas (exports), investors (total fixed capital formation), *etc.* Commodity production is typically consumption-oriented, with production activities adjusted according to market demand. Producers determine product types and quantities through research and forecasting to respond to market changes, optimize inventory, and improve efficiency. Changes in consumption demand directly affect production decisions and supply chain management, indirectly influencing production carbon emissions. This paper argues that involving the consumer side in sharing industry carbon responsibility can effectively promote carbon reduction. Using the electric vehicle battery industry as a case study, a simple scenario comparison illustrates this point.

- Scenario 1: Each link in the supply chain is solely responsible for its own carbon emissions associated with product production (referred to as the “base scenario”).
- Scenario 2: The electric vehicle battery industry assumes the carbon emission responsibility of upstream raw material production and the battery production and assembly process (a simplified version of the European Union’s new battery regulation, referred to as the “EU scenario”).
- Scenario 3: The electric vehicle battery industry bears part of the carbon emission responsibility for the upstream raw material production process while transferring part of the carbon emission responsibility to other downstream industries and final consumers (a simplified version of the industry responsibility allocation method in this study, referred to as the “innovation scenario”).

In these scenarios, it is assumed that to produce a certain number of electric vehicle batteries, the carbon emission responsibility of the raw material production process in Scenario 1 is E_1 , and the carbon emission responsibility of battery production and assembly (that is, the electric vehicle battery industry) is E_2 . The sum of the carbon emission responsibility of other industries is $E_3 = 0$. The sum of the carbon emission responsibility of the final consumer is $E_4 = 0$. The carbon responsibility allocation in the three scenarios is shown in [Table 2](#).

According to a report by the European Federation for Transport and Environment (T&E), the upstream part of battery production accounts for more than half of the carbon emissions of the power battery supply

Table 2. Carbon responsibility allocation in three scenarios

Scenario	Upstream	Midstream	Downstream	
	Raw material production	Battery production and assembly (electric vehicle battery industry)	Other industries (Directly or indirectly related to the electric vehicle battery industry)	Final consumer
Scenario 1 (Base Scenario)	E_1	E_2	$E_3 = 0$	$E_4 = 0$
Scenario 2 (EU Scenario)	0	$E_1 + E_2$	0	0
Scenario 3 (Innovation scenario)	$(100-a)\% \times (E_1) \leq E_1$	$(100-b)\% \times (E_2 + a\% \times E_1) \leq E_1 + E_2$	$b_1\% \times (E_2 + a\% \times E_1)$	$b_2\% \times (E_2 + a\% \times E_1)$

Note: $a\%$ represents the proportion of responsibility transferred from the raw material production process to the battery production and assembly process, while $b\%$ represents the proportion of responsibility transferred from the battery production and assembly process to other industries and end consumers. $b = b_1 + b_2$.

chain. Therefore, it can be said that $E_2 < 1/2E_1$. So, by assuming the limit values of a and b , it can be concluded that,

$$0 \leq (100 - b)\% \times (E_2 + a\% \times E_1) \leq \frac{3}{2}E_1 \tag{8}$$

To sum up, the carbon emission responsibility of the electric vehicle battery industry under the “innovation scenario” may be greater than, less than, or equal to the “basic scenario”, depending on the proportion of responsibility transferred from upstream to downstream (that is, the value of a and b). However, its carbon responsibility is always less than or equal to the “EU scenario.” In the “innovation scenario,” the carbon emissions responsibility of raw materials production is smaller than in the “basic scenario,” but larger than in the “EU scenario,” with other industries and end consumers also sharing some responsibility. Based on this, the paper posits that the proposed responsibility allocation strategy is effective in promoting emission reductions across all links in the supply chain.

In the “innovation scenario,” the electric vehicle battery industry shares carbon responsibility from upstream raw material production. Certain industries, like mining and refining, inherently produce higher emissions but are crucial for supplying raw materials in various supply chains. In the power battery supply chain, upstream raw material production significantly contributes to total carbon emissions. This responsibility allocation method alleviates the burden of upstream carbon responsibility and incentivizes emission reductions.

Allocating carbon responsibility to downstream stakeholders can relieve pressure on the electric vehicle battery industry, encouraging greater investment in green technologies. This approach also motivates related industries to reduce emissions, fostering emission reduction efforts across the entire supply chain.

With carbon responsibility allocation, consumers are more likely to choose low-carbon products, driving market demand for such goods. This demand influences product output, indirectly affecting production-related carbon emissions. To meet market demand and remain competitive, industries will invest in technological innovation and low-carbon production, promoting both emission reductions and the industry's green transformation.

Responsibility allocation enables entities to collaborate, exchange innovations, and jointly advance carbon reduction technologies. Government and investor participation can offer financial and policy support, lower emission reduction costs, and enhance sustainability for the industry.

Furthermore, stakeholders can adopt various strategies to promote carbon reduction. For example, technologies like blockchain can enhance supply chain transparency, enabling downstream industries to select low-carbon suppliers, thus encouraging upstream emission reductions. Additionally, stronger cooperation across the supply chain is essential for developing and implementing low-carbon technologies. Enterprises in various industries gradually carry out energy substitution, process innovation, and digital management in the production process. Gradually promote product carbon labeling, such as milk packaging to label the carbon footprint of the whole life cycle, and vehicle supply chain emissions data. Gradually optimize logistics, reduce repeated transportation, promote circular packaging, and so on.

For residential consumers, publicity and education can guide them to choose low-carbon products and prioritize environmental protection when using and recycling batteries. Understanding the products' carbon footprint can help consumers recognize their environmental impact and promote low-carbon consumption. Internalizing the cost of carbon emissions into the products' price helps consumers take carbon responsibility and encourages low-carbon product choices through price signals. For instance, Tesla reduces the demand for new materials by recycling lithium, cobalt, and nickel in batteries, transferring the recycling cost and carbon responsibility to the product price, and allowing consumers to participate in carbon reduction^[29,30]. Consumers can also participate in low-carbon emission reduction actions through home energy management (such as home energy storage systems connected to the grid, *etc.*), and the use of carbon inclusive platforms provided by the government or enterprises. In addition, Hainan Province imposes road maintenance fees on electric vehicles, calculates the mileage of electric vehicles in the province through Beidou satellite navigation, and charges road maintenance fees based on the mileage. Similarly, consumers can be charged related electricity by installing a separate meter charging system for electric vehicle charging stations, which can make downstream responsibility more reasonable for consumers.

The government can encourage enterprises and consumers to choose low-carbon products through policies such as carbon taxes, carbon trading markets, and subsidies for low-carbon technologies. Strict environmental standards should be established to ensure compliance throughout the battery industry and its supply chain. A carbon pricing system to charge enterprises should be established for excess emissions. Industry emission reduction standards can be formulated and clean energy networks can be invested to promote ultra-low emission technologies. Furthermore, the government can foster cooperation and experience sharing among enterprises on carbon reduction through industry associations.

For international coordination, the EU mandates that waste batteries be returned to the producing country for processing, which benefits EU environmental protection but poses challenges in terms of fairness and global emission reduction coordination. This underscores the importance of equitable carbon responsibility allocation in cross-border supply chains and the need for enhanced international cooperation to share emission reduction technologies and experiences. The "border carbon" issue presented by the EU Battery

Act significantly challenges China's power battery industries. Chinese companies must navigate "carbon barriers" in international trade to remain competitive. The carbon responsibility allocation logic in this study provides a new perspective for cross-border supply chains, asserting that overseas end consumers should also bear responsibility for the carbon emissions of electric vehicle batteries.

Investors can be incentivized to invest in low-carbon technologies and enterprises, promoting the industry's green transformation through the capital market. Strengthening the implementation and disclosure of corporate environmental, social, and governance standards will attract environmentally conscious investors.

In summary, allocating carbon responsibility across the supply chain - from upstream sources to the electric vehicle battery industry, downstream industries, and end consumers - can effectively promote carbon reduction for all parties involved. This carbon responsibility allocation method is not only applicable to the electric vehicle battery industry, nor is it confined to emerging development industries. It also offers effective strategies for emission reduction in traditional industries. For instance, implementing a similar responsibility-sharing mechanism in manufacturing supply chains, such as those in the steel, chemical, and other high-carbon industries, can yield significant benefits. By encouraging upstream and downstream industries and consumers to share carbon responsibility, suppliers are motivated to use low-carbon raw materials, manufacturing enterprises are incentivized to optimize production processes, and consumers are guided to choose green products. In the energy sector, carbon responsibility allocation can accelerate the development and utilization of clean energy by energy production enterprises, enhance energy efficiency, and reduce energy waste in downstream industries. End users can support low-carbon energy choices by adjusting their consumption behavior, collectively achieving multi-party collaborative emission reduction goals. This method galvanizes action through shared responsibility and, combined with policy support, market incentives, and technological innovation, can drive green transformation and sustainable development on a broader scale.

Further consideration

According to the carbon responsibility transferring and allocation model constructed in the paper, the carbon responsibility of industries and end-use categories is significantly affected by the allocation rule. With Equations (3)-(6), when x_k and y_k are certain, they directly determine the allocation ratio α and β . With the increase of the α and β values, the carbon responsibility of the electric vehicle battery industry decreases, while the carbon responsibility of other industries increases. In both Scenario III and Scenario II, the end-use category carbon responsibility under the value-added allocation rule is always lower than that under the profit-allocation rule. For the carbon responsibility allocated to various industries, except for the electrical machinery and equipment manufacturing industry (except the electric vehicle battery industry) in Scenario II, the carbon responsibility under the value-added allocation rule is also higher than that under the profit-based allocation rule.

By analyzing the data in the [Supplementary Table 2](#), it can be found that the allocation ratio based on profit is generally higher than that based on value added, usually around 0.9. The higher the allocation ratio, the less carbon responsibility the electric vehicle battery industry needs to bear. However, the core purpose of transferring and allocating carbon responsibility is to promote shared responsibility among various industries and foster coordinated development of the industrial chain, rather than merely transferring responsibility. Therefore, we should not arbitrarily judge which allocation rule is better based only on the allocation result, but should combine it with practical situations for testing and validation.

In addition, the method constructed in this study is compared with those of Zhang *et al.*^[21] and Gao *et al.*^[22] (see Table 3). The method adopted by Zhang *et al.* is based on specific industrial chain data^[21]. It is necessary to determine the carbon emission baseline value of each product type to further determine the carbon emission responsibility of each entity in the industrial chain. Under this approach, consumers bear full responsibility for carbon emissions, while producers are not necessarily held accountable. This approach has higher data quality requirements, emphasizes consumer responsibility, and provides a clearer division of responsibilities among all entities.

Building on the research by Gao *et al.*^[22], this study incorporates upstream carbon responsibilities from raw material production and transfers them to the product industry while also considering the sharing of carbon responsibilities among downstream industries and consumers. In many sectors, emissions from raw material production constitute a significant portion of the total carbon footprint; for instance, the production of power battery raw materials can account for up to 80% of total emissions^[31]. This study's approach, compared to Gao *et al.*^[22], emphasizes responsibility transfer between upstream and downstream sectors. While the electric vehicle battery industry's carbon responsibilities may have increased, this framework creates a more comprehensive allocation system through allocated upstream responsibilities. Both methods rely on input-output tables, maintaining relaxed data quality requirements and enabling flexible adjustments of carbon responsibilities via allocation ratios. Overall, the proposed approach enhances flexibility and comprehensiveness in responsibility allocation, taking into account the transfer of responsibility for upstream raw materials and achieving downstream industry responsibility allocation.

Limitations

Additionally, this study is based on the input-output theory of economics, which has its limitations: (1) The use of the input-output table simplifies the supply chain of the electric vehicle battery industry, overlooking some complex interactions and thus failing to fully reflect the actual supply chain situation; (2) The relevant data are derived from industry research and the input-output table. Due to subjective judgment and potential bias in the research, the data may not be entirely accurate, leading to certain deviations in the results. Nonetheless, the study has made significant progress in the sharing of carbon responsibility within the supply chain, particularly in the allocation of cross-industry carbon responsibility. However, there are still limitations regarding the detailed allocation of carbon responsibility at the end of consumption. The current analysis is confined to broad consumption categories, such as government, urban residents, rural residents, and exports, and does not delve into more detailed consumer behaviors or the division of responsibilities among specific consumer groups. For instance, residents of different age groups, income levels, or consumption habits may exhibit significant differences in carbon emissions. Furthermore, the study's allocation results indicate that the consumption side accounts for a substantial proportion of carbon responsibility. Therefore, future studies should further refine the allocation of carbon responsibility on the consumption side and provide a scientific basis for developing more targeted carbon emission reduction policies.

CONCLUSIONS

Using the electric vehicle battery industry as a case study, this paper analyzes carbon responsibility allocation from a whole supply chain traceability perspective. Through a responsibility transferring and allocation mechanism, the electric vehicle battery industry bears responsibility for both its production emissions and a portion of those from upstream raw material production, while downstream industries and end-users bear the remainder. Specifically, the electric vehicle battery industry bears only 6.6%-18.9% of its original carbon responsibility. The more stages allocated downstream, the more industries share the carbon responsibility, such as the computer, communication, and other electronic equipment manufacturing

Table 3. Approach comparison: the paper vs. Zhang et al.^[21] and Gao et al.^[22]

Method	Industrial chain and data	Responsibility allocation	Key point	The responsibility of the responsible subject
Zhang et al. ^[21]	Based on the actual industrial chain and data	Consumers bear full carbon emissions responsibility, while producers only bear the portion of the production emissions that exceed the industry average	To determine the carbon emission baseline value of each type of product in the industrial chain	Non-adjustable
Gao et al. ^[22]	Based on input-output tables	Producer and consumer responsibility allocation, only considering the responsibility transferring and allocation to the downstream	To determine the allocation ratio of responsibility that the industry transfers to downstream	It can be adjusted by allocation ratios
The approach proposed in this study	Based on input-output tables	Producer and consumer responsibility allocation, considering the industry upstream and downstream responsibility transferring and allocation	Building on the approach of Gao et al., further consider the responsibility transferring from the raw materials production stage to the industry products production stage, and determine the responsibility allocation ratios ^[22]	It can be adjusted by allocation ratios

industry, and the electrical machinery and equipment manufacturing industry (except the electric vehicle battery industry). Between 31%-58% of carbon responsibility is allocated to end-users, including residents, governments, investors, and international stakeholders.

Through this carbon responsibility allocation method, the government can gain a clearer understanding of the carbon responsibility at each link of the supply chain and the final consumption end, providing new scientific support for developing a reasonable, fair, and operational responsibility allocation plan. Additionally, the government can use this method to promote collaborative management among upstream and downstream enterprises in the supply chain, encouraging them to cooperate on emission reduction targets through policy support or incentive mechanisms. Furthermore, it provides a new scientific reference basis for the government to promote green transformation at the consumption end. This collaborative approach to responsibility allocation can help drive carbon reduction across the supply chain, requiring market-driven strategies, technological innovation, and policy support. It has positive implications for promoting more equitable carbon reduction targets and fostering global cooperation for sustainable development. In addition, based on the carbon responsibility allocation method in this paper, while reducing the carbon responsibility of the original industry (the electric vehicle battery industry in this paper), it will also make other industries become the focus of new responsibility allocation. Therefore, how to scientifically and reasonably allocate carbon responsibility among industries, not only to ensure balanced development of industries and steady economic growth, but also to promote collaborative emission reduction, will be an important direction of future research.

DECLARATIONS

Authors' contributions

Overall project supervision, conceptualization, project management, original draft writing, and final writing – review & editing: Liu, G.

Methodology development, execution, validation, and writing of early drafts and the original manuscript: Gao, Y.

Manuscript review and revision: Agostinho, F.; Almeida, C. M. V. B.; Giannetti, B. F.; Zhou, X.; Chen, C.; Gao, H

Availability of data and materials

The raw data supporting the findings of this study are available within this Article and its [Supplementary Materials](#). Further data are available from the corresponding author upon reasonable request.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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