

Article | Received 27 May 2026; Revised 17 June 2026; Accepted 21 June 2026; Published 17 September 2026
<https://doi.org/10.55092/phess20260014>

Synergistic development of intelligent digital transformation and green governance in China's lithium battery industry: challenges and strategies

Jiehui Yuan^{1,2*}, Wenli Yuan² and Fuying Lan^{1,2}

¹ Center for Western Jiangxi Regional Economic and Social Development, Yichun University, Yichun, China

² Institute of Energy & Resource, Environment and Carbon Neutrality, Yichun University, Yichun, China

* Correspondence author; E-mail: yuanjh_2015@tsinghua.org.cn.

Abstract: China's lithium battery new energy industry is at a critical juncture of transitioning from scale expansion to high-quality development. The synergistic effect between digital-intelligent transformation and green governance is increasingly becoming a core proposition for industrial competitiveness reconstruction. This paper constructs a four-dimensional synergy analytical framework consisting of institutional supply, technological empowerment, industrial ecosystem, and international rules, and applies it to systematically examine the current progress and prominent challenges. The study finds that while China's lithium battery industry has made significant strides in policy system construction, digital-intelligent technology application, and industrial chain collaborative governance, it still faces challenges including an imperfect carbon footprint accounting system, data silos and industrial chain synergy fragmentation, uneven digitalization levels in power battery recycling systems, and green trade barriers that compel governance upgrades. This paper emphasizes that the synergy between digital-intelligent transformation and green governance is a multi-dimensional coupling process involving institutional design, technological application, industrial ecosystems, and international rules—four interdependent and indispensable components. Accordingly, this paper proposes countermeasures including improving institutional supply and standard systems, accelerating deep application and integrated innovation of digital-intelligent technologies, building a full-industry-chain collaborative governance ecosystem, and actively participating in international rule-making and standard mutual recognition, aiming to provide theoretical references and practical insights for the high-quality development of the lithium battery industry.

Keywords: lithium-based new energy industry; intelligent digital transformation; green governance; synergistic development; synergy framework



Copyright©2026 by the authors. Published by ELSP. This work is licensed under Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium provided the original work is properly cited.

1. Introduction

Driven by the dual forces of global energy transition and China's dual carbon goals of carbon peaking and carbon neutrality, China's lithium battery new energy industry has achieved leapfrog development. From upstream mineral resource development to midstream battery manufacturing, and downstream to new energy vehicle applications and recycling, China has built the world's most complete lithium battery industrial chain [1]. Simultaneously, the industry faces unprecedented governance challenges: resource and environmental pressures from rapid capacity expansion, carbon footprint compliance requirements in international trade, and large-scale decommissioning of power batteries—all of which demand higher governance capabilities [2].

Digital-intelligent transformation—the deep integration of next-generation digital technologies such as big data, artificial intelligence (AI), the Internet of Things (IoT), industrial internet, and blockchain with industry—provides new technological pathways to address these governance challenges. In 2025, China's Ministry of Industry and Information Technology (MIIT) and two other departments jointly issued the Implementation Plan for Digital Transformation of the Electronic Information Manufacturing Industry [3]. The plan explicitly calls for accelerating the application of digital-intelligent technologies—such as advanced computing, industrial internet, IoT, and AI—in the R&D and manufacturing processes of lithium batteries and photovoltaic products, and for cultivating integrated industries featuring digital-green synergy. This policy direction reveals a critical proposition: digitalization is not merely a tool for improving production efficiency but also a crucial means for achieving green governance; the synergy between the two constitutes the core driver of high-quality development in the lithium battery industry [4].

However, both in theoretical research and practical implementation, the synergy between digitalization and green governance remains an underexplored issue. How can digital technologies genuinely empower green governance? How can all industry stakeholders optimize governance effectiveness through collaboration? These questions urgently require theoretical responses and practical exploration.

1.1. Literature review

In recent years, academic research on digital-intelligent transformation and green governance in the lithium battery industry has gradually increased, forming several notable scholarly trajectories. Research on industrial digital-intelligent transformation has explored pathways for multi-stakeholder collaboration in promoting digital transformation of the lithium battery industry based on the quadruple helix model, identifying mechanism fragmentation and data silos in current digital transformation efforts in some regions [5]. Other studies have focused on constructing digital-intelligent ecosystem models for the lithium battery industry chain, examining pathways for collaborative innovation under high-quality development [6]. International research has systematically revealed the complex trade-offs between economic efficiency and regional equity in the global lithium battery supply chain decarbonization process [7], while emerging studies have proposed blockchain-enabled frameworks for tracking and sourcing eco-friendly materials across the lithium supply chain [8]. These studies provide important foundations for understanding the driving mechanisms and barriers to digital-intelligent transformation

but predominantly focus on the technological application level, with limited attention to the intrinsic connection between transformation and governance.

Research on green governance and carbon footprint management has examined topics such as lithium battery carbon footprint accounting methodologies and life cycle environmental impact assessment [9]. In November 2025, the China Electronics Standardization Institute, in collaboration with over one hundred institutions including Tsinghua University, released version 3.0 of the Lithium Battery Carbon Footprint Background Database [10]. On June 17, 2026 (National Low-Carbon Day), China's first key industrial product carbon footprint database was officially launched, aggregating over 100,000 real-scenario data records from nearly a decade of domestic industrial carbon footprints, compiling over 1600 benchmark values for 300+ industrial products across 27 key industries including photovoltaics, lithium batteries, and non-ferrous metals [11]. Some scholars have examined the coupling development pathways between new energy storage industries and digitalization from a carbon neutrality perspective [12]. Comprehensive life cycle assessments comparing lithium-ion and secondary batteries have further enriched the methodological toolkit for environmental impact evaluation [13]. However, these studies largely remain at the technical methodology level, lacking systematic analysis of how green governance can form institutional synergies with digital-intelligent transformation.

Research on digital-green synergistic development at the macro level has embedded synergy theory and dissipative structure theory into economic frameworks, elucidating the theoretical logic, typical models, and implementation pathways of digital-green synergistic development [4]. Other studies have explored the theoretical logic of AI-empowered synergistic advancement of carbon reduction, pollution control, green expansion, and economic growth [14]. Research on digital battery passports has proliferated recently, with scholars conceptualizing their role in enabling circular and sustainable value chains [15], identifying stakeholder requirements for sustainability and circularity [16], and proposing technical architectures using composable NFTs and blockchain [14]. These studies provide theoretical resources for understanding digital-green synergy mechanisms at both macro and micro levels [17].

Research on power battery recycling and life cycle management has become a hotspot with the arrival of the era of large-scale decommissioned power batteries, focusing on digital management of recycling systems [18]. The quest for more circular battery value chains through the implementation of EU digital battery passports, along with the remaining challenges, has been critically examined [19]. On April 1, 2026, the Measures for the Management of Recycling and Comprehensive Utilization of Waste Power Batteries from New Energy Vehicles officially came into effect, establishing a national power battery traceability information platform and a digital identity card management system [20]. These institutional innovations provide new policy contexts for academic research. Blockchain technology has been proposed as an enabler for sustainable Li-ion battery supply chains [8], and IoT-holographic twin integration has shown promise in advancing sustainable synthesis from spent batteries [13].

Existing studies have achieved valuable results in their respective dimensions, but three limitations remain. One limitation is that research perspectives are relatively fragmented, with digital transformation, green governance, and international regulation often discussed separately, lacking an integrated analytical framework capable of encompassing these dimensions. Another is that the mechanisms of synergy are not sufficiently revealed, and the bidirectional interactive logic of how digitalization “empowers” green governance and how green governance “drives” digitalization has not

been fully articulated. A third limitation is that systematic research specifically targeting the lithium battery industry is scarce, with most studies remaining at the level of general discussion. These gaps constitute the academic contribution of this paper.

1.2. Four-dimensional synergy analytical framework

As identified in the literature review, existing studies have largely examined digital transformation, green governance, and international regulation along separate tracks, leaving a gap in integrated analytical frameworks capable of capturing their interdependencies. To address this gap, this paper constructs a four-dimensional synergy analytical framework comprising institutional supply, technological empowerment, industrial ecosystem, and international rules—to systematically examine the synergistic development of digitalization and green governance in the lithium battery industry, as illustrated in Figure 1. The selection of these four dimensions reflects the recognition that effective synergy requires not only technological capabilities but also clear institutional rules, coordinated industrial action, and strategic engagement with global regulatory regimes.

Dimension 1: Institutional Supply. Institutions are the foundational guarantee for synergy. Effective governance requires the coordination of legal frameworks and standards. Policy regulations, standard systems, and regulatory rules provide the legitimacy foundation and action boundaries for digital-green synergy. The comprehensiveness of institutional supply determines the ceiling of synergy [20,21].

Dimension 2: Technological Empowerment. Technology is the core driver of synergy. Digital-intelligent technologies—AI, big data, blockchain, and industrial internet—constitute the foundational capability base for empowering green governance. The depth and breadth of technological empowerment determine the size of the synergy toolbox [8,17].

Dimension 3: Industrial Ecosystem. Industry is the practical field for synergy. The lithium battery industry chain is lengthy, multi-linked, and actor-dispersed; the realization of collaborative governance depends on data integration, shared responsibility, and benefit sharing across all industrial chain links. The maturity of the industrial ecosystem determines the implementation capacity of synergy [6].

Dimension 4: International Rules. International rules represent both external constraints and opportunity windows for synergy. The EU's New Battery Regulation and other international green trade rules are reshaping the global lithium battery industry's competitive landscape, constituting both compliance pressures and drivers for domestic governance system upgrading [22,23]. The evolutionary direction of international rules determines the strategic depth of synergy [15,24].

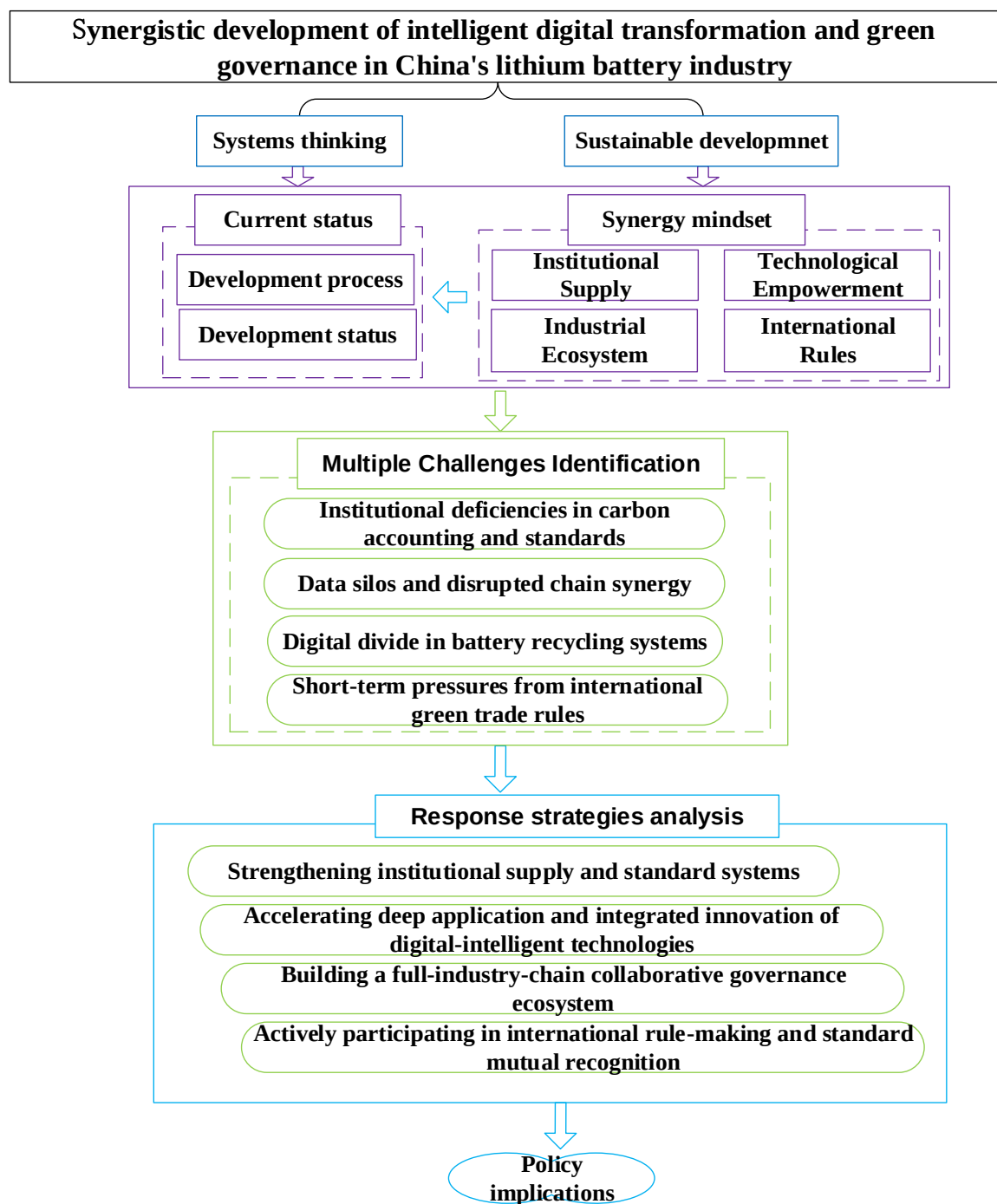


Figure 1. A framework for synergistic development of intelligent digital transformation and green governance in China’s lithium battery industry. (Source: the figure is drawn by the author).

These four dimensions are not isolated but constitute an interdependent, dynamically evolving organic whole: institutional supply defines the direction and boundaries for technological empowerment; technological empowerment provides means for digital governance of the industrial ecosystem; practical feedback from the industrial ecosystem drives iterative optimization of institutional supply; and international rules exert external driving forces that propel the upgrading of the first three dimensions [15,19]. The degree of coupling among these four dimensions determines the overall effectiveness of digital-green synergistic development in the lithium battery industry.

2. Current progress of digital-green synergistic development of China's lithium battery industry

2.1. Gradual improvement of institutional supply

Over the past years, China's policy framework for the lithium battery industry has undergone a notable evolution — from fragmented sector-specific guidelines toward a more integrated and systematic architecture, driven by the dual carbon goals, rapid NEV market expansion, and mounting international carbon regulations. This evolution reflects a growing recognition that digital empowerment and green governance are mutually reinforcing pillars of industrial competitiveness. Accordingly, policy intervention has expanded from conventional concerns of production efficiency to emerging issues such as life-cycle carbon accounting, full-chain digital traceability, battery passport systems, and cross-border data governance. Table 1 summarizes the key policy documents across the three interrelated realms of digital-intelligent transformation, green governance and recycling, and carbon footprint management, covering the period from 2021 to 2026.

Realm	Policy Document	Year Issuing Authority
Digital-intelligent transformation	Lithium-ion battery industry standardization system construction guide (2023 Edition)	2023 MIIT
	Implementation plan for digital transformation of the electronic information manufacturing industry	2025 MIIT <i>et al.</i>
	Reference guidelines for scenario-based and graph-based promotion of digital transformation in key industries (2025 Edition)	2025 MIIT
Green governance & recycling	Measures for the echelon utilization of power batteries from new energy vehicles	2021 MIIT <i>et al.</i>
	Notice on ensuring the coordinated and stable development of the lithium-ion battery industry chain and supply chain	2022 MIIT, SAMR
	Standard conditions for comprehensive utilization of waste power batteries from new energy vehicles (2024 Edition)	2024 MIIT
	Action plan for improving the recycling system for power batteries of new energy vehicles	2025 State Council
Carbon footprint management	Opinions on accelerating the establishment of product carbon footprint management systems	2023 NDRC <i>et al.</i>
	Lithium battery carbon footprint background database version 3.0	2025 China Electronics Standardization Institute
	China's first key industrial product carbon footprint database	2026 China Academy of Industrial Internet

Table 1. Major policies supporting digital-green synergy in China's lithium battery industry (2021–2026). (Source: compiled by the author)

In the realm of digital-intelligent transformation, in May 2025, MIIT, the National Development and Reform Commission (NDRC), and the National Data Administration jointly issued the Implementation Plan for Digital Transformation of the Electronic Information Manufacturing Industry [3], proposing to raise the key process numerical control rate of electronic information manufacturing enterprises above designated size to over 85% by 2027. The plan explicitly requires building trusted data spaces for life-cycle carbon emissions of key products and promoting enterprises to build carbon footprint foundational data platforms and life-cycle digital carbon management platforms. It also aims to cultivate and promote solutions such as intelligent process analysis, cooling circulation system monitoring, and full-chain product quality traceability for

lithium batteries and new energy storage sub-sectors. MIIT also issued the Reference Guidelines for Scenario-Based and Graph-Based Promotion of Digital Transformation in Key Industries (2025 Edition), advancing lithium battery industry digital transformation through a one-diagram, four-lists approach [25].

In the realm of green governance, in 2025, China's State Council executive meeting approved the Action Plan for Improving the Recycling System for Power Batteries of New Energy Vehicles [26]. On December 31, 2025, MIIT and five other departments jointly issued the Measures for the Management of Recycling and Comprehensive Utilization of Waste Power Batteries from New Energy Vehicles, effective April 1, 2026 [20]. The Measures emphasize full-channel, full-chain, full-life-cycle characteristics, establishing a national power battery traceability information platform to monitor and enable informational traceability across the entire life cycle—production, sales, maintenance, replacement, disassembly, recycling, and comprehensive utilization. This marks the institutionalization of one-battery-one-code full-process traceability as an industry legal requirement.

In the realm of carbon footprint management, on June 17, 2026, China's first key industrial product carbon footprint database was officially launched. Built under the leadership of the China Academy of Industrial Internet, the database aggregates over 100,000 real-scenario data records from nearly a decade of domestic industrial carbon footprints, compiling over 1600 benchmark values for more than 300 industrial products across 27 key industries including photovoltaics, lithium batteries, and non-ferrous metals [11]. The database employs a three-tier "industry–region–enterprise" architecture, providing enterprises and certification bodies with one-stop public-interest services from data verification and compliance certification to automated carbon footprint report generation.

2.2. Technology-enabled acceleration of integration

Under the deep empowerment of digital-intelligent technologies, green governance in the lithium battery industry is transitioning from experience-driven to data-driven. Breakthroughs in digitalization of carbon footprint management have been achieved. In November 2025, the China Electronics Standardization Institute, jointly with over one hundred institutions including Tsinghua University and Kunming University of Science and Technology, released version 3.0 of the Lithium Battery Carbon Footprint Background Database [10]. This version, incorporating AI large-model technology, provides more detailed characterization of material flows, energy flows, and pollution streams across the entire lithium battery industry chain. Key capabilities achieved comprehensive upgrades: total data entries increased by 50% to over 1,200; the data covers 28 major production locations across China's lithium battery industry chain, encompassing 98% of material types and 99.5% of total life-cycle carbon emissions; data quality ratings of "excellent" or above exceeded 92%, with post-2020 data accounting for over 92% [10]. Leveraging the "Lithium Battery Industry Standardization Management and Traceability Public Service Platform," the project team simultaneously developed a carbon footprint accounting service platform that has provided carbon footprint accounting and certification services for over 100 lithium battery products from more than 30 enterprises. The 2026 launch of the key industrial product carbon footprint database extended this capability from the lithium battery industry to 27 key industries [11].

Significant results have been achieved in intelligent and green manufacturing integration. In March 2022, CATL's Sichuan Times received the global battery industry's first PAS2060 carbon neutrality

certification, becoming the world's first battery zero-carbon factory [27]. From its initial planning, Sichuan Times simultaneously initiated the planning and construction of photovoltaics, energy storage, and green electricity. The entire plant is powered by hydroelectricity and features self-developed waste heat recovery heat pump technology. 4IR technologies are deeply applied throughout lithium battery manufacturing: AI central control systems precisely manage coating accuracy, CFMS systems optimize carbon neutrality through smart operations, and 5G with autonomous driving technology reshapes internal logistics. Subsequently, Sichuan Times led eight supply chain enterprises in Sichuan to achieve carbon neutrality, building a zero-carbon industrial cluster [27].

In January 2026, EVE Energy's Jingmen Base Plant 13, integrating multiple cutting-edge technologies with cylindrical battery manufacturing through over 40 digital-intelligent solutions, became the world's first cylindrical battery Lighthouse Factory. The Lighthouse Factory achieves 100% automation in key production processes, with a single production line reaching an efficient capacity of 300 cells per minute [2]. By deploying an AI energy-efficiency optimal curve model for real-time diagnosis and dynamic optimization of core energy systems such as air conditioning and air compression, system energy consumption was reduced by 5% to 10%. From 2022 to 2025, production-end unit carbon emissions decreased by over 60% and unit product energy consumption by over 55%. The company's carbon management system, automating manual accounting processes, improved personnel efficiency by 80%.

Digital transformation in upstream segments also merits attention. Ganfeng Lithium has promoted intelligent manufacturing and digital transformation since 2022, building a trinity digital-intelligent system integrating production, management, and ecology [29,30]. Its Fengcheng Ganfeng Lithium was selected as one of Jiangxi Province's first batch of "Digital Smart Factory" demonstration enterprises in 2025. EVE Power invested RMB 1.3 billion to build a full-process digital-intelligent smart factory for lithium battery products, leveraging 5G, AI large models, and digital twin technologies to achieve transparent production processes and full life-cycle product traceability [28].

2.3. Synergistic development of the industrial ecosystem

Green governance in the lithium battery industry is transitioning from "point"-based breakthroughs at individual enterprises to "surface"-based coordination across the entire industry chain. The power battery recycling system has entered its 2.0 era. Through collective efforts, China's waste power battery recycling system has been preliminarily established. It is estimated that domestic waste power battery generation in 2025 reached nearly 400,000 tons, and will exceed 1 million tons by 2030 [31]. Replacing the previous integrated traceability management platform, it encompasses core functions including information traceability, enterprise compliance evaluation, traceability data analysis, and industry-specific research, providing both data support for government regulatory precision and compliance services for industry chain enterprises. Each power battery is assigned a unique digital identity card as its core identifier. Based on this, the platform builds a full-chain digital traceability system covering production, installation, usage, maintenance, decommissioning, recycling, and comprehensive utilization, forming a closed-loop management mechanism that enables sources to be identifiable and destinations traceable [20,32].

Digital governance tools are accelerating implementation. The battery passport of EVE Energy integrates over 100 data items across the product life cycle, covering more than 200,000 data

nodes in the industry chain, assigning each cell a unique digital identity ID [28]. In 2026, Sunwoda's self-developed battery passport platform successfully completed system-level integration with the EU Digital Product Passport (DPP) official registry test environment, passing identity verification, data submission, and registration archiving in a single process [33]. In May 2026, China Resources Recycling Group launched a battery recycling service platform featuring four functions—data traceability, compliant trading, carbon asset management, and recycled material certification—building a full-life-cycle regulatory closed loop through digital means [34].

Industry chain enterprises are actively integrating into digital governance ecosystems. At the end of 2025, NDRC and two other ministries announced the first batch of 52 national-level zero-carbon industrial park construction lists, including production bases of CATL, Envision Energy, BYD, Gotion High-Tech, and EVE Energy [29]. EVE Energy's Jingmen and Qujing bases were both selected, with Jingmen Base as Hubei Province's only selected park, representing a zero-carbon development model based on the full industrial chain closed loop [29]. The Dongqiao Economic and Technological Development Zone, leveraging the characteristics of the lithium battery new energy industry, has advanced a collaborative innovation pilot for pollution reduction and carbon reduction, actively building a zero-carbon park [35].

2.4. Upgrading driven by international rules

The accelerated reconstruction of international green trade rules is becoming an important external force compelling domestic lithium battery industry governance upgrading. The EU New Battery Regulation (Regulation (EU) 2023/1542), effective August 2023, is the world's first legal instrument regulating the full life cycle of batteries [22,23]. Its core requirements include three aspects: (1) carbon footprint declaration and limits—carbon footprint reports required from February 2025, performance class labeling from August 2026 [23]; (2) digital battery passport—from February 18, 2027, all power batteries, light means of transport batteries, and industrial batteries above 2 kWh placed on the EU market must carry a unique digital battery passport, recording approximately 90 mandatory data attributes; (3) recycling and recycled content requirements—50% lithium recovery rate by 2027, 90% for cobalt, copper, lead, and nickel [22,23]. Products without registered battery passports cannot be sold in the EU market.

Digital battery passports have been conceptualized as a key instrument for enabling circular and sustainable value chains [15], with research identifying stakeholder requirements for sustainability and circularity across the battery life cycle [16]. Technical architectures using composable NFTs and blockchain have been proposed to create EV battery digital passports with robust sustainability and traceability features [17], while leveraging LCA data in digital battery passports has been shown to enhance sustainability in automotive marketplaces [36].

In response, domestic policies and industry are actively adapting. At the policy level, the “digital identity card” system in the Management Measures closely parallels the EU battery passport in governance logic, reflecting proactive alignment of domestic institutions with international rules [20, 24]. At the industry level, Sunwoda's completion of the official platform integration test validates that domestic power battery enterprises possess the technical capability to meet EU green regulatory requirements [33], providing a replicable reference for domestic new energy industry chain enterprises navigating global green trade regulations. CATL and BMW have signed a cooperation agreement to

jointly promote battery passport pilots, deepening collaboration on cross-border battery passport data pilots and supply chain carbon footprint collaborative reduction [37].

3. Major challenges in digital-green synergistic development of China's lithium battery industry

3.1. Institutional deficiencies in carbon accounting and standards

Although China has made notable strides in establishing carbon footprint databases for the lithium battery industry—including both the dedicated lithium battery carbon footprint background database and the broader key industrial product carbon footprint database covering 27 industries [10,11]—significant gaps persist in the completeness and operability of the overall accounting system. These deficiencies are not merely technical but also institutional, reflecting challenges in standardization, enterprise-level implementation, and the delicate balance between transparency and trade secret protection. These gaps manifest in three interrelated dimensions.

Lack of unified carbon footprint accounting standards remains a major issue. Accounting results from different institutions and methodologies may differ significantly, affecting the comparability and credibility of carbon footprint data [37]. The alignment of carbon footprint accounting methodologies with international standards (such as the EU PEF method) requires strengthening, which directly impacts export compliance costs [24]. Research indicates that if China's lithium-ion battery carbon footprint is calculated using EU database electricity carbon factors, the results would be significantly higher than those of other countries, with China potentially bearing an additional 230,000 tons of carbon emissions and RMB 180 million in environmental costs by 2025. Discrepancies in data scope, accounting boundaries, and emission factors across different databases mean that the same product's carbon footprint under different accounting systems could vary substantially [9,13].

Insufficient integration between carbon footprint accounting and actual enterprise production operations poses another challenge. Effectively connecting macro-level database data with enterprise-specific production data to form operable and verifiable enterprise-level carbon footprint accounting solutions remains a technical challenge [10,11]. Although the lithium battery carbon footprint background database covers 98% of material types in the industry chain [10] and the key industrial product database covers over 300 industrial products [11], a conversion gap persists between “macro benchmarks” and “enterprise applications”. A large number of small and medium-sized enterprises still lack the capability to conduct independent carbon footprint accounting, while reliance on third-party service providers faces high cost barriers [9].

Conflict between data cross-border transfer and trade secret protection has also emerged. Battery passport systems require enterprises to disclose substantial supply chain data including mineral sources, smelting processes, and composition information [23,24], creating a new governance challenge in balancing international compliance requirements with protection of core trade secrets [16,19]. Some enterprises are concerned that excessively transparent data disclosure could lead to leakage of key process information, weakening competitive advantages [33].

3.2. Data silos and disrupted chain synergy

The lithium battery industry chain is characterized by its length and fragmentation—spanning mining, smelting, materials, cells, battery packs, complete vehicles, and finally recycling—with each link involving distinct actors operating on heterogeneous information systems. This structural complexity, while necessary for specialized production, creates formidable barriers to seamless data circulation across the value chain [1]. The challenge is not merely technical but also organizational, as divergent data standards, competing commercial interests, and varying digital capabilities across segments have led to what research identifies as mechanism fragmentation and persistent data silos in the digital transformation of the lithium battery industry [5,6]. The consequences of such fragmentation are twofold.

The direct consequence of data silos is the inability to achieve truly comprehensive life-cycle carbon footprint traceability. Environmental impacts across the “mining–smelting–use–recycling” stages cannot be precisely accounted and responsibility-tracked [9,13]. Although the traceability platform is operational [27], significant challenges remain in achieving full industry-chain integration from policy design to implementation [20]. Power batteries may undergo multiple transfers from vehicle installation to decommissioning, involving vehicle owners, maintenance enterprises, scrappage and dismantling enterprises, and recycling/utilization enterprises. Ensuring timely and accurate information upload and update at each stage, while safeguarding data security and privacy, requires further exploration [18]. In current practice, information chain breaks are common, particularly during the transition from vehicle owners to recycling channels, where the completeness rate of traceability information still has considerable room for improvement [27,32].

Digitalization levels vary dramatically across industry chain segments. Leading battery manufacturers’ factories have achieved “Lighthouse Factory” status [2,28], but upstream mining enterprises and downstream small-to-medium recycling enterprises remain at early digitalization stages [30]. Ganfeng Lithium’s practice demonstrates that while upstream digital transformation has begun, significant distance remains from full industry-wide adoption [30]. This “digital divide” creates structural barriers to full industry-chain data integration [6]. Weak environmental data collection capabilities in upstream mining, uneven carbon accounting precision in midstream materials, and insufficient information coverage in downstream recycling—data deficiencies at any link can lead to failure of life-cycle traceability [1,18].

More critically, data silos not only affect governance efficiency but may also constrain international competitiveness. Failure to establish an autonomous, internationally compatible battery full-life-cycle digital management system in a timely manner could expose China’s battery industry to increased compliance costs, compromised data sovereignty, and diminished international discourse power [24,33].

3.3. Digital divide in battery recycling systems

Power battery recycling represents both a critical frontier for environmental governance and an indispensable scenario for digital empowerment in the lithium battery industry [18, 31]. As the industry faces the impending wave of massive battery retirements—with annual decommissioned volumes projected to surpass one million tons by 2030—the ability to digitally track, evaluate, and recover valuable materials from end-of-life batteries has become a strategic imperative for closing the material loop and achieving true life-cycle sustainability. Yet despite its importance, recycling remains the weakest link in the industry’s digital governance chain. The digitalization level of the current recycling

system varies dramatically across different actors and regions, creating a pronounced “last-mile” gap that threatens to undermine the integrity of the entire traceability system [32]. This disparity manifests in several critical dimensions.

Digital coverage in recycling is far lower than in production. While leading battery enterprises have established comprehensive digital manufacturing systems and traceability capabilities [2,28], a large number of small-to-medium recycling enterprises still rely on traditional manual records and crude management [31,32]. Although the traceability platform is operational [27], its effectiveness depends on active data entry by all actors. The proportion of recycling enterprises capable of full-process digital traceability remains limited, with significant quantities of decommissioned batteries still escaping effective monitoring [31]. Industry research data indicates that less than 30% of recycling enterprises currently achieve full-process digital traceability; substantial quantities of decommissioned batteries flow into informal channels and exit the traceability system [32].

Scattered recycling channels and persistently low formal-channel recovery rates remain problematic. Power battery management in the NEV sector has had loopholes—some batteries that should have been decommissioned re-entered the market, while others entered workshops lacking recycling technology, creating safety hazards and environmental pollution risks [31,32]. The Management Measures aim to force “small, scattered, and unregulated” enterprises out of the market by establishing clear waste power battery transfer requirements and safety/environmental “thresholds” for comprehensive utilization enterprises [20]. However, the transition from policy to effective implementation will take time [27].

Lack of data standards in recycling exacerbates the problem. Different enterprises employ varying data collection standards, data formats, and information interfaces across decommissioned battery inspection/evaluation, echelon utilization, and dismantling/recycling stages, creating technical barriers to data exchange even when traceability is intended [31,32]. Particularly in critical data dimensions such as battery state-of-health (SOH) assessment and remaining life prediction, the absence of unified testing standards and data specifications severely constrains the standardized development of echelon utilization markets [18,32]. Blockchain technology has been proposed as a potential solution to address information asymmetry and trust issues in closed-loop supply chains [8,21].

3.4. Short-term pressures from international green trade rules

The EU New Battery Regulation’s three major barriers—carbon footprint barriers, recycling barriers, and supply chain ESG risk barriers—pose systemic challenges to China’s lithium battery industry exports [22,23]. From January to May 2026, China exported 1.833 million new energy vehicles, a year-on-year increase of 110%, with NEVs accounting for approximately 45% of total vehicle exports [37]. Given the substantial share of the EU market, any changes in EU regulations have profound implications for China’s lithium battery industry [24].

Urgency and stringency constitute dual pressures. The digital battery passport system becomes mandatory on February 18, 2027, leaving Chinese enterprises less than one year to prepare [23,24]. The approximately 90 mandatory data attributes cover foundational information, material sources, supply chain due diligence, recycled content, and more—many data dimensions for which mature collection and management mechanisms have not yet been established in the domestic industry system [16,22]. Additionally, the EU Carbon Border Adjustment Mechanism (CBAM) entered its implementation phase on January 1, 2026 [24]. As environmental regulations and compliance requirements in relevant

countries continue to rise, Chinese power battery exports face increasing compliance costs and operational challenges [33].

Lack of standard mutual recognition exacerbates compliance uncertainty. Alignment between China's carbon footprint accounting methodologies and international standards (such as the EU PEF method) requires strengthening [9,37]; rules for cross-border data flows remain unclear, leaving enterprises with significant uncertainty in choosing compliance pathways [19,24]. Research on consumer adoption of digital product passports has revealed that regulatory clarity and perceived trust are critical factors influencing acceptance [36]. Although Sunwoda has completed the DPP integration test [33], the vast majority of SMEs remain in a wait-and-see mode. This polarization of response capabilities may further exacerbate industry fragmentation.

Sunwoda noted that the industry faces three major pain points—insufficient full-process digital monitoring capabilities, imperfect carbon footprint accounting systems, and conflicts between data cross-border transfer and trade secret protection—and that “compliance capability is becoming the new core competitiveness” [33]. How to avoid excessive cost transfer to enterprises while meeting international rule requirements, and how to gain discourse power in international standard-setting, are urgent issues requiring resolution [15,24].

4. Response strategies for promoting digital-green synergistic development of China's lithium battery industry

4.1. Strengthening institutional supply and standard systems

Institutional supply is the foundational guarantee for synergistic development, requiring coordinated progress in standardization, institutional connectivity, and data governance. Accelerate the development of unified data management standards for the lithium battery industry life cycle. Clarify data collection scope, format specifications, interface standards, and security requirements to provide a “common language” for data exchange across industry chain links. Particularly in the implementation of “battery passport” and “digital identity card” systems, supporting implementation rules and operational specifications should be expedited, clarifying data reporting obligations and operational procedures for each link's actors. With the traceability platform operational and the management measures in effect, the supporting standard system should be accelerated, aiming for a full-industry-chain data standard system framework.

Improve carbon footprint accounting methodology systems and certification systems. Promote integration of the lithium battery carbon footprint background database, key industrial product carbon footprint database, and enterprise-level accounting platforms, forming a three-tier “macro-database–industry benchmarks–enterprise accounting” carbon footprint management architecture [9]. With the key industrial product carbon footprint database already covering 27 key industries, methodological standardization should be accelerated to establish accounting rules aligned with the EU PEF method.

Establish a tiered data classification management system. Balance international compliance requirements with protection of enterprise trade secrets. For data cross-border transfer issues, battery industry data export guidelines should be expedited, clarifying which data must be disclosed, which can be anonymized, and which qualify as trade secrets eligible for exemption, providing clear compliance guidance for enterprises.

In terms of policy instruments, incorporate enterprise digitalization levels and green governance performance into industrial support policy evaluation systems. MIIT has proposed encouraging local exploration of policy support tools linked to product carbon footprints [3,25]—this direction should be accelerated.

4.2. Accelerating deep application and integrated innovation of digital-intelligent technologies

Technological application is the core driver of synergistic development. However, as the preceding problem analysis reveals, the mere deployment of technology does not automatically generate synergistic effects—the absence of data standards undermines the effectiveness of traceability systems, the immaturity of the industrial ecosystem constrains the realization of technological value, and the rapid evolution of international rules may expose technological investments to compliance risks. Therefore, the formulation of technological empowerment strategies requires, alongside a clear technology roadmap, simultaneous attention to standardization, industrial coordination, and alignment with international rules, forming an integrated technology–institution–industry–rule framework. Specifically, deep integration of AI, blockchain, industrial internet, and other digital-intelligent technologies in lithium battery industry green governance should be promoted, advancing from point-based applications to systemic integration.

In the field of carbon footprint management, further develop lithium battery industry carbon management large models should be further developed. Industrial internet identification and energy consumption prediction algorithms should be integrated to dynamically optimize equipment parameters and energy scheduling. EVE Energy's AI energy-efficiency optimal curve model achieving 5%–10% system energy reduction provides a replicable technical paradigm [28]. Ganfeng Lithium's trinity digital-intelligent system integrating production, management, and ecology demonstrates that upstream segments can also achieve green transformation through digitalization [29].

In the recycling domain, blockchain technology can be applied to build immutable battery life-cycle data chains. The authenticity, completeness, and trustworthiness of traceability information should be ensured. With the national power battery traceability information platform operational, platform functions should be further enriched by introducing smart contract technology for automatic verification and incentives for recycling. China Resources Recycling Group's battery recycling service platform—with its four functions of data traceability, compliant trading, carbon asset management, and recycled material certification—provides a useful reference for the industry [34].

Simultaneously, promote digital technology accessibility. For SMEs with insufficient digital capabilities, reduce digitalization barriers through industry-level digital transformation promotion centers and lightweight SaaS tools. MIIT's one-diagram, four-lists approach to advancing lithium battery industry digital transformation should be further detailed and implemented. Leading enterprises should play “chain master” roles, exporting intelligent manufacturing and digital management experience to industry chain partners. Sichuan Times' experience of leading eight supply chain enterprises to carbon neutrality demonstrates that technology spillover from chain masters is an effective pathway for overall industry chain upgrading [28,29].

4.3. Building a full-industry-chain collaborative governance ecosystem

Building a collaborative governance ecosystem requires participation and effective interaction among multiple stakeholders. Government should play the role of institutional supply and regulatory guidance. Continuously improve the national power battery traceability information platform and data-sharing infrastructure, removing information barriers across departments and regions. In regulatory approach, shift from traditional on-site inspection to a combination of “data-driven supervision + on-site verification” to improve regulatory efficiency and precision. For the “small, scattered, and unregulated” recycling problem, leverage traceability platform big data analytics to accurately identify abnormal decommissioned battery flows.

Industry associations and standards organizations should play bridging roles. Promote industry standard development and dissemination, and organize exchanges and sharing of best practices in digitalization and green governance. China Battery Industry Association, China Chemical and Physical Power Sources Association, and others should take the lead in building industry-level carbon footprint data-sharing platforms and establishing mutually recognized carbon accounting rules within the industry [37].

Leading enterprises should demonstrate technological export and standard-setting leadership. Sichuan Times’ trajectory—from zero-carbon factory to zero-carbon industrial cluster to driving its park’s inclusion in the national zero-carbon industrial park construction list—provides instructive insights: using chain master enterprises as drivers to promote upstream and downstream collaborative carbon reduction. This model should be promoted more broadly. EVE Energy’s Jingmen Base as a representative of full-industry-chain closed-loop zero-carbon development also offers valuable experience.

At the regional level, establish digital transformation promotion centers. Build demonstration zones for digital-green synergistic development. The Dongqiao Economic and Technological Development Zone advances collaborative innovation pilots for pollution reduction and carbon reduction based on lithium battery industry characteristics. Yibin, meanwhile, promotes a dual-mode approach combining zero-carbon factory and Lighthouse Factory construction [29]. These practices provide references for the green transformation of national lithium battery industry clusters [35].

4.4. Actively participating in international rule-making and standard mutual recognition

Facing international green trade barriers, passive response is inferior to active participation; pressure should be transformed into motivation for participating in global rule-making. Accelerate China–EU mutual recognition of carbon footprint accounting methodologies. Actively participate in lithium battery-related standard-setting work of international standards bodies such as IEC and ISO. In the formation of international rules for emerging governance tools like “battery passports,” China’s practical experience and standard proposals should be incorporated into international frameworks. With China–EU battery sector standard dialogue mechanisms initially established, dedicated technical working groups should be set up to focus on carbon footprint accounting and battery passport data specifications.

Leverage carbon footprint database advantages to gain international discourse power. China’s lithium battery carbon footprint background database covers 28 major production locations and 98% of material types in the industry chain; the key industrial product carbon footprint database covers 300+ industrial

products across 27 industries. This should be leveraged to promote international recognition of China's carbon footprint accounting standards and methodologies, converting data advantages into rule-setting discourse power.

Accelerate construction of the power battery data trusted cross-domain collaboration platform. Already positioned around the 2027 battery passport effective date, the platform advances battery data classification and grading rules through dual-track industry standards and group standards [37]. CATL and BMW's battery passport pilot cooperation provides a useful model for international collaboration.

At the enterprise level, establish compliance management systems aligned with international rules. Internalize external carbon constraints as strategic assets and operational momentum. Sunwoda's pioneering completion of EU DPP registry integration demonstrates that early compliance capability deployment can translate into competitive advantage [33]. Research on consumer adoption of digital product passports suggests that proactive compliance strategies can enhance brand trust and market acceptance.

5. Policy implications

5.1. Interrelationships among the four dimensions

This study's core finding is that the synergistic effect between digitalization and green governance does not occur automatically but depends on the degree of alignment and interaction among the four dimensions. Together, they constitute an interdependent and indispensable organic whole. Institutional supply defines the direction and boundaries for technological empowerment. Technological empowerment, in turn, provides the means for digital governance of the industrial ecosystem. Feedback from industrial ecosystem practice drives the iterative optimization of institutional supply, while international rules generate external driving forces that propel the upgrading of the first three dimensions.

The policy implication of this finding is that promoting synergistic development cannot proceed through the single-dimensional advancement. Premature promotion of technological application without adequate institutional supply may render technologies difficult to implement or ineffective [5]. Similarly, premature alignment with international rules without industrial ecosystem maturity may result in excessive compliance costs with limited actual governance effectiveness [24]. The lithium battery industry's experience shows that Sichuan Times' zero-carbon factory success and expansion to the zero-carbon industrial cluster depended on the simultaneous presence of carbon footprint accounting standards at the institutional level [27], AI and industrial internet empowerment at the technological level [28], supply chain coordination mechanisms at the industrial ecosystem level [29], and global carbon neutrality consensus at the international level [23]—none of the four could be absent. Conversely, the uneven digitalization in recycling stems from clear mismatches across all four dimensions: imperfect recycling standard systems, insufficient SME digital capabilities, scattered recycling channels, and increasingly stringent recycled material requirements [31,32].

5.2. Balanced development across dimensions

The bucket effect is particularly evident in collaborative governance. Current digital-green synergy in the lithium battery industry has made significant progress in technological empowerment, represented by Lighthouse Factories and carbon footprint databases, but notable shortcomings remain in institutional supply, industrial ecosystem, and international rules. The direct consequence of this uneven development is that even when technology and data conditions are in place, institutional and industrial ecosystem lags still constrain full release of synergistic effects.

Taking carbon footprint management as an example, China has built the world's most extensive lithium battery carbon footprint database and an industrial product database covering 27 industries [10, 11]. However, due to non-unified carbon footprint accounting standards [37], insufficient SME accounting capabilities [9], and incomplete international mutual recognition [24], the governance effectiveness of the databases has not been fully realized. Policymakers should recognize this capability mismatch and simultaneously assess support capabilities in other dimensions when advancing breakthroughs in any single dimension.

The policy implication is that industrial policy-making should adopt a systematic approach rather than single breakthrough thinking. Digital transformation policies should simultaneously consider green governance institutional needs [3]; carbon footprint standards should anticipate international rule development directions [23,24]; recycling system development should treat digital capability as an enterprise access threshold [20,32]. The Implementation Plan for Digital Transformation of the Electronic Information Manufacturing Industry, which institutionally links digital transformation with carbon footprint management [3], exemplifies this systematic approach and should be consistently applied in subsequent policy implementation [25].

5.3. International rules as drivers for governance upgrading

Although international rules like the EU New Battery Regulation impose compliance pressures and cost increases on Chinese enterprises in the short term, their positive effects should not be overlooked in the long run. It is precisely the EU's carbon footprint declaration requirements and battery passport system that have accelerated domestic carbon footprint database development, digital identity card system implementation, and traceability platform launch. The 2026 launch of the key industrial product carbon footprint database and the national power battery traceability platform was directly driven, in part, by the need to respond to international market compliance requirements.

This demonstrates that international rules can serve as "catalysts" for domestic governance system improvement. The mechanism: international rules directly link external market access thresholds with domestic industry governance capabilities [23], creating a cascading effect domestically—enterprises proactively upgrade governance capabilities to maintain market access, governments accelerate institutional supply to protect industrial interests, and technology providers accelerate innovation to meet market demands [24,33].

Policymakers should fully leverage this mechanism, converting international rule compliance requirements into opportunities for domestic governance capability enhancement. Sunwoda's pioneering EU DPP integration demonstrates that early international compliance deployment can

translate into competitive advantage [33]. CATL and BMW's battery passport pilot cooperation exemplifies turning compliance pressure into international cooperation opportunities [37].

5.4. Multi-dimensional policy instrument design

Traditional industrial policies have often relied on single-dimensional interventions, such as subsidizing technological innovation or expanding production capacity. While such measures can address discrete market failures, they are poorly suited to the cross-cutting challenges of digital-green synergistic governance. Under the new collaborative governance paradigm, policy instrument design therefore requires greater attention to multi-dimensional alignment—ensuring that regulatory standards, fiscal incentives, infrastructure investment, and international engagement reinforce rather than contradict one another.

First, establish cross-departmental coordination mechanisms at the policy formulation stage. Digitalization and green governance in the lithium battery industry involve multiple departments including industry and information technology, ecology and environment, commerce, and market regulation—no single department can achieve synergistic goals alone [20]. An inter-ministerial coordination mechanism for digital-green synergistic development in the lithium battery industry should be established. The Implementation Plan for Digital Transformation of the Electronic Information Manufacturing Industry, jointly issued by MIIT, NDRC, and the National Data Administration, and the Management Measures, jointly issued by six departments, exemplify this multi-department collaborative regulatory model that should be continued and deepened [3].

Second, establish dynamic evaluation and adjustment mechanisms at the policy implementation stage. The alignment among the four dimensions is not static but continuously changes with technological progress, market evolution, and international rule development. Policy implementation should establish dynamic monitoring indicator systems to regularly assess progress and alignment across the four dimensions, promptly identifying “short boards” and making policy adjustments [32].

Third, balance incentives and constraints in policy instrument selection. Enterprises with leading digitalization and green governance performance should receive incentives such as tax preferences, green finance support, and priority procurement [3,25]; entities with insufficient digital capabilities, lagging green governance, or non-compliant behavior should face effective constraints through industry access conditions, market thresholds, and regulatory enforcement [20,31]. The Management Measures' approach of forcing small, scattered, and unregulated enterprises out through safety and environmental thresholds for comprehensive utilization enterprises exemplifies constraining policy instruments [20,27].

6. Conclusion

China's lithium battery new energy industry stands at a critical juncture, transitioning from an era of scale leadership to one increasingly shaped by standard leadership. This transformation is propelled not only by the industry's own developmental logic but also by the evolving landscape of global green governance, where the ability to set or align with internationally recognized standards has become a decisive factor in competitive advantage. The synergy between digitalization and green governance is therefore not a passive, compliance-driven response to external trade barriers, but rather an inherent and strategic requirement for achieving high-quality, sustainable industrial development. As this paper

has demonstrated, digital-intelligent technologies provide the essential tools for transparent and efficient environmental management across the battery life cycle, while the demands of green governance in turn drive further digital innovation and system integration.

The institutional supply–technological empowerment–industrial ecosystem–international rules four-dimensional synergy framework, as constructed and applied in this study, reveals that the realization of this synergy is contingent upon the balanced and interconnected development of all four dimensions. Institutional supply establishes the foundational rules and standards that guide technological application and data governance. Technological empowerment furnishes the capabilities for precise carbon accounting, traceable supply chains, and optimized production processes. The industrial ecosystem provides the practical context in which these technologies are deployed and governance is collectively shaped by diverse stakeholders. International rules function as both external catalysts and strategic benchmarks, compelling domestic systems to upgrade and align with global best practices while also offering opportunities to shape future governance frameworks. When any one of these dimensions lags or operates in isolation from the others, the overall effectiveness of the synergy is constrained, as evidenced by the persistent challenges of data silos, fragmented traceability, and uneven digital capabilities across the recycling value chain.

The findings of this research carry important implications for policymakers, industry leaders, and international collaborators. For policymakers, the priority lies in providing coherent and forward-looking institutional frameworks, including unified data standards, interoperable carbon accounting methodologies, and clear guidelines for cross-border data sharing—all of which are essential for fostering trust and efficiency in the digital-green nexus. For industry actors, the strategic imperative is to embed digital and environmental capabilities into core business operations, recognizing that long-term competitiveness will increasingly depend on data transparency, carbon literacy, and supply chain resilience. For international partnerships, the path forward requires active engagement in dialogue and negotiation, particularly in areas such as mutual recognition of carbon footprint methodologies, harmonization of battery passport data protocols, and collaborative research on sustainable material cycles.

As the implementation of battery passport systems advances globally, as carbon footprint accounting becomes more standardized and automated through AI and digital twin technologies, and as recycling infrastructure matures with enhanced digital traceability, the governance paradigm of the lithium battery industry is set to undergo profound and lasting change. This transition—from experience-based management to data-driven governance, from end-of-pipe environmental controls to full-life-cycle stewardship, and from isolated domestic compliance to integrated international cooperation—demands sustained commitment, adaptive governance, and collaborative innovation across all stakeholder groups. Only by simultaneously advancing across the four dimensions of institutional supply, technological empowerment, industrial ecosystem development, and international rule engagement can China's lithium battery industry not only meet the challenges of the present but also shape the rules and standards of the future, thereby achieving the transition from an industry follower to a global leader in the new era of green governance.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. The authors take full responsibility for the content of the manuscript.

Acknowledgments

Funding: This work was funded by the Key Research Base of Philosophy and Social Sciences of Jiangxi Province with grant number 25ZXSKJD40, Science and Technology Research Project from the Department of Education of Jiangxi Province with grant number GJJ2201709 and funded by the Humanities and Social Sciences Research Youth Foundation of Ministry of Education of China with grant number 20YJCZH220.

Authors' contribution

Conceptualization, F.L.; methodology, W.Y. and J.Y.; validation, W.Y.; investigation, F.L. and W.Y.; resources, J.Y.; writing—original draft preparation, F.L., W.Y. and J.Y.; writing—review and editing, W.Y. and J.Y.; visualization, F.L.; supervision, J.Y. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare that there are no potential conflicts of interest.

References

- [1] Wang H, Yang L, Zhu C. Lithium battery green supply chain evaluation system construction. *J. Hangzhou Dianzi Univ. (Soc. Sci.)* 2023, 19(3):1–10.
- [2] Luo J, Chen L, Cai G. From wastes to resources: the future of residential EV batteries in China through cascade utilization, recycling, and energy storage. *Waste Manage.* 2025, 205:115008.
- [3] Ministry of Industry and Information Technology, National Development and Reform Commission, National Data Administration. Implementation plan for digital transformation of the electronic information manufacturing industry (In Chinese). 2025. Available: https://www.miit.gov.cn/gyhxxhb/jgsj/dzxxsnew/zcwj/art/2025/art_3a22bef04add4f3aa9fa4669b7c59f0c.html (accessed on 27April 2026).
- [4] Ma X, Bai Y. Theoretical logic, practical challenges, and implementation pathways for the synergistic development of digitalization and greenization (In Chinese). *Price: Theory & Practice* 2025, (7): 91–96 + 238.
- [5] Liu Y, Wu J, Li Y, Ge Li. Quadruple helix model empowering digital transformation: a case study of Yichun lithium battery industry (In Chinese). *Battery Industry* 2025, 29(6):560–562.
- [6] Huang Z, Bu Y, Guo J. Research on digital-intelligent ecosystem model of lithium battery new energy industry chain based on high-quality development background (In Chinese). *Enterp. Reform Manag.* 2024, (17):161–163.
- [7] Baars J, Domenech T, Bleischwitz R, Melin HE, Heidrich Q. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nat. Sustainability* 2021, 4(1):71–79.
- [8] Moawad K, Musamih A, Chadly A, Mayyas A, Salah K. Blockchain-enabled sustainability of Li-ion batteries supply chain: tracking and sourcing eco-friendly materials. *Int. J. Prod. Res.* 2025, 63(24):9529–9570.

- [9] Luo D, Zheng H, Pan J, Sun W. Sustainable synthesis of cathode precursors from spent lithium-ion batteries by IoT-holographic twin integration: process optimization and electrochemical performance evaluation. *J. Environ. Chem. Eng.* 2026, 14(4):123371.
- [10] Beijing Saixi Certification Co., Ltd. China's first lithium battery carbon footprint background database updated and released version 3.0 at the New Industry Standardization Pilot Forum (In Chinese). 2025, Available: <http://www.cc.cesi.cn/news/show-5077.aspx> (accessed on 27 April 2026).
- [11] Zhao Z. China's First Key Industrial Product Carbon Footprint Database (In Chinese). 2026. Available: <http://finance.people.com.cn/n1/2026/0618/c1004-40743166.html> (accessed on 27 April 2026).
- [12] Li F, Cui J, Wang Y, Zhu Z. Research on the coupling development path of the new energy storage industry and digitalization from the perspective of carbon neutrality (In Chinese). *Inf. Sci.* 2023, 41(11):94–102.
- [13] Arshad F, Azam MU, Manurkar N, Zhang F, Idrees BS, *et al.* Life cycle assessment of lithium-ion and secondary batteries: a comparative analysis on environmental impacts and graphite recycling. *eTransportation* 2026, 27:100514.
- [14] Hasan HR, Hasan K, Mayyas A, Musamih A, Yaqoob I, *et al.* Using composable NFTs and blockchain for the creation of EV battery digital passports with sustainability and traceability features. *Sustainable Futures* 2025, 10:100847.
- [15] Berger K, Schöggel JP, Baumgartner RJ. Digital battery passports to enable circular and sustainable value chains: conceptualization and use cases. *J. Cleaner Prod.* 2022, 353:131492.
- [16] Pohlmann A, Popowicz M, Schöggel JP, Baumgartner RJ. Digital product passports for electric vehicle batteries: stakeholder requirements for sustainability and circularity. *Cleaner Prod. Lett.* 2025, 8:100090.
- [17] Yang T, Luo D, Zhang X, Gao S, Gao R, *et al.* Sustainable regeneration of spent cathodes for lithium-ion and post-lithium-ion batteries. *Nat. Sustain.* 2024, 7(6): 776–785.
- [18] Fan W, Pan J, Wang Y. Research on life cycle management of power battery driven by digital twin (In Chinese). *Automot. Dig.* 2023, (5):38–44.
- [19] Losa R, Torjesen S. The quest for more circular battery value chains: Implementing the EU digital battery passport and remaining challenges. *Cleaner Prod. Lett.* 2025, 9:100118.
- [20] Ministry of Industry and Information Technology, National Development and Reform Commission, Ministry of Ecology and Environment, Ministry of Transport, Ministry of Commerce, *et al.* Interim measures for the management of recycling and comprehensive utilization of waste power batteries for new energy vehicles (In Chinese). 2025. Available: https://www.gov.cn/gongbao/2026/issue_12686/202604/content_7066104.html (accessed on 27 April 2026).
- [21] Bakhshi N, Dehghani E, Jabalameli MS. Advancing green lithium-ion battery supply chains: a two-stage framework integrating reinforcement learning and mathematical modeling. *J. Energy Storage* 2026, 153:120927.
- [22] European Commission. Regulation (EU) 2023/1542 on batteries and waste batteries. 2023. Available: <https://circular-cities-and-regions.ec.europa.eu/support-materials/eu-regulations-legislation/regulation-eu-20231542-batteries-and-waste-batteries> (accessed on 27 April 2026).

- [23] Ma N, Shi H, Yao L, Fan B, Ren L, *et al.* The motivation analysis of EU battery regulation and China's response strategies. In *Proceedings of the 2024 3rd International Conference on Public Service, Economic Management and Sustainable Development (PESD 2024)*, Xi'an, China, September 27–29, 2024, pp. 502–512.
- [24] Wang L, Qiao B, Wang X. German battery passport implications for China's battery industry (In Chinese). *BATTERY BIMONTHLY* 2025, 55(6):1378–1382.
- [25] Ministry of Industry and Information Technology. Reference Guidelines for Scenario-Based and Graph-Based Promotion of Digital Transformation in Key Industries (2025 Edition) (In Chinese) . 2025. Available: https://www.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2025/art_c8db9a81264746dc8ac1052d1b4dbbc2.html (accessed on 27 April 2026).
- [26] Xinhua News Agency. State Council executive meeting explainer: China to strengthen the recycling and utilization of power batteries for new energy vehicles (In Chinese) . 2025. Available: https://www.gov.cn/zhengce/202502/content_7004966.htm (accessed on 27 April 2026).
- [27] Sichuan Contemporary Amperex Technology Limited (CATL-SC). CATL's Sichuan plant certified as world's first zero-carbon factory in new energy industry. 2026. Available: <https://www.catl.com/en/news/912.html> (accessed on 27 April 2026).
- [28] EVE Energy. World's First Cylindrical Battery Lighthouse Factory: EVE Energy Sets a New Benchmark in Smart Manufacturing. 2026. Available: <https://www.evebattery.com/en/news-1891> (accessed on 27 April 2026).
- [29] Lan F, Hou L. Problems and countermeasures of green digital transformation of lithium battery industry in western Jiangxi (In Chinese). *Old District Construction* 2025, (4):14–22.
- [30] Yan D. National platforms launched to boost recycling efforts. 2026. Available: <https://global.chinadaily.com.cn/a/202511/17/WS691a710da310d6866eb29c6a.html> (accessed on 27 April 2026).
- [31] Institute of Process Engineering, Chinese Academy of Sciences, Beijing Resource Mandatory Recycling Environmental Protection Industry Technology Innovation Strategic Alliance. *China retired power battery recycling technology and industry development report (2025) (In Chinese)*. Beijing: Chemical Industry Press, 2026.
- [32] China Automotive Technology and Research Center Co., Ltd. China's first national traceability information platform for new energy vehicle power batteries has been officially launched and put into operation (In Chinese). 2026. Available: <http://www.sasac.gov.cn/n2588025/n2588124/c35396853/content.html> (accessed on 27 April 2026).
- [33] Sunwoda. Sunwoda showcases digital battery passport and advanced energy storage solutions at Energy Storage Summit 2026. 2026. Available: <https://en.sunwoda.com/article/1521> (accessed on 27 April 2026).
- [34] Tajik M, Yousefi S, Tosarkani BM, Makui A. Digitalization-driven circular economy in battery closed-loop supply chain network design. *J. Cleaner Prod.* 2025, 496:145054.
- [35] Fumagalli L, Badalotti F, Fattarelli C, Perossa D, La Rosa AD. Leveraging life cycle assessment data in digital battery passports to enhance sustainability in automotive marketplaces. *IFAC-PapersOnLine* 2025, 59(10):2468–2473.

-
- [36] Popowicz M, Pohlmann A, Schögl J-P, Baumgartner R J. Digital product passports as information providers for consumers—The case of digital battery passports. *Bus. Strateg. Environ.* 2025, 34(6):7700–7722.
- [37] Liu W, Liu M, Zhang M, Pan X, Zhang Q, *et al.* Assessing the potential impact of the EU batteries and waste batteries regulation on the carbon footprint of Chinese power lithium-ion batteries (In Chinese). *J. Saf. Environ.* 2025, 25(9):3352–3361.