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Policy-Driven and Standardization Research on Quality Management in the New Energy Vehicle Battery Supply Chain: An Empirical Analysis Based on Policy Comparison among China, the EU, and the US

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Abstract. Under the impetus of global carbon neutrality goals, quality management in the new energy vehicle (NEV) battery supply chain has become a central focus of national policy agendas. This study systematically analyzes policy documents and industry data from China, the European Union, and the United States between 2015 and 2024, with emphasis on three aspects. First, regarding differences in policy instruments: China's mandatory coding and traceability system (GB/T34014) has reduced defect recall rates by 32%; the EU's market-oriented carbon footprint labeling scheme under the New Battery Regulation increased compliance costs by 15% but reduced accident rates by 28%; and U.S. state-level legislation (e.g., California's AB-2832) requiring ESG disclosure has influenced corporate quality practices. Second, concerning the dilemma of lagging standards: emerging technologies such as fast charging and solid-state batteries lack internationally unified standards, compelling firms to establish independent testing systems at a 40% higher cost (with CATL as a case example). Third, in terms of policy synergy and innovation: Guangdong Province's traceability platform enables cross-departmental sharing of full life-cycle battery data, raising the efficiency of dispute resolution by 60%. This study advances three recommendations: (1) establish a dynamic standards framework combining "basic national standards" with "technical consortium standards"; (2) implement a dual-carbon assessment system for battery supply chain quality; and (3) strengthen mutual recognition of China–EU policies. The findings provide theoretical support for constructing a global governance framework for battery quality.

Keywords: power battery, supply chain policy, quality standards, carbon footprint

1. Introduction

1.1. Research background

Driven by global carbon neutrality objectives, the NEV industry is experiencing explosive growth, while the quality management of power battery supply chains faces severe challenges. According to

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the U.S. National Highway Traffic Safety Administration, 42% of global vehicle recalls in 2023 stemmed from battery quality issues. Tesla alone recalled over 100,000 vehicles due to defects in its battery management system, incurring direct losses of several hundred million USD, thereby exposing deep-rooted weaknesses in the supply chain management system [1].

In response, governments have introduced targeted policies. China's Power Battery Coding and Traceability Management Measures (GB/T34014), implemented in 2021, enabled full life-cycle traceability, lowering battery defect recall rates by 32%. The EU's New Battery Regulation of 2023 adopted market-based instruments such as carbon footprint traceability to strengthen oversight. The two approaches show divergent outcomes: China's mandatory measures yield rapid short-term results, whereas the EU's market-oriented model fosters the development of a long-term quality ecosystem.

Nevertheless, two structural contradictions remain evident. First, emerging technologies such as fast charging and solid-state batteries have outpaced existing standards. The absence of unified testing protocols forces firms to independently develop systems, increasing costs by 40%, wasting resources, and introducing potential risks. Second, tensions between globalized supply chains and localized regulation are intensifying. International inconsistency in carbon footprint accounting and raw material traceability compels firms like CATL to incur an additional 15% in quality management costs to meet dual standards in its European factories.

Establishing a management system that aligns with industrial dynamics while safeguarding quality has become a major academic and policy challenge. This study undertakes a comparative analysis of China, the EU, and the US to identify optimization pathways, thereby contributing theoretical and policy insights for the sustainable development of the NEV industry under the carbon neutrality agenda.

1.2. Research questions

Against the backdrop of global carbon neutrality strategies and the rapid growth of the NEV industry, the quality management of power battery supply chains has emerged as a critical determinant of industry health. This study aims to systematically address three core questions:

1. Differentiated mechanisms of policy instruments: examining the administrative regulatory pathway of mandatory policies (e.g., China's GB/T34014), the price and consumer-choice mechanisms of market-oriented policies (e.g., the EU's New Battery Regulation), and the reputational incentive mechanisms of voluntary policies (e.g., California's ESG disclosure requirements), along with their disparities in effectiveness, compliance costs, and international compatibility. 2. Constraints of lagging standards on emerging technologies: assessing the inadequacies of current standards in testing methods, performance indicators, and safety requirements; the contradiction between standard-setting cycles and the pace of technological innovation; and the cost implications of cross-national standard disparities for globalized supply chains. 3. Pathways for policy synergy and optimization: exploring the construction of dynamic standards systems, complementary functions of policy tools, and the barriers and breakthroughs to international policy mutual recognition, thereby providing references for a global battery quality governance framework.

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2. Policy analysis framework

2.1. Theoretical foundations

This study adopts Howlett and Ramesh's policy instrument theory as its analytical framework. The theory classifies policy instruments into three categories: mandatory (e.g., China's coding and traceability system), market-based (e.g., the EU's carbon footprint labeling), and voluntary (e.g., corporate ESG disclosures), thus providing a theoretical foundation for cross-regional comparison among China, the EU, and the US. In addition, supply chain governance theory is introduced, with a focus on the "policy–behavior–performance" transmission mechanism, which posits that policy instruments influence quality behaviors through regulatory, market, and normative pathways, thereby producing differentiated outcomes. To this, new institutionalism is added to examine how institutional environments (e.g., the maturity of the EU carbon market) moderate the effectiveness of policy tools. Furthermore, the theory of standard lag provides a perspective for analyzing the temporal gap between technological innovation and institutional response, empirically testing the phenomenon of "institutional vacuum" in the battery sector (e.g., fast-charging technology standards lagging by 24 months). Collectively, these theories form the study's integrated analytical framework.

2.2. Analytical dimensions

Building on policy instrument theory and supply chain governance theory, this study develops a three-dimensional framework. Policy Instrument Type: Examining the administrative regulatory features of China's mandatory tools (e.g., GB/T34014), the economic incentive mechanisms of the EU's market-oriented tools (e.g., carbon footprint labels), and the normative self-regulatory role of the U.S. voluntary tools (e.g., California's ESG disclosure), as well as their differing degrees of constraint. Mechanism of Action: Analyzing the pathways through which different tools affect supply chain quality behaviors: mandatory tools constrain via regulatory enforcement, market-based tools guide through economic levers, and voluntary tools promote through normative influence. The differences in these pathways result in distinct governance effects. Effectiveness Evaluation: Constructing an evaluation system incorporating quality improvement, compliance costs, and institutional compatibility, thereby providing a scientific basis for comparing policy practices across China, the EU, and the US.

3. Differences in policy instrument effectiveness

3.1. Effects and limitations of China's mandatory tools

China primarily employs mandatory policy instruments in managing the quality of power battery supply chains, most notably the Power Battery Coding and Traceability Management Measures (GB/T34014) implemented in 2021. This policy established a life-cycle traceability system, obligating enterprises to register information across production, sales, usage, and disposal stages. Following implementation, defect recall rates dropped significantly by 32% (MIIT, 2023), reflecting the direct constraint of administrative oversight. However, the model also exhibits limitations: compliance costs for small and medium-sized enterprises (SMEs) rose on average by 25% (China Automotive Power Battery Innovation Alliance survey data), and the lack of policy flexibility has hampered rapid responses to technological innovations. For instance, one second-tier battery manufacturer withdrew from the low-end market due to excessive investment in traceability systems, suggesting that the policy may inadvertently increase market concentration [2].

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3.2. Incentive mechanisms of the EU's market-based tools

The European Union, through Regulation (EU) 2023/1542 (New Battery Regulation), has established a market-oriented governance framework. At its core is the mandatory carbon footprint labeling system, requiring enterprises to disclose full life-cycle environmental data. By leveraging consumer choice and market competitiveness, this mechanism exerts reverse pressure on quality improvements. For example, Sweden's Northvolt, with a product carbon footprint score below 45 $kgCO_2/kWh$, secured 70% of Volkswagen Group's new orders in 2023. The model has proven effective, reducing battery accident rates by 28% (EU Battery Alliance, 2024). Nevertheless, deficiencies remain: compliance costs for SMEs accounted for 3.2% of revenues, higher than the industry average, and in less-developed regions such as Eastern Europe, the policy's effectiveness was reduced by 40%, underscoring the sensitivity of market-based tools to institutional environments [3-4].

3.3. Differentiated practices of U.S. state-level legislation

In the United States, supply chain quality governance relies largely on state-level legislation with a voluntary-normative orientation. A representative case is California's AB-2832 (2022), which mandates ESG information disclosure, thereby establishing a voluntary system of supply chain quality reporting. This mechanism leverages market reputation and investor pressure to drive quality improvement. Following implementation, the supply chain transparency scores of NEV enterprises registered in California rose on average by 35% (California Environmental Protection Agency, 2023). However, decentralized governance has inherent drawbacks: variations in state legislation have increased corporate compliance costs by 18% (as illustrated by Tesla's cross-state operations), while the voluntary nature of the framework lacks sufficient coercive power. Only 62% of enterprises in the sector have participated (NREL Report, 2023), highlighting limitations in uniformity and coverage, particularly in the absence of unified federal legislation.

4. Policy causes of standard lag

4.1. Gaps in technology–standard compatibility

In the field of power batteries, a significant misalignment exists between technological innovation and the standards system. For fast-charging technology, key parameters such as the peak power duration of 800V high-voltage platforms and instantaneous thermal rise control lack unified testing standards, resulting in divergent testing practices among firms (e.g., Tesla applies a 10-minute continuous test, while BYD adopts a 15-minute cyclic test).

In solid-state batteries, safety assessment standards for interfacial impedance and lithium dendrite suppression have yet to be established, extending the average commercialization cycle by 11 months (Benchmark Minerals, 2023). Industry data show that lagging standards increase R&D costs by 35–40%, with 25% attributable to repetitive testing (China Automotive Power Battery Innovation Alliance survey). A leading enterprise, in order to comply with divergent standards in China, Europe, and the U.S., had to maintain three parallel certification systems, with a single product certification costing as much as USD 3.2 million (CATL annual report). This underscores how the standards system constrains technological innovation.

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4.2. Deficiencies in the standard-setting mechanism

The current standard-setting process suffers from systemic delays, with cycles mismatched to the pace of technological iteration. Empirical evidence shows that the average development cycle of group standards for power batteries in China is 14 months, while revisions to EU CE certification average 22 months (IEA, 2023)—both far longer than the nine-month technology iteration cycle.

These delays arise from three deficiencies: (1) insufficient professional capacity of standard-setting bodies, with participating enterprises accounting for only 32% of the industry (China Automotive Technology and Research Center survey); (2) difficulty in reconciling interests, as illustrated by disputes over China–EU carbon footprint accounting that delayed standards by 18 months; and (3) rigid updating procedures requiring six layers of approval. Consequently, 40% of new technologies face a “standards vacuum period” (Tsinghua University Research Report, 2023), thereby constraining industrial innovation.

4.3. International competition in standards

The global power battery standards system exhibits regionalized competition, where technical standards and market influence reinforce each other. CATL’s standards, supported by the scale of China’s domestic market, have achieved a 58% adoption rate in Southeast Asia (GG Lithium, 2023), emphasizing life-cycle traceability and cascade utilization norms. Japan’s JIS standards hold a 39% share in the same region, offering technical advantages in safety standards such as thermal runaway protection. The EU’s ECE R100 standard, by embedding carbon footprint accounting, has created technical barriers that raised export certification costs for Asian battery firms by 22% in 2023 (EU Battery Alliance data). Essentially, standard competition is a struggle for industrial dominance. South Korean firms, to comply with both Chinese and U.S. standards, raised R&D investment to 6.8% of revenue (LG Energy Solution annual report), highlighting the negative impacts of fragmented international standards on global supply chain efficiency [5].

5. Practical pathways for policy synergy and optimization

5.1. Building a dynamic standards system

To address the contradiction between rapid technological iteration and lagging standards, this study proposes constructing a dual-layer dynamic standards system of “basic national standards + consortium standards.” National standards would focus on core indicators such as safety and environmental protection, remaining relatively stable (revision cycles ≤ 24 months). Consortium standards, in contrast, would establish rapid-response mechanisms for emerging technologies such as fast-charging and solid-state batteries, with formulation cycles compressed to 6–8 months (drawing on pilot experience from the China Automotive Power Battery Innovation Alliance) [6].

This system would operate through a “trigger–response” mechanism, whereby standard-setting is automatically initiated once a new technology achieves a 15% market penetration rate (MIIT’s New Energy Vehicle Industry Development Plan, revision proposals, 2023). In practice, Guangdong Province’s consortium standards platform has adopted this model, raising the efficiency of standardization for new technologies by 40% and shortening the commercialization cycle of R&D outcomes to nine months (Guangdong Provincial Department of Industry and Information Technology report). This model safeguards baseline quality while preserving flexibility for technological innovation.

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5.2. Synergy between quality and environmental policies

This study proposes integrating supply chain quality indicators into the "dual-carbon" assessment framework as a means of policy coordination. For example, Shanghai's Measures for the Green Development Evaluation of the New Energy Vehicle Battery Supply Chain (2023) innovatively linked quality metrics such as defect rates and raw material traceability with carbon emission data to form a composite scoring system [7].

Data show that 21 pilot enterprises reduced average quality costs by 18% while achieving a 23% increase in carbon emission reductions (Shanghai Municipal Bureau of Ecology and Environment report, 2024). This mechanism operates through three pathways: (1) quality traceability data support carbon accounting (CATL thereby raised carbon data accuracy to 95%); (2) environmental requirements drove process improvements (one firm optimized its drying process, raising the compliance rate for battery moisture levels from 92% to 98%); and (3) unified assessments lowered compliance costs by about 30%, offering new solutions to the problem of fragmented policy implementation.

5.3. International policy mutual recognition

Promoting international policy mutual recognition is key to overcoming the fragmented governance of the battery supply chain. Based on China–EU practice, this study proposes a phased approach: initially establish equivalence in carbon footprint accounting methods (expected to reduce trade costs by 15%), and subsequently advance reciprocal recognition of core safety standards.

A 2023 Sino–German pilot project on battery passport data sharing demonstrated that blockchain-enabled data interoperability shortened bilateral customs clearance times by 40% and reduced quality disputes by 25% (General Administration of Customs of China data). However, three challenges remain: (1) disputes over data sovereignty (with the EU insisting on localized storage); (2) methodological divergences in testing (China emphasizes cycle life, while the EU stresses low-temperature performance); and (3) allocation of regulatory authority (between U.S. federal and state governments). The study recommends relying on multilateral platforms such as the IEA and initiating regional pilots in ASEAN as a stepping stone toward building a globally recognized framework.

6. Conclusion and recommendations

6.1. Main findings

Through a systematic comparison of policy practices in China, the EU, and the United States, this study arrives at the following core conclusions:

Effectiveness of policy instruments: The three governance models differ significantly. China's command-and-control approach delivers remarkable short-term results (12–18 months), reducing defect recall rates by 32%. However, compliance costs increased by 25%, imposing heavier burdens on SMEs. The EU's market-oriented governance progressed more slowly at the outset but proved highly sustainable, with accident rates declining 28% after two years of implementation, thus contributing to the development of a long-term quality ecosystem. In the U.S., voluntary and normative governance showed strong regional variation: in California, supply chain transparency rose by 35%, yet nationwide participation reached only 62%, exposing its inherent limitations.

Impact of standard lag on technological innovation: Current standard-setting cycles (14 months in China; 22 months in the EU) are far longer than the nine-month technology iteration cycle. As a result, 40% of new technologies face a "standards vacuum period," increasing R&D costs by 35–40% and extending product commercialization timelines by more than 11 months. Meanwhile, intensifying international competition in standards has raised certification costs for Asian firms to as much as USD 3.2 million per single product.

Effectiveness of policy synergy pilots: Coordinated governance experiments have achieved notable results. The Guangdong traceability platform demonstrated that data sharing increased the efficiency of resolving quality disputes by 60%. Shanghai's dual evaluation pilot, combining quality and environmental criteria, enabled participating firms to reduce quality costs by 18% and increase carbon emission reductions by 23%, offering valuable lessons for improving governance systems.

6.2. Policy recommendations

Based on these findings, this study proposes the following policy optimization measures:

Firstly, establish a dynamic standards-setting mechanism: Construct a dual-layer framework of "basic national standards + consortium standards." The revision cycle for basic standards should be kept within 24 months. For emerging technologies such as fast-charging and solid-state batteries, a "trigger-based" mechanism should be applied, whereby consortium standards are automatically initiated once market penetration reaches 15%. Drawing on Guangdong's experience, digital platforms can compress the formulation cycle of consortium standards to 6–8 months, reducing firms' standardization costs by 40%.

Secondly, advance coordination between quality and environmental policies: Scale up the Shanghai pilot nationwide by integrating quality indicators—such as defect rates (<0.5%) and raw material traceability completeness (>95%)—into the dual-carbon assessment framework. This approach could lower firms' overall compliance costs by 30% while improving carbon reduction efficiency by 23% [8].

Thirdly, strengthen international policy alignment and mutual recognition: Priority should be given to establishing mutual recognition mechanisms between China and the EU in areas such as carbon footprint accounting and safety testing, potentially reducing trade barrier costs by 28%. Leveraging international cooperation platforms, blockchain technology can be employed to ensure secure sharing of core data, with the scope of mutual recognition expanded in reference to the Sino–German battery passport pilot.

Last, improve the policy implementation support system: Measures include establishing a Power Battery Standards Expert Committee (with enterprise representatives accounting for no less than 40%), creating dedicated funds to subsidize up to 30% of SMEs' compliance costs, and developing policy impact pre-evaluation tools with reports released semi-annually.

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