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Research on the Economic Environmental Impact and Carbon Reduction Pathways of Power Battery Industry Development - A Case Study of Yibin City

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Abstract

The power battery industry in China is experiencing rapid development, with the swift expansion of capacity potentially posing challenges to environmental protection and carbon reduction. Using the development plan of the power battery industry in Yibin City as a case study, this paper employs the Material Flow Analysis and Tapio decoupling model to deeply explore the economic benefits and environmental burdens brought by the development of power battery key industry under scenarios, proposing optimized pathways to promote low-carbon industrial development. The results indicate that the industrial output value can increase from 92.1 billion CNY in the baseline year to 382.6 billion CNY in 2030, with carbon emissions rising from 0.55 million tons to 2.32 million tons. The adjustment of product structure has limited effect on carbon reduction in the power battery industry. In the short term, optimizing the energy structure has greater carbon reduction potential than improving energy efficiency, and clean energy utilization has the highest marginal carbon reduction effect. Implementing measures to optimize the energy structure and improve efficiency simultaneously can achieve weak decoupling of economic growth and carbon emissions, though strong decoupling is challenging to attain. The proportion of local renewable energy generation also impacts the low-carbon capability of the industry, suggesting that regions with abundant renewable energy should be prioritized for industrial layout. Promoting the decoupling of economic growth and environmental impact in the power battery industry can be facilitated by supporting environmental governance infrastructure, driving the green energy transition, and encouraging low-carbon technological innovation.

JEL classification numbers: F062.2
Keywords: Power battery, Scenario analysis, Material flow, Economic environmental impact, Carbon emissions.

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1. Introduction

Since the implementation of the reform and opening-up policy, China's economic development has entered a phase of rapid growth, garnering remarkable global recognition (Li et al., 2023a). This rapid economic expansion has consumed substantial amounts of energy, leading to a significant rise in China's carbon emissions (Yang et al., 2022). Consequently, China has become the largest carbon emitter in the world (Cheng and Gai, 2022), causing a series of environmental problems in many regions (Xu and Tian, 2023). In recent years, as China's economy transitions from rapid growth to high-quality development, several strategic emerging industries have flourished, such as new energy and new energy vehicles (Zhang et al., 2020).

The power battery industry is crucial for the high-quality development of the new energy vehicle sector (Jia et al., 2022; Kuang et al., 2022) and has experienced rapid growth. China's power battery installed capacity reached 292 GWh in 2022, with projections to reach 570 GWh by 2025 and enter the "TW era" by 2028 (Chen et al., 2022). However, the disorderly rapid development of the power battery industry may bring environmental pressures (Feng et al., 2022). Although batteries serve as carriers of clean energy, their production stage consumes large amounts of energy, resulting in excessive carbon emissions (Lai et al., 2022b), which are the primary source of emissions throughout the battery's lifecycle (Dai et al., 2019; Kallitsis et al., 2020). Therefore, reducing carbon emissions from battery production is a crucial pathway to achieving a "zero carbon" industry.

Yibin City is a key sector in China's power battery industry layout. In 2022, Yibin City's power battery production was 72 GWh, with a planned capacity of 305 GWh by 2030, requiring an annual growth rate of nearly 20% to meet the target. Along with capacity expansion, the resulting carbon emissions and environmental load cannot be ignored. Hence, this paper uses Yibin City's power battery industry as a case study to explore its economic and environmental impacts and carbon reduction pathways.

Currently, the academic community has conducted extensive research on the environmental impacts of power batteries and achieved substantial results (Lai et al., 2022a; Nowsheen et al., 2023). Most studies quantitatively analyze the environmental impacts of the entire process of battery production, use, and recycling (Chen et al., 2022; Ren et al., 2023) based on the lifecycle theory. Ellingsen et al. (2014) focused on 13 environmental impacts during the battery production stage, including global warming potential, human toxicity potential, and terrestrial acidification potential, finding that battery cells, cathode materials, and anode current collectors had the greatest environmental impact. Wu et al. (2023) studied NCM811 batteries, focusing on calculating carbon emissions at various stages of the battery's lifecycle, finding the highest emissions in the production stage. Additionally, some scholars compared the environmental impacts of different batteries, confirming that lithium iron phosphate batteries have a better overall environmental performance than ternary lithium batteries, while the latter has more significant recycling value (Feng et al., 2022). Most of these studies focus on the environmental impact assessment at the product level of power batteries, lacking evaluations at the industry level.

In the environmental impact assessment of other key industries, material flow analysis (MFA) is a method used by many scholars. MFA can clarify the material flow, direction, and environmental load in a specific system, providing a basis for optimizing management and scientific decision-making (Liu et al., 2019). Zhang et al. (2021) selected cases of the steel structure building industry in western, northeastern, and central China, using MFA to understand the types and weights of materials flowing in the steel structure construction process, thus proposing suggestions for improving the economic and environmental efficiency of steel structure buildings. Although MFA can effectively evaluate material flow and the resulting environmental impacts throughout the production process, it is difficult to quantify the level of balanced economic and environmental development. Therefore, in recent years, some scholars have combined MFA with the Tapio decoupling model (Tapio, 2005) to conduct economic and environmental benefit evaluation research. Yang et al. (2024) combined MFA with decoupling analysis to establish the relationship between per capita steel flow, stock, and per capita GDP in 23 countries, analyzing the decoupling status between material flow, stock indicators, and economic growth from upstream iron ore to downstream assembled steel.

The rapid development of industrial scale and clustering inevitably brings corresponding environmental burdens. Thus, accurately assessing the environmental impact brought by rapid economic growth is crucial for high-quality industrial development. Xiang et al. (2023) integrated scenario simulation and the decoupling model into the material-energy-value flow model, predicting resource and energy increments and environmental impacts brought by ethylene capacity expansion under different future scenarios, exploring synergistic paths for ethylene pollution reduction and carbon emission reduction. However, most current related studies are based on historical data, with few evaluations of the economic and environmental benefits during the future development of the industry.

In summary, current research on the environmental impact of power batteries primarily focuses on the product level, with limited exploration at the industry level. Additionally, most studies conduct status quo analyses, but there is insufficient research on the economic and environmental impacts of the future development of the power battery industry. To address these gaps, this study focuses on high-growth industries, building a comprehensive economic and environmental assessment model to predict the economic benefits and environmental impacts brought by industrial development. This model aims to provide a scientific basis for formulating policies for environmental pollution control and carbon reduction in key industries. Firstly, by combining material flow and scenario analysis methods, and based on the Yibin City power battery industry plan, its economic benefits and environmental load under different future development scenarios are evaluated from a macro-industrial perspective, and changes in carbon emissions and carbon productivity under various measures are explored. Then, using the Tapio decoupling model, we analyze the decoupling status between future greenhouse gas emissions and industrial development. Finally, based on these analyses, we propose suggestions for the low-carbon development of the industry.

2. System Boundary and Methodology

2.1 System Boundary

Currently, power battery market mainly includes two types: ternary lithium batteries and lithium iron phosphate batteries in China (Dou et al., 2024). During the various stages of the battery lifecycle, the production stage is the primary source of carbon emissions (Lai et al., 2022a), accounting for 67% of the entire lifecycle (Wu et al., 2023). In the production stage, the carbon emissions of the four main materials (cathode materials, anode materials, separators, and electrolytes) account for 84.3% (Chen, 2023). Additionally, these four main materials, as key components for lithium battery production (Li et al., 2023b; Wang et al., 2018), constitute 88% of the total cost of power batteries (Huajing Industry Research Institute, 2022). Therefore, based on recent environmental impact reports from representative power battery and main material enterprises in China, this study conducts a quantitative analysis of the resources, energy, environmental, and economic impacts brought by the production of the power battery industry. The system boundary is shown in Figure 1.

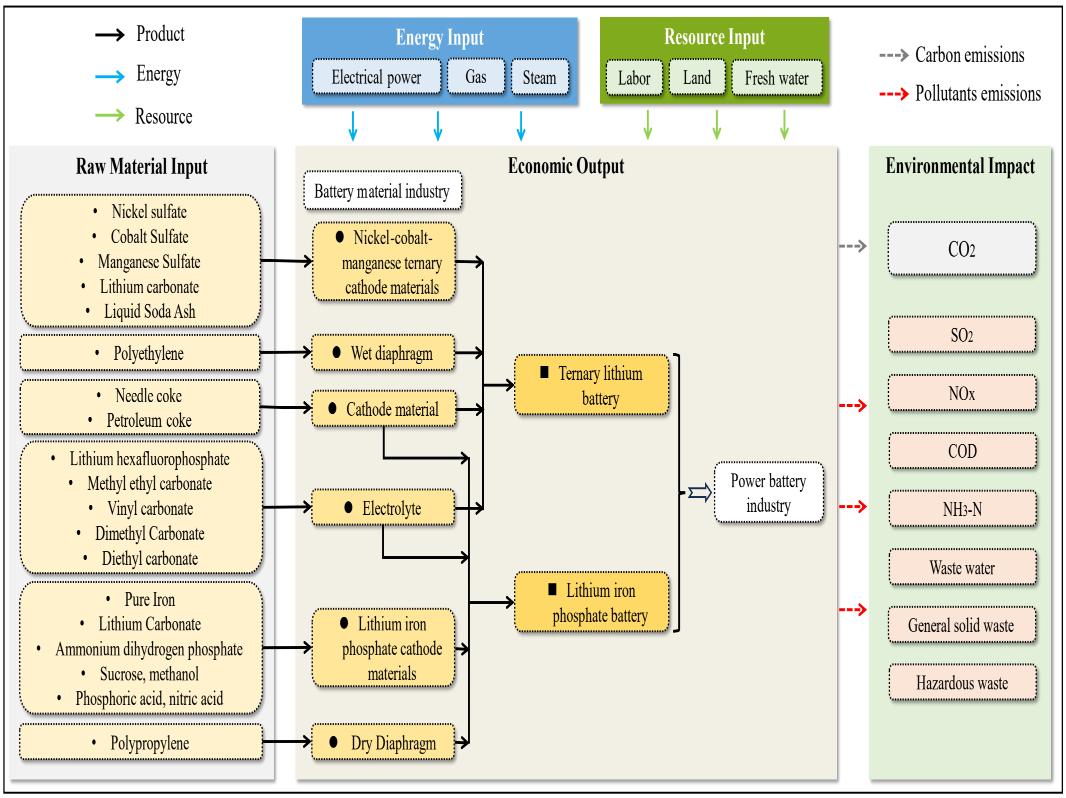

Figure 1: System boundary

2.2 Model Equations

(1) Product Output

$$Q_{i,j}(t) = Q(t) \times scen_i \times ratio_j, \ i = 0,1,2,A,B,C,D,E, \ j = 1,2 \quad (1)$$

Where $scen_i$ denotes scenario i, and $ratio_j$ signifies the proportion of output corresponding to battery j, with $j = 1,2$ representing ternary lithium batteries and lithium iron phosphate batteries respectively. $Q_{i,j}(t)$ represents the output of battery j under scenario i in year t, with t denoting the year, where 2022 serves as the base year and 2030 as the target year. $Q(t)$ represents the total battery output in year t.

$$Q_{i,j,k}(t) = Q_{i,j}(t) \times \alpha_{i,j,k}, \ k = 1,2,3,4 \quad (2)$$

Where $k = 1,2,3,4$ respectively represent cathode materials, anode materials, electrolytes, and separators; $\alpha_{i,j,k}$ represents the output of main material k required to support battery j under scenario i. $Q_{i,j,k}(t)$ represents the output of the main material k required to support battery j under scenario i in year t.

(2) Raw Material Input

$$Q_{i,j,k,m}(t) = Q_{i,j,k}(t) \times \beta_{i,j,k,m}, \ m = 1,2 \ldots \quad (3)$$

Where $m = 1,2 \ldots$ denotes raw material m. $\beta_{i,j,k,m}$ represents the input amount of raw material m required for producing main material k required to support battery j under scenario i. $Q_{i,j,k,m}(t)$ represents the input amount of raw material m required for producing main material k required to support battery j under scenario i in year t.

(3) Pollutants

$$P_{i,j,n}(t) = Q_{i,j}(t) \times \gamma_{i,j,n}, \ n = 1,2,3,4,5,6,7 \quad (4)$$

$$P_{i,j,k,n}(t) = Q_{i,j,k}(t) \times \gamma_{i,j,k,n}, \ n = 1,2,3,4,5,6,7 \quad (5)$$

$$P_{i,n}(t) = \sum_{j=1}^{2} P_{i,j,n}(t) + \sum_{j=1}^{2} \sum_{k=1}^{4} P_{i,j,k,n}(t), \ n = 1,2,3,4,5,6,7 \quad (6)$$

Where $n = 1,2,3,4,5,6,7$ respectively represent SO_2, NOx, COD, NH_3-N, wastewater, general solid waste, and hazardous waste. SO_2, NOx, COD, and NH_3-N denote emissions, while wastewater, general solid waste, and hazardous waste represent generation. $\gamma_{i,j,n}$ represents the amount of pollutant n generated by producing one unit of battery j under scenario i. $P_{i,j,n}(t)$ denotes the amount of pollutant n generated by producing battery j under scenario i in year t. $\gamma_{i,j,k,n}$ represents the amount of pollutant n generated by producing one unit of main material k required to support battery j under scenario i. $P_{i,j,k,n}(t)$ denotes the amount of pollutant n generated by producing main material k required to support battery j under scenario i in year t. $P_{i,n}(t)$ represents the total amount of pollutant n in year t under scenario i.

(4) Resources

$$R_{i,j,s}(t) = Q_{i,j}(t) \times \rho_{i,j,s}, \quad s = 1,2,3 \tag{7}$$

$$R_{i,j,k,s}(t) = Q_{i,j,k}(t) \times \rho_{i,j,k,s}, \quad s = 1,2,3 \tag{8}$$

$$R_{i,s}(t) = \sum_{j=1}^{2} R_{i,j,s}(t) + \sum_{j=1}^{2} \sum_{k=1}^{4} R_{i,j,k,s}(t), \quad s = 1,2,3 \tag{9}$$

Where $s = 1,2,3$ respectively represent labor, land, and fresh water resources. $\rho_{i,j,s}$ represents the amount of resource s consumed to produce one unit of battery j under scenario i. $R_{i,j,s}(t)$ denotes the amount of resource s consumed to produce one unit of battery j under scenario i in year t. $\rho_{i,j,k,s}$ represents the amount of resource s consumed to produce one unit of main material k required to support battery j under scenario i. $R_{i,j,k,n}(t)$ denotes the amount of resource s consumed to produce main material k required to support battery j under scenario i in year t. $R_{i,s}(t)$ represents the total amount of resource s consumed in year t under scenario i.

(5) Energy

$$CE_{i,j,p}(t) = E_{i,j,p}(t) \times \mu_p = Q_{i,j}(t) \times \delta_{i,j,p} \times \mu_p, \quad p = 1,2,3 \tag{10}$$

$$CE_{i,j,k,p}(t) = E_{i,j,k,p}(t) \times \mu_p = Q_{i,j,k}(t) \times \delta_{i,j,k,p} \times \mu_p, \quad p = 1,2,3 \tag{11}$$

$$CE_{i,p}(t) = \sum_{j=1}^{2} CE_{i,j,p}(t) + \sum_{j=1}^{2} \sum_{k=1}^{4} CE_{i,j,k,p}(t), \quad p = 1,2,3 \tag{12}$$

$$CE_i(t) = \sum_{p=1}^{3} CE_{i,p}(t) = \sum_{p=1}^{3} \left(\sum_{j=1}^{2} Q_{i,j}(t) \times \delta_{i,j,p} \times \mu_p + \sum_{j=1}^{2} \sum_{k=1}^{4} Q_{i,j,k}(t) \times \delta_{i,j,k,p} \times \mu_p \right) \tag{13}$$

Where $p = 1,2,3$ represent three types of energy sources: electricity, natural gas, and steam, respectively. μ_p denotes the standard coal coefficient for energy source p. $\delta_{i,j,p}$ signifies the physical quantity of energy source p consumed by producing one unit of the battery j under scenario i. $\delta_{i,j,k,p}$ denotes the physical quantity of energy source p consumed by producing one unit of the main material k required to support battery j under scenario i. $E_{i,j,p}(t)$ represents the amount of energy source p consumed in physical units for producing battery j under scenario i in year t. $E_{i,j,k,p}(t)$ represents the amount of energy source p consumed in physical units for producing one unit of main material k required to support battery j under scenario i in year t. $CE_{i,j,p}(t)$ indicates the amount of energy source p consumed in standard coal units for producing battery j under scenario i in year t. $CE_{i,j,k,p}(t)$ denotes the amount of energy source p consumed in standard coal units for producing one unit of main material k required to support battery j under scenario i in year t. $CE_{i,p}(t)$ represents the total consumption of energy source p in standard coal units for scenario i in year t. $CE_i(t)$ represents the comprehensive energy consumption for scenario i in year t measured in standard coal units.

(6) Carbon emissions

$$C_{i,j,p}(t) = E_{i,j,p}(t) \times \theta_p = Q_{i,j}(t) \times \delta_{i,j,p} \times \theta_p, \ \ p = 1,2,3 \quad (14)$$

$$C_{i,j,k,p}(t) = E_{i,j,k,p}(t) \times \theta_p = Q_{i,j,k}(t) \times \delta_{i,j,k,p} \times \theta_p, \ \ p = 1,2,3 \quad (15)$$

$$C_{i,p}(t) = \sum_{j=1}^{2} C_{i,j,p}(t) + \sum_{j=1}^{2}\sum_{k=1}^{4} C_{i,j,k,p}(t), \ \ p = 1,2,3 \quad (16)$$

$$C_i(t) = \sum_{p=1}^{3} C_{i,p}(t) = \sum_{p=1}^{3}\left(\sum_{j=1}^{2} Q_{i,j}(t) \times \delta_{i,j,p} \times \theta_p + \sum_{j=1}^{2}\sum_{k=1}^{4} Q_{i,j,k}(t) \times \delta_{i,j,k,p} \times \theta_p\right) \quad (17)$$

Where θ_p denotes the CO_2 emission factor for energy source p. $C_{i,j,p}(t)$ represents the CO_2 emissions resulting from the consumption of energy source p in producing battery j under scenario i in year t. $C_{i,j,k,p}(t)$ denotes the CO_2 emissions resulting from the consumption of energy source p in producing one unit of the main material k required to support battery j under scenario i in year t. $C_{i,p}(t)$ represents the total CO_2 emissions due to the consumption of energy source p in scenario i in year t. $C_i(t)$ represents the total CO_2 emissions from all energy sources in scenario i in year t.

(7) Economic benefits

$$GOVB_i(t) = \sum_{j=1}^{2} GOV_{i,j}(t) = \sum_{j=1}^{2} Q_{i,j}(t) \times price_j \quad (18)$$

$$GOVM_i(t) = \sum_{j=1}^{2}\sum_{k=1}^{4} GOV_{i,j,k}(t) = \sum_{j=1}^{2}\sum_{k=1}^{4} Q_{i,j,k}(t) \times price_{j,k} \quad (19)$$

$$GOV_i(t) = GOVB_i(t) + GOVM_i(t) \quad (20)$$

Where $price_j$ represents the unit price of battery j (the unit price of the product takes the value of June 2022); $price_{j,k}$ represents the unit price of the main material k of the battery j (the unit price of the product takes the value of June 2022); $GOV_{i,j}(t)$ denotes output value from producing battery j for scenario i in year t; $GOV_{i,j,k}(t)$ represents output value from producing main material k required to support battery j under scenario i in year t; $GOVB_i(t)$ represents the output value from battery for scenario i in year t; $GOVM_i(t)$ represents the total output value from main material for scenario i in year t; $GOV_i(t)$ represents the total output value of the power battery industry under scenario i in year t.

(8) Carbon productivity

Carbon productivity under scenario i in year t:

$$CP_i(t) = GOV_i(t)/C_i(t) \quad (21)$$

(9) Decoupling model

$$D_i = \frac{\Delta C_i(t)/C_0(t)}{\Delta GOV_i(t)/GOV_0(t)} = \frac{\left(C_i(2030) - C_0(2022)\right)/C_0(2022)}{\left(GOV_i(2030) - GOV_0(2022)\right)/GOV_0(2022)} \quad (22)$$

Where D_i represents the decoupling index for scenario i; ΔC_i measuring the ratio of the change in CO_2 emissions to the change in industry output relative to a baseline year; ΔGOV_i represents the change of industrial output value in the target year relative to the baseline year under scenario i; $\Delta C_i/C_0$ represents the growth rate of carbon emission in the target year of scenario i relative to the baseline year; $\Delta GOV_i/GOV_0$ represents the growth rate of industrial output in the target year of scenario i relative to the baseline year. The decoupling status is shown in Table 1.

Table 1: Division of decoupling status

Decoupling index	**Carbon emissions growth rate**	**Economic growth rate**	**Decoupling status**	
0<D<0.8	>0	>0	decoupling	Weak decoupling
D<0	<0	>0		Strong decoupling
D>1.2	<0	<0		Recessive decoupling
0.8<D<1.2	>0	>0	coupling	Expansive coupling
0.8<D<1.2	<0	<0		Recessive coupling
0<D<0.8	<0	<0	negative decoupling	Weak negative decoupling
D<0	>0	<0		Strong negative decoupling
D>1.2	>0	>0		Expansive negative decoupling

Note: Table 1 refers to Tapio's (2005) delineation criteria.

3. Assessment of Economic and Environmental Impacts of Power Battery Capacity Expansion

3.1 Economic and Environmental Impacts of Power Battery Product Structure Adjustment

Optimizing product structure is a primary choice for the development planning of power battery enterprises. To assess the economic and environmental impacts of industry expansion and different product structure adjustments, three scenarios are set in this section (see Table 2). Based on official data from Yibin City and the market structure in the baseline year, product output and structure are set at 72 GWh with a ratio of 4:6 for NCM (Ternary Lithium) to LFP (Lithium Iron Phosphate) batteries in Scenario 0. In Scenario 1, the output is increased to 305 GWh according to the Yibin plan, with the product structure remaining the same as Scenario 0. Due to the increased market share in recent years driven by cost-effectiveness and technological advancements, Scenario 2 adjusts the NCM to LFP ratio to 3:7, with the output remaining the same as Scenario 1 at 305 GWh.

Table 2: Scenario setting (product adjustment)

Scenario	Product output	Product adjustment
Scenario 0 (baseline year Scenario)	2022 (baseline year), 72GWh	NCM:LFP =4:6
Scenario 1 (product structure remaining)	2030 (target year), 305GWh	NCM:LFP=4:6
Scenario 2 (product structure adjustment)	2030 (target year), 305GWh	NCM:LFP=3:7

As shown in Figures 2(a), (b), and (c), due to rapid production growth, the total output under both target year scenarios significantly increases compared to the baseline year scenario. However, pollutant emissions also rise accordingly. For instance, in Scenario 2, the output increases to 4.2 times that of the base year scenario, while pollutants such as SO_2, NOx, COD, NH_3-N, wastewater, general solid waste, and hazardous waste increase to 3.3, 4.5, 3.8, 3.8, 3.9, 3.3, 4.5, and 3.4 times the base year scenario, respectively. labor, land, and water resource demands also rise to 3.9, 3.6, and 4.2 times the baseline year scenario. The rapid development of the industry exceeds the existing capacity to bear environmental loads. Therefore, it is necessary to consider constructing sufficient facilities for treating environmental pollutants such as sewage treatment plants and hazardous waste storage facilities to prevent environmental deterioration. Simultaneously, ensuring an adequate supply of various resources and energy is essential.

Figure 2(d) illustrates the changes in various indicators in Scenario 2 relative to Scenario 1. With the increased proportion of lithium iron phosphate batteries, the cost of battery materials decreases by 5 billion CNY. This is mainly due to the cost advantage of LFP cathode materials, which do not contain the expensive metal elements unique to NCM cathode materials. In terms of resource input, labor and land inputs decrease by 9% and 14%, respectively, while water consumption increases by only 0.25%. Overall, the resource consumption pressure in Scenario 2 is reduced compared to Scenario 1, especially with a significant reduction in land use by 3.37 million square meters, indicating significant savings. In terms of environmental load, COD and NH_3-N pollutants decrease by 10.9% and 10.4%, respectively, in Scenario 2, maintaining synchronous reductions. While NOx emissions increase by 6%, SO_2 decreases by 23%, with the SO_2 reduction rate being 3.8 times the NOx increase rate. Among solid waste, general solid waste increases by 6%, while hazardous waste decreases by 20%, with the reduction rate of hazardous waste being 3.3 times the increase rate of general solid waste. It is evident that the overall environmental load in Scenario 2 is smaller than in Scenario 1, with all pollutants except NOx and general solid waste decreasing, and the decrease in pollutants being more substantial. The adjustment of product structure has brought about positive economic and environmental impacts. In terms of energy consumption and carbon emissions, the comprehensive energy consumption and CO_2 emissions in Scenario 2 increase by 1.8% and decrease by 1.4%, respectively.

This indicates that while total energy consumption increases, the energy system becomes more carbon-efficient. Although carbon emissions have decreased, compared to the improvement in environmental pollution, the carbon reduction effect brought about by the adjustment of product structure is very limited.

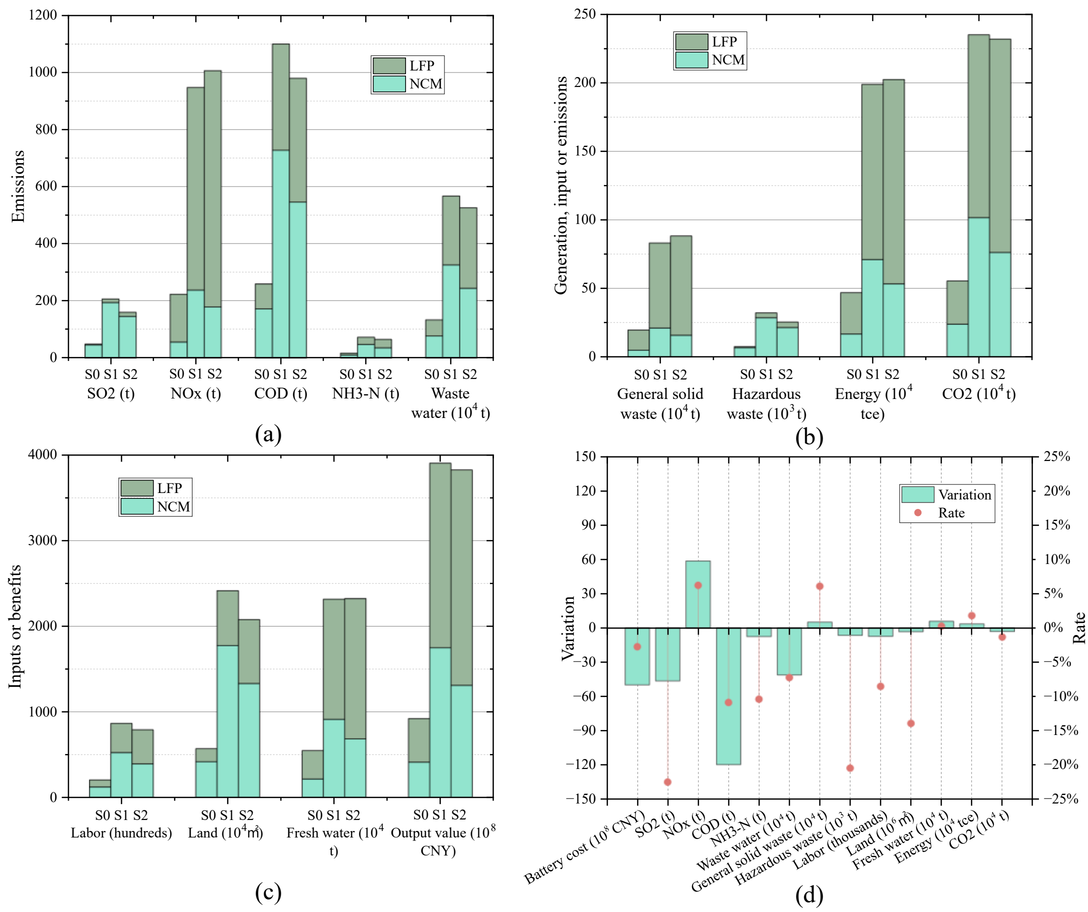

Figure 2: Economic and environmental impacts

3.2 Low-Carbon Emission Potential of Energy System Optimization for Power Battery Capacity Expansion

Analyzing three scenarios of product adjustment revealed that increasing the proportion of lithium iron phosphate batteries helps reduce carbon emissions, but the effect is minimal. The deeper issue of carbon emissions lies in the energy problem, specifically optimizing the energy structure and efficiency to achieve "decarbonization" of the energy system (Xiang and Xu, 2022). As the deadline for carbon peaking approaches, the demand for reducing carbon emissions becomes increasingly urgent. Therefore, this paper further explores effective measures to promote the low-carbon development of the power battery industry from the perspectives of energy structure and efficiency.

To explore the impact of different energy measures on carbon emissions, five scenarios are set in this section (see Table 3). Scenario A uses current energy parameters, with electricity accounting for 62% and 74% of the energy structure for NCM and LFP, respectively. Scenarios B and C are energy structure optimization scenarios. Following the "electrification of industrial energy use" direction in the "Carbon Peaking Implementation Plan in the Industrial Sector," the electricity proportions for NCM in Scenarios B and C are increased to 70% and 80%, respectively, and for LFP, to 80% and 90%, respectively. Scenario D focuses on energy efficiency improvement, based on the "Action Plan for Carbon Peaking by 2030" and the "Fourteenth Five-Year Plan for Energy Development in Sichuan Province." The energy efficiency optimization level is set according to industry standards or advanced values of similar projects. Scenario E combines structure and efficiency optimization, setting energy efficiency to the optimized level while increasing the proportions of electricity for NCM and LFP to 80% and 90%, respectively.

Table 3: Scenario setting (energy adjustment)

Scenario	**Optimization of energy structure (Increased share of electricity)**		**Energy efficiency improvement (Reduction of energy consumption)**	**Target year, output and product structure parameters**
	Electricity: Gas: Steam (NCM)	Electricity: Gas: Steam (LFP)	Comprehensive energy consumption per unit of product	
Scenario A	62:14:24	74:26:0	Status quo level	2030 305GWh NCM:LFP =3:7
Scenario B	70:10:20	80:20:0	Status quo level	
Scenario C	80:5:15	90:10:0	Status quo level	
Scenario D	63:14:23	78:22:0	Optimization level	
Scenario E	80:5:15	90:10:0	Optimization level	

The carbon emissions and carbon productivity under each scenario are shown in Figure 3. Overall, from Scenario A to Scenario E, the changes in carbon emissions and carbon productivity show similar trends. Under the structure-efficiency dual-control measures, the carbon reduction effect is optimal. Compared to the 2.32 million tons of CO_2 and 165,000 CNY/tCO_2 in Scenario A, the carbon emissions and carbon productivity in Scenario E are reduced to 1.85 million tons of CO_2 and increased to 207,000 CNY/tCO_2, respectively. This indicates the necessity of focusing on optimizing the energy use structure, promoting industrial electrification, introducing energy-saving technologies, and adopting multiple measures to promote low-carbon development in the industry. Compared to Scenario A, the carbon emissions in Scenarios B, C, D, and E decrease by 5.5%, 14%, 10%, and 20%, respectively, while carbon productivity increases by 6%, 16%, 11%, and 25%, respectively. The increase in carbon productivity surpasses the decrease in carbon emissions for all scenarios, indicating that considering economic benefits, the adjustments in energy structure and efficiency provide greater carbon reduction benefits.

In Scenario D, the carbon emissions and carbon productivity are 2.09 million tons of CO_2 and 18.3 million CNY per ton of CO_2, respectively. Positioned between Scenarios B and C, Scenario D's energy efficiency has reached an advanced level with existing technology. Although Scenario C exhibits a 10% increase in the proportion of electricity in its energy structure compared to Scenario B, there remains room for further optimization. If the proportion of electricity continues to rise, greater carbon reduction effects can be achieved. Additionally, enhancing energy efficiency somewhat alters the energy structure by increasing the proportion of electricity in the production process. Consequently, the results of Scenario D overlap with the effects of adjusting the energy structure. This suggests that, at the current technological level, optimizing the energy structure holds greater potential for short-term carbon emission reduction compared to enhancing energy efficiency.

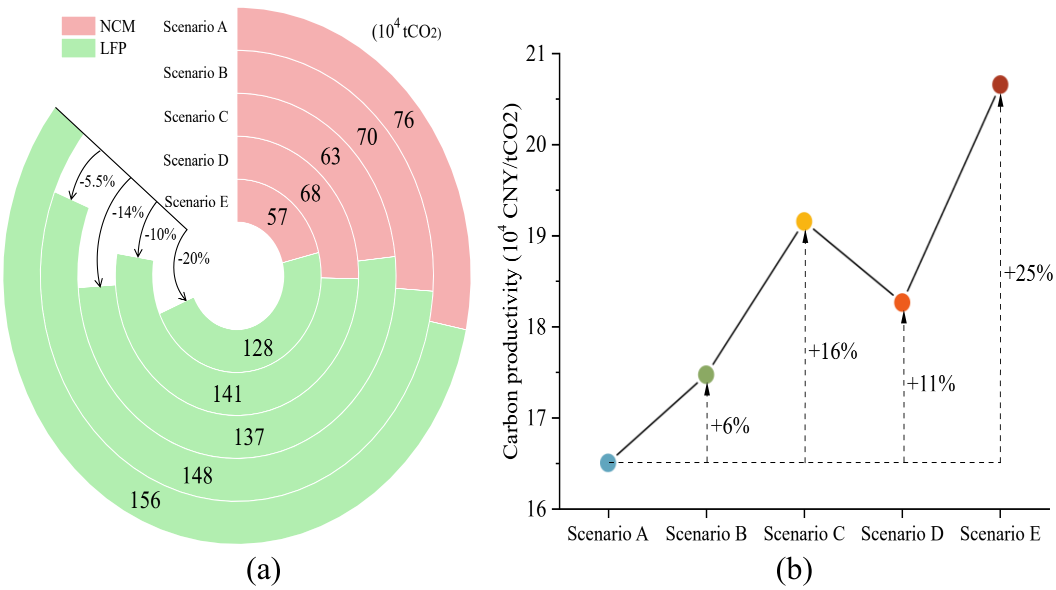

Figure 3: Carbon emissions (a) and carbon productivity (b) under five scenario

In the power battery industry, the proportion of electricity in the energy utilization structure exceeds 60%. Due to the relatively high consumption of new energy electricity in the Sichuan region, increasing the proportion of electricity results in reduced carbon emissions in Scenarios B and C compared to Scenario A. A higher proportion of new energy electricity is highly beneficial for local industries in achieving low-carbon emissions. When planning industrial layouts, it is essential to fully leverage regional advantages. For regions where electricity consumption is primarily dominated by thermal power generation, optimizing the energy structure should not blindly increase the proportion of electricity. Each region needs to tailor its approach based on local conditions, consider drawing insights from the energy transformation experiences of other regions, and promote the increase in the proportion of new energy generation.

3.3 Analysis of Decoupling Status in Various Scenarios

As depicted in Figure 4, both optimization of the energy structure and enhancement of energy efficiency promote the decoupled development between CO_2 emissions and the economy. Increasing the proportion of electricity reduces the decoupling index from 1.008 in Scenario A to 0.935 and 0.825 in Scenarios B and C, respectively, representing decreases of 7% and 18%. By adjusting the energy structure, electricity with a lower carbon emission factor substitutes for natural gas and steam with higher carbon emission factors, thus reducing carbon emissions while keeping total energy consumption constant, propelling the decoupled development of the industry. Improvements in energy efficiency lower Scenario D's decoupling index to 0.881, a 13% decrease from Scenario A. The decrease in overall energy consumption driven by a reduction in unit product comprehensive energy consumption results in reduced carbon emissions. While the decoupling indices in Scenarios B, C, and D have all decreased, they remain above 0.8, indicating that economic development and carbon emissions are still in a coupled growth state. This suggests that the growth in power battery production and the increase in industrial output still release a considerable amount of carbon emissions, and environmental pressure has not been adequately alleviated. Although adjusting either the energy structure or energy efficiency individually contributes to reducing the decoupling index, it is insufficient to improve decoupling status. Miao et al. (2023) simulated the decoupling status of economic growth and carbon emissions in Jiangsu Province from 2021 to 2035, and the results similarly indicated that improving energy efficiency and adjusting the energy structure promote decoupled development, but the effect of implementing a single emission reduction measure is relatively small.

In Scenario E, simultaneous optimization of the energy structure and efficiency lowers the decoupling index to 0.742, a 26% decrease compared to Scenario A. The decoupling index is less than 0.8 but higher than 0, indicating a positive association between output value and carbon emissions, the growth rate of carbon emissions gradually slows compared to the growth of output value. Under the structure-efficiency dual-control measures, not only does total energy consumption decrease, but the energy structure also becomes cleaner, shifting the decoupling status from coupled growth to weak decoupling. While structure-efficiency dual-control measures can achieve weak decoupled development of the industrial economy and the environment, relying solely on adjustments in energy structure and efficiency remains insufficient to achieve strong decoupled development of the economy and the environment. Even in Scenario E, with structure-efficiency dual-control measures, carbon emissions still significantly increase from 550,000 tons of CO_2 in 2022 to 1.85 million tons of CO_2 in 2030. Therefore, while pursuing carbon reduction through adjusting energy structure and efficiency, it is also necessary to adopt measures such as promoting the use of production processes with higher degrees of cleanliness, such as encouraging the use of waste heat recovery technologies, to further promote the low-carbon development of the industry.

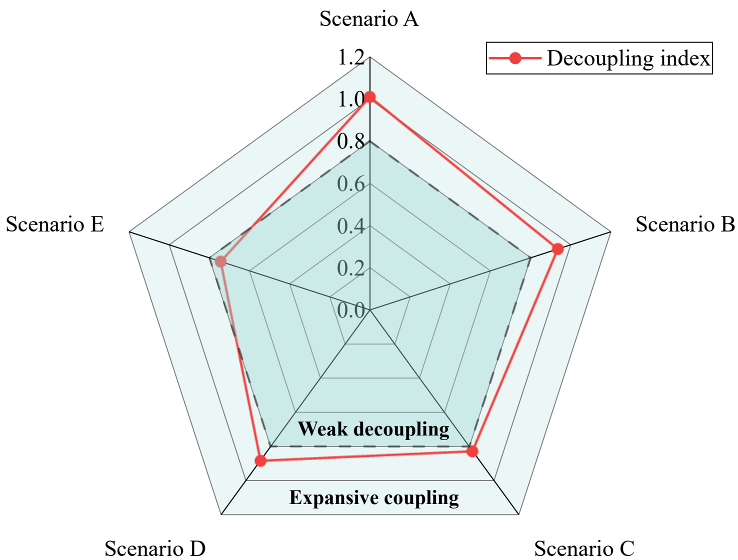

Figure 4: Decoupling index and decoupling status under five scenarios in 2030

4. Conclusion and Recommendations

Based on the development plans of major power battery manufacturers, the future of China's power battery industry will see rapid growth. Against the backdrop of China's entry into the stage of high-quality economic development and the goals of "carbon peak" and "carbon neutrality," it is of great significance to make advance predictions and assessments of the economic and environmental impacts brought about by the development of the power battery industry, to promote the industry's green and low-carbon development. In 2022, the sales of power batteries in Yibin City accounted for 15.5% of those in China, and its power battery industry is in a period of rapid development. Therefore, based on the future development plan of the power battery industry in Yibin City, this study has assessed the environmental burden during the development process of the power battery industry, and explored the path of low-carbon development of the power battery industry from the perspectives of product structure optimization, energy cleanness and efficiency enhancement, proposing effective measures to promote the decoupled development of the economic and environmental aspects of the industry.

The research findings indicate:

1. Under the scenario of product structure adjustment, the industrial output value by 2030 will increase to 415% of that in the baseline year, but it will also bring about synchronous growth in carbon emissions. The CO_2 emission reduction effect brought about by adjusting the product structure is extremely limited, but it can to a certain extent restrain the increase in SO_2, COD, NH_3-N, wastewater, and hazardous waste. The main pollutants will increase to 3.3-4.5 times that of the baseline year. By then, the existing pollutant treatment capacity will be difficult to meet the increased environmental burden.
2. During the simulation period, adjusting the energy system can achieve

significant carbon emission reduction effects, and in the short term, energy structure optimization has greater potential for carbon emission reduction than energy efficiency improvement.

3. Implementing measures to optimize energy structure and enhance energy efficiency can achieve weak decoupled development between the economy and carbon emissions, but it is difficult to achieve a state of strong decoupling.
4. Sichuan Province has a relatively high proportion of new energy electricity, and the abundant new energy electricity in the region also has a positive impact on the low-carbon capacity of the industry.

Based on the above findings, this paper puts forward corresponding policy suggestions:

1. In the process of rapid industrial development, various environmental pollutants inevitably increase. It is necessary to implement new requirements for ecological environment management, strengthen environmental supervision, conduct early environmental assessments, and ensure the construction of sufficient pollution treatment infrastructure based on the existing foundation to reduce environmental burdens while achieving economic benefits.
2. Greening energy is the foundation and source of carbon reduction in the power battery industry. Efforts should be made to optimize the energy structure, increase the proportion of electricity, and actively guide enterprises to transform energy through subsidies and other means. For example, in regions with abundant green electricity such as the southwestern region of China, consideration could be given to implementing preferential electricity pricing policies to encourage enterprises to increase the consumption of green electricity. The transformation of energy structure requires a certain economic and time cost, therefore, a reasonable buffer period should be set up to gradually promote the process of energy greening.
3. The rapid expansion of key industries inevitably leads to a substantial increase in carbon emissions under current conditions. In addition to adjusting product structures and optimizing energy systems, further efforts should be made to promote low-carbon development in industries from the perspective of improving production technology. For instance, encouraging the adoption of waste heat recovery technology can reduce total energy consumption without reducing output, thereby lowering carbon emissions.
4. High proportions of regional new energy can also help industries reduce carbon emissions. When planning industrial layouts, consideration should be given to favoring such regions to fully leverage their geographical advantages.

This study is committed to providing new research methods and ideas for achieving green and low-carbon development in rapidly growing industries. The research results are expected to provide reference for the sustainable development of the power battery industry and other similar rapidly expanding industries, and to provide scientific basis for local governments to formulate effective management policies.

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