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Economic Performance and Spatial Layout of China's Lithium Battery Industry in the Context of Energy Transition

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ABSTRACT
Aim. To investigate the evolution of the spatial structure and economic efficiency of China's lithium-ion battery industry against the backdrop of the global energy transition. **Methods.** The study employs value chain analysis to assess industrial linkages and Stochastic Frontier Analysis (SFA) to measure the technical efficiency of production across 30 Chinese provinces from 2015 to 2023. **Results.** Significant regional agglomeration is identified in East China (Yangtze River Delta); however, a structural imbalance exists between production capacity and resource utilization efficiency. The data indicate that mere scale expansion is no longer the primary driver of efficiency. **Conclusions.** To achieve sustainable development, the industry must shift from extensive growth to spatial layout optimization and technological upgrading, strengthening inter-regional coordination.
Keywords: energy transition, lithium-ion battery industry, spatial agglomeration, technical efficiency, Stochastic Frontier Analysis (SFA), regional disparity
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Экономическая эффективность и пространственная структура литий-ионной промышленности Китая в контексте энергетического перехода

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РЕФЕРАТ
Цель. Исследовать эволюцию пространственной структуры и эффективности литий-ионной промышленности Китая на фоне глобального энергетического перехода. **Методология.** В работе используется анализ цепочки создания стоимости для оценки промышленных связей и метод стохастической границы (SFA) для измерения технической эффективности производства в 30 провинциях Китая за период 2015–2023 гг. **Результаты.** Выявлена значительная региональная агломерация в Восточном Китае (дельта реки Янцзы), однако наблюдается структурный дисбаланс между мощностями производства и эффективностью использования ресурсов. Данные показывают, что простое расширение масштабов перестало быть драйвером эффективности. **Выводы.** Для устойчивого развития отрасли Китаю необходимо перейти от экстенсивного роста к оптимизации пространственного размещения и технологической модернизации, усилив межрегиональную координацию.
Ключевые слова: энергетический переход, литий-ионная аккумуляторная промышленность, пространственная агломерация, техническая эффективность, стохастический анализ границ эффективности (SFA), региональное неравенство

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Structural Evolution and Spatial Characteristics of China's Lithium Battery Industry

Industrial Scale Expansion and the "Energy-Economy" Efficiency Paradox

Based on the analysis of industrial panel data from 2015 to 2023, the development of China's lithium battery and electrical machinery manufacturing industry exhibits significant "nonlinear growth" characteristics. As shown in Figure 1, during the late "13th Five-Year Plan" period (2018–2020), affected by macro-deleveraging policies and the subsidy retreat, the total industrial revenue experienced a brief plateau, maintaining around 6.5 trillion RMB. However, since 2021, driven by the dual momentum of the global energy transition and the explosive demand for New Energy Vehicles (NEVs), the industry has entered a new cycle of robust growth. By 2023, the total industry revenue exceeded 10.09 trillion RMB (approximately 1.4 trillion USD), representing an increase of 50.7% compared to 2015[1].

However, this scale expansion is accompanied by increasingly severe resource and environmental constraints. The dual-axis curve in Figure 1 reveals a notable "efficiency paradox": although industrial technology continues to advance, the industry's *Energy Intensity (E/Y)* has not declined continuously as expected. Conversely, after reaching a low point (0.035 tons of standard coal per 10,000 RMB) in 2017, this indicator rebounded between 2018 and 2021, fluctuating at a high level of 0.052–0.056.

This phenomenon indicates that mere scale effects are no longer sufficient to automatically drive marginal efficiency improvements. The structural reasons for this may lie in:

Expansion of high-energy-consuming upstream segments: To secure supply chain safety, a large amount of production capacity for mineral processing and cathode material sintering — which are energy-intensive — has been released domestically.

Insufficient capacity utilization: Investment overheating in certain years led to structural overcapacity, diluting the economic output per unit of energy consumption.

This "high growth, high consumption" extensive model highlights the urgency of transitioning from "factor-driven" to "efficiency-driven" development.

"East Strong, West Advancing": Restructuring Characteristics of Spatial Layout

The geographical distribution of China's lithium battery industry is undergoing a profound adjustment from "coastal unipolar agglomeration" to "regional collaborative division of labor". By comparing the main business revenue data of various provinces in 2015 and 2023 (see Figure 2), the following spatial evolution patterns can be identified:

First, the absolute dominance of the Yangtze River Delta and the Greater Bay Area. Jiangsu Province and Guangdong Province, as the twin engines of China's manufacturing sector, firmly occupy the first tier of the industrial landscape. In 2023, the industrial revenue of Jiangsu and Guangdong reached 2.19 trillion RMB and 2.11 trillion RMB, respectively. Together, they account for over 42% of the national total[2]. This extremely high *Industrial Concentration Ratio (CR2)* indicates that mature supply chain matching and downstream terminal markets (NEV manufacturing bases) remain the core gravitational forces for industrial agglomeration.

Second, the rise of new industrial highlands and landscape reshaping. Compared with 2015, the top 10 rankings in 2023 have changed significantly:

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1 National Bureau of Statistics of China. China Statistical Yearbook 2023. Beijing: China Statistics Press, 2023 [Electronic resource]. URL: https://data.stats.gov.cn/ (accessed: 15.12.2015).

2 Calculated by the Author Using the Raw Data from the China Industry Statistical Yearbook (2016 and 2024 editions).

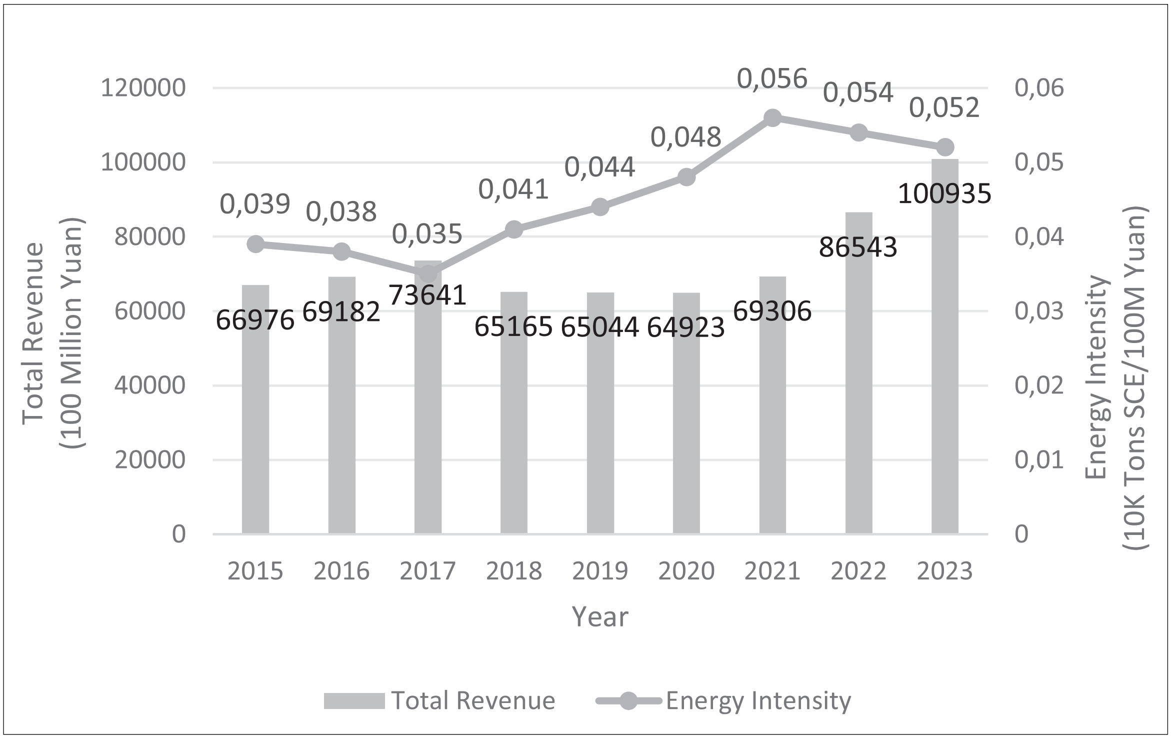


Fig. 1. Evolution of Industry Scale and Energy Efficiency (2015–2023)

Рис. 1. Эволюция промышленного производства и энергоэффективности (2015–2023 гг.)

Source: Calculated by the author based on data from the China Industry Statistical Yearbook and China Energy Statistical Yearbook[1]

Fujian Province, leveraging the "chain master" effect of leading enterprises like CATL, saw its revenue surge from 157.8 billion RMB to 480.1 billion RMB, an increase of over two-fold, establishing its hub status in global power battery manufacturing;

Sichuan Province has emerged abruptly, jumping from 14th place in 2015 to 9th place in 2023 (revenue of 311.0 billion RMB). This leap benefits from its abundant hydropower resources (low-carbon manufacturing advantage) and lithium resource reserves, attracting a significant influx of cathode material and battery manufacturing capacity. This represents a concrete manifestation of the "West-to-East Power Transmission" strategy at the industrial chain level.

In contrast, the share of some traditional industrial provinces (such as Shandong) has relatively shrunk, reflecting the accelerated transfer of the industry towards regions with technological advantages (Fujian) or cost advantages (Sichuan, Jiangxi).

Chapter Summary

In summary, China's lithium battery industry has formed a gradient layout of "Eastern R&D and High-end Manufacturing + Western Resources and Material Processing". However, while enjoying the industrial dividends, different regions face distinct challenges: the East faces the "ceiling" constraints of land and energy consumption quotas, while the West must be wary of the environmental externalities brought by undertaking high-energy-consuming capacity. This spatial imbalance and the structural contradiction in efficiency constitute the logical starting point for our empirical research using the Stochastic Frontier Analysis (SFA) model in the next chapter.

[1] Calculated based on: Department of Energy Statistics, National Bureau of Statistics. China Energy Statistical Yearbook (2016–2024). Beijing : China Statistics Press.

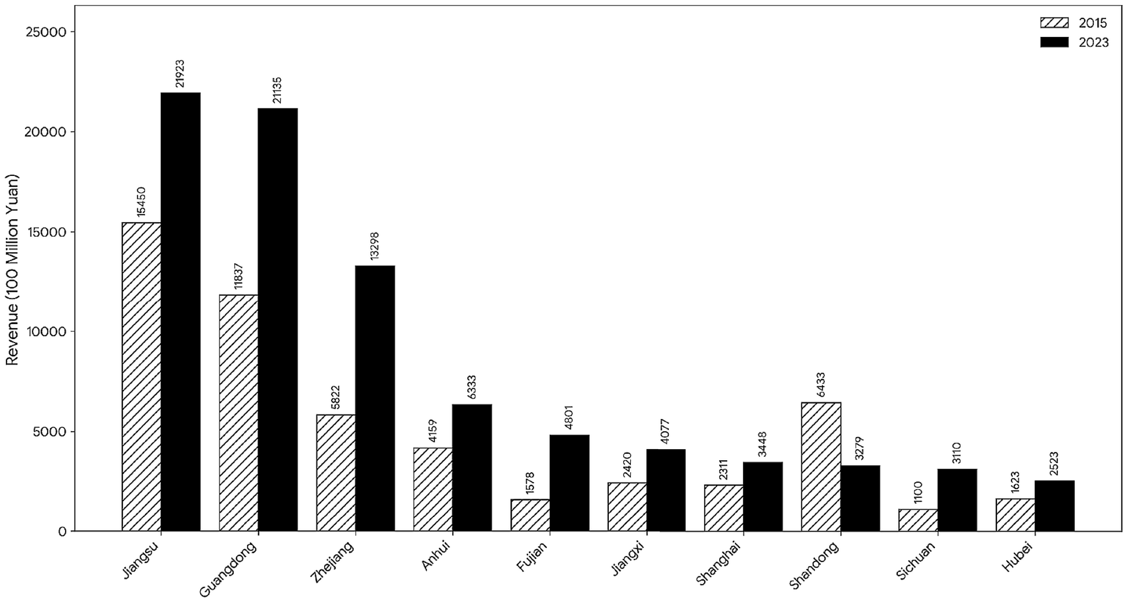


Fig. 2. Regional Revenue Comparison: Top 10 Provinces (2015 vs 2023)

Рис. 2. Сравнение региональных доходов: топ-10 провинций (данные 2015 и 2023 гг.)

Source: Calculated by the author based on panel data

Empirical Analysis

Model Specification and Variable Selection

To accurately measure the production efficiency of China's lithium battery industry and identify the sources of inefficiency, this study employs the Stochastic Frontier Analysis (SFA) method proposed by Aigner, Lovell, and Schmidt [1, p. 21]. Unlike traditional Data Envelopment Analysis (DEA), SFA allows for the decomposition of the error term into random noise (ν_{it}) and technical inefficiency (u_{it}) [6, p. 93], providing a more robust estimation in the presence of external shocks (e. g., policy shifts or raw material price volatility) [Ibid.].

We construct a log-linear Cobb-Douglas production function model as follows:

$$\ln(Y_{it}) = \beta_0 + \beta_K \ln(K_{it}) + \beta_L \ln(L_{it}) + \beta_E \ln(E_{it}) + \beta_{RD} \ln(RD_{it}) + \nu_{it} - u_{it},$$

where:

Y_{it} — Total industrial output value (proxy for industry scale);

K_{it}, L_{it}, E_{it} — Inputs of Capital (Net Fixed Assets), Labor (Year-end Employment), and Energy (Total Energy Consumption), respectively;

RD_{it} — Internal R&D expenditure, representing the technology factor;

u_{it} — The non-negative technical inefficiency term, which is assumed to be a function of external environmental variables: $u_{it} = \delta_0 + \delta_1 OPEN_{it} + \delta_2 ER_{it\ t} + \omega_{it}$;

$OPEN_{it}$ — Degree of openness (Ratio of total import/export to GDP);

ER_{it} — Environmental Regulation Intensity (Ratio of industrial pollution control investment to industrial value-added).

Estimation Results of the Production Frontier

The estimation results (Table 1) reveal the input-output characteristics of the industry. The model fits well (R^2 = 0,996), indicating that the selected input factors explain the vast majority of output variations.

Table 1

Stochastic Frontier Production Function Estimates

Таблица 1. Оценки стохастической границы производственной функции

Variable	Coefficient	Std. Error	t-Statistic	P-value	Significance
Constant	3.4398	0.0741	46.45	0	***
ln(K) — Capital	0.0397	0.0203	1.95	0.0517	*
ln(L) — Labor	0.1846	0.0155	11.93	0	***
ln(E) — Energy	0.7797	0.0158	49.33	0	***
ln(RD) — R&D	–0.0132	0.0091	–1.46	0.1457	—
*Note: ***, *, * indicate significance at the 1%, 5%, and 10% levels, respectively					

Source: Compiled by the author

The results present a striking structural feature: *Energy is the dominant driver*, with an output elasticity of *0.780*. This implies that for every 1% increase in energy consumption, industrial output increases by 0.78%. In contrast, the elasticity of Capital (0.040) is relatively low, and R&D shows a statistically insignificant negative coefficient (–0.013). This finding confirms the "Efficiency Paradox" raised in the previous section: China's lithium battery industry is still largely *"energy-factor driven"* rather than "innovation-driven". The insignificant R&D coefficient suggests a "Solow Paradox" in the sector — massive R&D investments have not yet translated into immediate productivity gains, likely due to the long gestation period of solid-state battery technologies and material science breakthroughs.

Determinants of Inefficiency

We further analyzed the factors affecting technical inefficiency (u_{it}). The results (Table 2) strongly support the positive role of external pressures.

Table 2

Determinants of Technical Inefficiency

Таблица 2. Детерминанты технической неэффективности

Variable	Coefficient	Std. Error	t-Statistic	P-value	Significance
Constant	0.3418	0.012	28.58	0	***
OPEN (Openness)	–0.0695	0.0283	–2.46	0.0145	**
ER (Env. Regulation)	–10.9577	2.5216	–4.35	0	***
Note: The dependent variable is the inefficiency term (u_{it}). A negative coefficient implies that the variable reduces inefficiency (i. e., improves efficiency)					

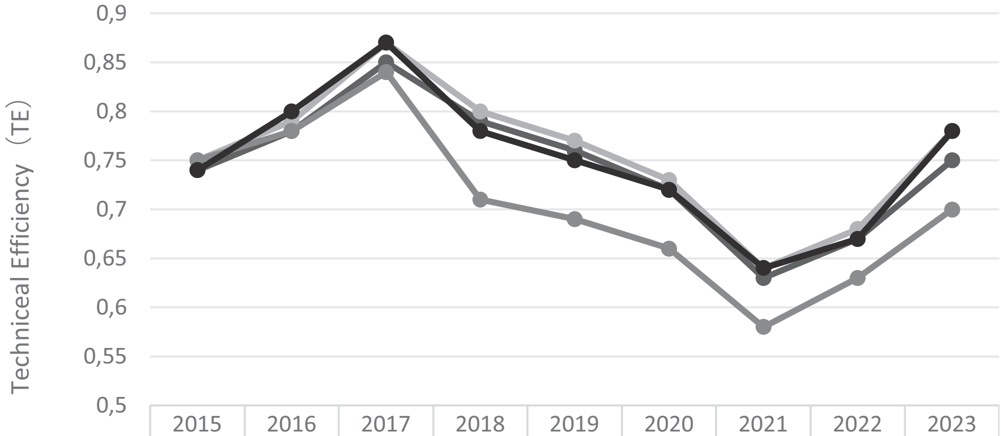
Source: Compiled by the author

Openness (OPEN): The negative coefficient (–0.070) indicates that higher exposure to international markets significantly reduces inefficiency. This validates the "learning by exporting" hypothesis, where Chinese firms improve management and technology standards to meet stringent global requirements (e. g., EU Battery Regulation).

Environmental Regulation (ER): The strongly negative coefficient (–10.96) provides empirical evidence for the **"Porter Hypothesis"** in China's lithium sector. Strict environmental regulations have not stifled the industry; instead, they have forced enterprises to innovate and optimize resource allocation, thereby improving overall technical efficiency.

Spatiotemporal Evolution of Efficiency

Based on the model, we calculated the Technical Efficiency (TE) scores for each province. Figure 3 illustrates the regional trends from 2015 to 2023.



	2015	2016	2017	2018	2019	2020	2021	2022	2023
Central	0,74	0,78	0,85	0,79	0,76	0,72	0,63	0,67	0,75
East	0,75	0,79	0,87	0,80	0,77	0,73	0,64	0,68	0,78
Northeast	0,75	0,78	0,84	0,71	0,69	0,66	0,58	0,63	0,70
West	0,74	0,80	0,87	0,78	0,75	0,72	0,64	0,67	0,78

Fig. 3. Evolution of Technical Efficiency by Region (2015–2023)

Рис. 3. Эволюция технической эффективности по регионам (2015–2023 гг.)

Source: Calculated by the author

Three distinct patterns emerge:

Western Catch-up: Surprisingly, the Western region (e. g., Sichuan, Qinghai) has achieved a high efficiency level (mean TE ~0.78 in 2023), matching the Eastern coastal region. This convergence is driven by the "West-to-East Calculation/Energy" strategy, where new, state-of-the-art mega-factories are directly built in resource-rich western provinces, bypassing the legacy inefficiencies of older industrial bases;

Eastern Stability: The Eastern region remains the efficiency benchmark, benefiting from mature industrial clusters and advanced management practices;

Northeast Lag: The Northeast region (0.70) continues to lag, highlighting the difficulty of transitioning old industrial bases to new energy economies.

Chapter Summary

The empirical evidence in this chapter reveals a "Dual-Track" reality. While the industry relies heavily on energy inputs (extensive growth), external forces like globalization and environmental regulation are effectively pushing the frontier outward (intensive improvement). The unexpected rise of Western China suggests that *optimizing spatial layout* — moving production to renewable-energy-rich regions — is a viable path to breaking the "Energy-Efficiency Paradox".

Conclusions and Policy Implications

Research Conclusions

This study empirically analyzed the spatial structure evolution and technical efficiency determinants of China's lithium battery industry from 2015 to 2023, utilizing Stochastic Frontier Analysis (SFA) on provincial panel data [4, p. 5; 8, p. 12]. The core findings are as follows:

Verification of the "Efficiency Paradox". Although China's lithium battery industry has achieved exponential growth in scale (revenue exceeded 10 trillion RMB in 2023), the energy intensity has not declined synchronously but rather fluctuated at a high level. Empirical results indicate that the industry is still dominated by "energy factor driving" (elasticity 0.780) rather than "innovation driving" (R&D coefficient is insignificant), revealing a "Solow Paradox" characteristic in the current technological transformation phase, *which is consistent with the findings of Chen et al* [3, p. 108] *regarding regional R&D efficiency.*

Validation of the "Porter Hypothesis" [9, p. 98]: Environmental Regulation (ER) has a significant negative correlation with inefficiency (–10.96), meaning strict environmental standards have effectively forced enterprises to improve resource allocation efficiency [10, p. 800]. Similarly, openness (OPEN) significantly promotes efficiency through the "learning by exporting" effect.

Spatial Rebalancing and "Westward Shift". The technical efficiency of the Western region (e. g., Sichuan, Qinghai) has rapidly converged with or even surpassed that of traditional Eastern industrial bases. This validates the effectiveness of the national strategy to layout battery manufacturing capacities near renewable energy sources (hydropower/lithium mines), forming a new pattern of "Western Manufacturing + Eastern Application" [5, p. 4295].

Policy Implications Based on the above conclusions, the following recommendations are proposed to promote the high-quality development of the industry in the context of the Eurasian energy transition:

First, optimize the spatial allocation of energy and capacity. Policymakers should further encourage the transfer of high-energy-consuming upstream links (such as cathode material sintering) to renewable-energy-rich regions in the West (Sichuan, Yunnan). Establishing "Zero-Carbon Battery Industrial Parks" in these regions can leverage green electricity advantages to break the ""energy-efficiency paradox" and meet the carbon footprint requirements of the EU Battery Regulation [2, p. 242].

Second, strengthen the "innovation consortium" mechanism. To address the insignificance of R&D efficiency, the government should shift subsidies from "production scale" to "technical breakthrough". Establishing cross-regional innovation consortiums involving leading enterprises (like CATL, BYD) and research institutes is crucial to overcoming bottlenecks in solid-state batteries and lithium recycling technologies [7, p. 79].

Third, persist in high-standard environmental opening-up. Given the positive effect of ER and Openness on efficiency, China should not relax environmental standards due to economic slowdown pressures. Instead, it should actively participate in the formulation of international battery standards (ISO/IEC) and align domestic regulations with global sustainability frameworks As Zhou et al. [11, p. 2] noted, consistent policy signals are vital for sustaining industrial competitiveness.

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