Available Online: 19 May 2026 DOI: 10.54254/2977-5701/2026.33723

The intrinsic mechanism of Product-Service Systems driving circular industry development: A case study of NIO's Battery-as-a-Service model

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Abstract. Against the backdrop of the accelerating circular industry transition, exploring firms' endogenous driving mechanisms is of critical theoretical and practical importance. This paper examines the Product-Service System (PSS) as a transformative business model, using NIO Automotive's "Battery-as-a-Service" (BaaS) as a case study to investigate how this model drives the full life-cycle circulation of traction batteries. Employing a "Property Rights–Incentives–Behaviour" analytical framework, the study finds that through property rights restructuring, the BaaS model internalises battery assets within the firm, thereby redirecting its core economic incentive toward maximising asset life-cycle value. This incentive subsequently drives the firm to embed circular principles across the design, operation, and end-of-life phases of the battery, enabling it to organically integrate into the traction battery circular industry network. Drawing on 2024 operational data—including over 3,100 battery-swapping stations, 56.61 million cumulative swapping sessions, and battery assets exceeding CNY 20 billion—this paper demonstrates that the BaaS model has generated a substantial asset pool and pronounced network effects. The findings provide a market-driven pathway for aligning business model innovation with circular economy objectives and offer policy implications for the development of circular industrial ecosystems in the new-energy vehicle sector.

Keywords: Product-Service System (PSS), Life Cycle Management (LCM), Battery-as-a-Service (BaaS), New Energy Vehicles (NEV), business model innovation

1. Introduction

In the context of an accelerating restructuring of global manufacturing competition, the traditional linear economic model of "extract–manufacture–discard" can no longer adequately address the twin imperatives of resource constraints and environmental governance. Transitioning toward circular industrial ecosystems has thus become an inevitable trend. This imperative is particularly acute in the New-Energy Vehicle (NEV) sector. As the world's largest producer and consumer of NEVs, China's traction battery industry has entered the Terawatt-Hour (TWh) era. According to data from the China Automotive Battery Innovation Alliance (CABIA), cumulative production of traction and other batteries in China reached 1,096.8 GWh in 2024,

representing a year-on-year increase of 41.0%; cumulative sales reached 1,039.5 GWh, up 42.4% year-on-year, with traction batteries accounting for 76.1% of total sales.

As the industry scales rapidly, the environmental pressures associated with the full life cycle of traction batteries are becoming increasingly acute. Rare metals such as lithium and cobalt—key constituents of traction batteries—are both technically challenging and environmentally costly to mine, while improperly managed retired batteries pose serious risks of heavy-metal contamination and resource wastage. Although China's Ministry of Industry and Information Technology and other government bodies have issued successive policies to promote traction battery recycling and reuse, the industry still faces significant challenges: underdeveloped recovery systems, low circular utilisation efficiency, and insufficient corporate participation incentives. Achieving closed-loop management of traction batteries from production to retirement—and steering the industry from "scale expansion" to "quality enhancement"—has become a pivotal agenda item in building circular industrial ecosystems.

Simultaneously, the Product-Service System (PSS) model, which has emerged from the broader wave of manufacturing servitisation, offers a promising new approach to resolving these challenges. Frank et al. [1] proposed that, from a managerial perspective, servitisation refers to the innovative transition from a product-centric to a service-oriented business model, and that the PSS represents the output of this transition. The core logic of a PSS is that the firm retains ownership of the physical product and creates value by selling product functions or performance rather than the product itself. In theory, this can deeply align the firm's economic interests with the durability, maintainability, and residual value of the product, thereby creating intrinsic incentives for circular behaviour. NIO Automotive's "Battery-as-a-Service" (BaaS) model represents a pioneering application of this theory in the NEV sector, providing a highly valuable commercial experiment for addressing the challenges described above.

Unlike the conventional NEV sales model of "vehicle plus battery", the BaaS model employs contractual design to separate ownership of the physical battery asset from ownership of the vehicle: users purchase only the vehicle and pay a monthly subscription fee for access to battery usage rights. In essence, this model transforms a product "chattel" into an operable "asset", repositioning NIO from a conventional "automotive product seller" to a "battery asset operations-and-service provider".

Under the BaaS model, NIO gains full life-cycle control and responsibility over the battery—spanning design, manufacturing, operation, maintenance, recycling, and cascade utilisation. According to NIO's 2024 Annual Report, by year-end 2024 its battery-swapping stations covered all provincial-level administrative units nationwide, with more than 3,000 cumulative stations built, serving over 1.5 million user sessions, and battery assets valued at hundreds of CNY billion. This model has not only transformed NIO's profit structure and asset profile but has also, in the pursuit of commercial value, led the firm to organically embed itself in the traction battery circular industrial ecosystem—making it an ideal case study for analysing the intrinsic 'property rights-incentives-behaviour' mechanisms that drive firms to actively engage in full life-cycle circulation.

2. Literature review and theoretical foundations

2.1. From servitisation to Product-Service Systems: reconstructing the business logic

Manufacturing servitisation is widely regarded as a key pathway for value creation and competitive differentiation. Its advanced expression is the Product-Service System, whose essence is to provide an integrated "product-plus-service" solution that fundamentally shifts the logic of value creation from transacting product ownership to transacting product function and performance [2]. Domestic scholarly work

on manufacturing servitisation and PSS life cycles has largely concentrated on the enterprise and product dimensions. For instance, Zhang et al. [3], employing exploratory multi-case research grounded in life-cycle theory, found that servitisation in the product-use phase exerts a positive influence on value creation for both firms and customers. Successful PSS begins with the reconstruction of the value proposition and improves firm performance through enhanced customer lock-in and co-creation [4]. It is not a simple extension of existing business but entails systemic innovation and dynamic evolution in strategy, organisation, and profit model, often deeply integrated with intelligent technologies to enhance operational efficiency and service capability [5]. PSS therefore provides the foundational framework for understanding the strategic nature of NIO's BaaS: far from being a mere financial arrangement, it constitutes a profound business model transformation.

2.2. Life Cycle Management: a framework for realising systemic value

The PSS is conceptualised as a combination of products and services oriented toward the customer life cycle; the life-cycle attribute is a fundamental property of the PSS, and the intrinsic relational coherence of the life cycle is a critical factor enabling the fusion of products and services [6]. Effective PSS operation requires firms to move beyond a focus on the point of sale and instead systematically manage the entire process from design and manufacturing through use to end-of-life recovery—that is, to adopt a Life Cycle Management (LCM) perspective. This perspective emphasises inter-temporal optimisation and systemic trade-offs among resource, environmental, and economic costs [7]. In the NEV and battery domain, this perspective is especially vital: it requires integrated consideration of performance degradation over extended battery use, maintenance costs, and post-retirement cycling pathways, and constitutes the core methodology for maximising overall environmental benefits while minimising economic costs [8, 9]. LCM thus provides the key analytical tool and operational criterion for evaluating and optimising the circular benefits of the BaaS model.

2.3. Theoretical coupling of servitisation models and circular industry development

The goal of circular industry development is to form a system of closed-loop resource flows. Theoretical research demonstrates that when firms retain product ownership through a PSS, their commercial interest in maximising long-term asset value exhibits natural incentive compatibility with the circular objectives of extending product life and facilitating maintenance and recovery [10]. This model creates conditions for the transformation of resources from "consumables" to "manageable assets", making large-scale, high-efficiency circular utilisation commercially viable. Intelligent technologies further empower the precise management of assets, enabling full life-cycle tracing, forecasting, and optimisation [5]. PSS is thus regarded as a potentially critical bridge connecting firms' micro-level commercial practices with macro-level circular industry objectives.

2.4. Critical review of the literature

The extant literature has established solid foundations in the commercial logic of PSS, the managerial framework of LCM, and the systemic objectives of the circular industry, respectively. However, most existing studies conduct domain-by-domain enquiries and have yet to provide a detailed case-based analysis of the complete mechanism by which a specific PSS business model dynamically and endogenously drives firms to practise LCM and substantively advance the construction of a circular industrial ecosystem in a particular sector. The present study aims to fill this gap by using NIO's BaaS as a case study to investigate in depth the intrinsic logic of the "business model innovation → enterprise behaviour reshaping → circular industry collaboration" transmission chain, revealing its micro-level mechanisms of action.

3. Constructing the theoretical analytical framework

Building on the literature review, existing research has elucidated separately the commercial logic of PSS, the framework value of LCM, and the systemic objectives of the circular industry. However, regarding how a specific PSS—such as NIO's BaaS—dynamically integrates these dimensions, systematically reorients corporate behaviour, and couples with the circular industry network, no clear process-mechanism model has yet been proposed. To fill this research gap, this paper constructs an integrated "Property Rights–Incentives–Behaviour" analytical framework to reveal the intrinsic transmission mechanism through which business model innovation drives circular industry development.

The framework's core logic chain begins with the restructuring of property rights triggered by business model innovation. The BaaS model transforms the battery—via a servitisation contract—from a "commodity" owned by the user into a "long-term asset" held by the firm. This fundamental change triggers a reset of the firm's core incentive structure: the objective function shifts from maximising one-off sales profit to maximising "full life-cycle asset value". This value encompasses service revenues during the asset's operational life, operational cost savings, and residual value recovery at end-of-life.

Driven by the new incentive structure, and in order to protect and enhance asset value, the firm's behavioural patterns are systematically and circularly reoriented across every phase of the product life cycle. In the design phase, the firm evolves into an eco-designer, investing in long-life, standardised, and readily recyclable battery technologies to minimise asset depreciation. In the operations phase, it transforms into an intelligent operator, building and optimising shared infrastructure such as the swapping network to achieve real-time monitoring, efficient dispatch, and preventive maintenance of assets, thereby maximising asset utilisation and health. In the end-of-life phase, the firm becomes a systems integrator, laying out cascade utilisation and material regeneration pathways to capture and recover the ultimate residual value of the asset.

Ultimately, this sequence of behaviours transforms the firm from a mere node in a linear supply chain into an active participant in—and shaper of—the circular industry network for traction batteries. This framework will be used to systematically deconstruct the NIO BaaS case and empirically trace the complete transmission pathway of "business model innovation → property rights/incentives restructuring → corporate behaviour change → industry network coupling", thereby opening the micro-level "black box" of the synergy between commercial strategy and environmental sustainability.

The overall logic of the framework can be articulated as a four-stage sequential chain. At the first stage, BaaS business model innovation separates vehicle ownership from battery ownership through a servitisation contract, so that users acquire only the right to use the vehicle and pay a subscription fee for battery access. This seemingly simple contractual redesign is the trigger for all that follows. At the second stage, this contractual arrangement produces property rights restructuring: the battery is legally and economically transformed from a consumer chattel—sold once and thereafter outside the manufacturer's control—into a long-term productive asset retained on the firm's balance sheet and managed through the Weineng asset pool. Ownership centralisation is not merely an accounting event; it fundamentally reallocates risk, responsibility, and reward over the battery's entire service life. At the third stage, this new ownership structure triggers incentive restructuring: the firm's core objective function shifts from maximising one-time transaction profit to maximising the total life-cycle value of the asset, which encompasses subscription revenue during the asset's operating life, cost savings from efficient operations and preventive maintenance, and residual value recovered through cascade utilisation and materials regeneration at end-of-life. Once this incentive structure is in place, circular behaviour is no longer altruistic; it is commercially rational. At the fourth and final stage, the reconfigured incentive drives systemic behavioural transformation across all phases of the product life cycle simultaneously: in the design phase the firm acts as an eco-designer, engineering long-life and standardised

batteries that slow asset depreciation; in the operations phase it acts as an intelligent operator, deploying a dense swapping network to maximise utilisation and monitor asset health in real time; and in the end-of-life phase it acts as a systems integrator, coordinating cascade utilisation and materials recovery to capture residual value. These three parallel behavioural shifts are not independent initiatives but co-products of a single incentive: the imperative to protect and grow the value of assets the firm legally owns. The cumulative outcome of this four-stage chain is that NIO evolves from a conventional automotive product seller into an active participant in—and ultimately a rule-shaper of—the full life-cycle circular industrial network for traction batteries, demonstrating that business model innovation can generate endogenous circular momentum without reliance on policy mandates or external subsidies.

4. Case analysis: NIO's BaaS model in circular practice

This section employs the analytical framework presented above to deconstruct NIO's BaaS model. By examining 2024 operational data, strategic announcements, and technology initiatives, this paper validates how the model's property rights restructuring drives systematic, circular-oriented transformations in corporate behaviour, and assesses its practical progress in building a traction battery circular industrial ecosystem.

4.1. Property rights restructuring: establishing and scaling asset-based operations

The core of the BaaS model is to transform batteries from consumer goods into productive assets held by the firm. NIO's official documents already position the company beyond the role of a conventional automaker. The firm declares its commitment to becoming "a smart electric vehicle company offering a full-experience service", with energy services (NIO Power) as one of its core business segments. NIO's founder, Li Bin, has repeatedly stated publicly that BaaS and the battery-swapping model represent "systematic competitive advantages", the significance of which lies in "managing batteries as a recyclable, upgradeable asset across its full life cycle".

In 2024, this property rights restructuring deepened and scaled further. According to NIO's annual earnings reports and industry analyses, the share of users opting for BaaS has remained at a consistently elevated level, signalling that the market's acceptance of the model—which separates "the right to use the vehicle" from "battery ownership"—has matured. This strategic repositioning is directly reflected in the company's business model and asset structure. Through BaaS, battery asset ownership is transferred from consumers to NIO and its asset management partners, notably Wuhan Weineng Battery Asset Co., Ltd. (Weineng). The asset pool managed by Weineng achieved significant growth in 2024. Drawing on the company's disclosed battery pack volumes, capacities, and industry valuation models, cumulative battery assets under management had entered the "tens of GWh" range by end-2024, with a corresponding asset value of hundreds of CNY billion (estimated from NIO's 2023 Form 20-F and relevant 2024 quarterly earnings data). As shown in Table 1, this substantial asset base constitutes the material and financial foundation for NIO's practice of full life-cycle circular management, deeply binding its profit model to the long-term operational efficiency and residual value management of battery assets.

Table 1. Key operational data for NIO's BaaS model based on 2022–2024 public reports

Indicator	2024 Data	Circular Economy Implications
BaaS user penetration rate	> 80%	The model has become mainstream, providing a stable foundation for the scaled, centralised management of battery assets.

Table 1. Continued

Battery assets under management	> 20 GWh; valued at > CNY 20 billion	Establishes the asset base required for circular economy operations; the large asset pool is a prerequisite for technology iteration, health management, and cascade utilisation.
Cumulative battery-swapping stations (end of 2024)	≈ 3,100 stations	A continuously expanding physical infrastructure network underpins precision asset management and serves as a technical guarantee for vehicle–battery separation and efficient cycling.
Cumulative battery-swapping sessions (to Oct. 2024)	> 5 6.61 million sessions	Reflects the high-frequency turnover and shared utilisation efficiency of battery assets—a direct expression of value-maximising asset operations.
Annual vehicle deliveries (2024)	221,970 units	Sustained business scale growth continuously injects new increments into the asset pool and circular network.

Note: Data for battery assets under management are estimates derived from publicly available disclosures and industry pricing benchmarks.

4.2. Design behaviour: eco-design in service of asset value preservation and enhancement

Driven by the incentive of "maximising full life-cycle asset value", NIO's battery design has comprehensively pivoted toward serving long-term operations and circular utilisation. In 2024, the company for the first time systematically unveiled an operations-oriented "Long-Life Battery Strategy". This strategy aims, through material innovation and systems optimisation, to limit total capacity degradation to less than 20% after 12 years of use—a target that directly addresses the core need of an asset operator to minimise the per-unit-time depreciation cost of the battery.

The standardised battery-pack design for battery-swapping vehicles is another exemplar of eco-design. Despite the additional engineering complexity and initial costs involved in developing a single-specification pack for the entire vehicle lineup, this approach creates asset universality and network effects. A unified standard allows the pool of battery assets—numbering in the tens of thousands—to circulate freely across all NIO models and, potentially, across vehicles of other brands that join the swapping alliance in the future, substantially increasing the utilisation rate and potential service life of each individual battery asset. At its core, this design behaviour embeds the principles of "design for circularity" and "design for sharing" at the product-definition stage, laying the groundwork for subsequent large-scale, efficient circular utilisation.

4.3. Operational behaviour: the swapping network as a hub for asset efficiency optimisation

The battery-swapping network is the core infrastructure through which the BaaS model translates property rights advantages into operational efficiency. In 2024, NIO's swapping network made the leap from "deployment" to "densification". As shown in Table 2, cumulative stations surpassed 3,100 by year-end, with more than 1,000 new stations added during the year—maintaining a high rate of construction. Network coverage expanded in depth from the major national highway arteries (the "9 × 9" grid) to 19 urban agglomerations, and a "build-on-demand" and "battery-friendly neighbourhood" coverage initiative was launched to improve network accessibility.

Table 2. Key asset and operations data for NIO's BaaS model (2023–2024)

Dimension	Key Indicator	2023 Status/Data	2024 Latest Progress/Data	Source & Notes
Property Rights & Assets	BaaS user penetration rate	Sustained at high level (per Q4 earnings)	Stable at a high level	Based on management commentary in quarterly earnings reports
	Battery assets under management	~Tens of GWh (estimated)	Valued at hundreds of CNY billion	Estimated from Weineng ABS filings, battery pack volume, and industry average pricing
Infrastructure	Cumulative swapping stations	2,385 stations	~3,100 stations (as of 31 Dec 2024)	NIO official NIO Power Day and monthly operational data
	Stations added in year	1,080 stations (full-year 2023)	> 1,000 stations (2024)	NIO 2024 NIO Power Day announcement
	Highway swapping network coverage	"9 vertical × 9 horizontal" national highway network	Upgraded to "9 × 9 + 19 major urban agglomerations"	NIO 2024 NIO Power release
Operational Efficiency	Cumulative swapping sessions	> 38 million (as of end-2023)	56.61 million (as of Oct. 2024)	NIO 2024 NIO Power Day announcement
Technology Strategy	Battery longevity target	Long-term R&D direction	"Long-Life Battery Strategy" announced: target < 20% total capacity loss after 12 years	NIO 2024 NIO Day announcement

Note: Battery asset scale figures are estimates; all cumulative session data are sourced from NIO Power Day official announcements.

The extensive network supports impressive asset turnover. Cumulative battery-swapping sessions reached 56.61 million by October 2024 [11]. The significance of these high-frequency swapping operations extends far beyond energy replenishment: they underpin a continuously operating, large-scale, real-time battery asset monitoring and dispatching system that constitutes the operational backbone of the model's value proposition.

4.4. End-of-life behaviour: circular strategic deployment for industrial closed-loop construction

As early-deployed batteries progressively reach retirement criteria, NIO's end-of-life deployments have moved from technology reserves toward commercial practice. In the cascade utilisation domain, NIO has pursued diverse approaches. Its swapping stations inherently constitute a distributed energy storage network capable of participating in grid peak-shaving services through Vehicle-to-Grid (V2G) initiatives. More significantly, the company is collaborating with third-party energy storage operators to advance demonstration and application

projects deploying retired battery packs in commercial and industrial energy storage, low-speed electric vehicles, and base-station backup power—aiming to establish a scalable, high-value "second life" pathway for retired assets.

In the materials recovery phase, while NIO does not engage directly in metallurgical processing, it exercises deep involvement in closed-loop management through supply chain cooperation and strategic investment. The company implements "cradle-to-grave" traceability for its batteries, ensuring that retired packs flow to technologically advanced, regulatory-compliant partner recyclers to enable the efficient and environmentally sound recovery of critical metals such as cobalt, lithium, and nickel. NIO began disclosing information on battery material recovery in its 2023 ESG Report and has committed to continuously improving recovery rates.

Concurrently, NIO's "swapping alliance" open strategy, actively advanced in 2024, has seen strategic cooperation agreements signed with several major automakers including Changan Automobile, Geely Holding, and Chery Automobile. If successfully implemented, this initiative will drive the standardisation of battery packs across brands. Standardisation is a prerequisite for large-scale, automated disassembly and materials recovery, and can substantially reduce the total cost and complexity of traction battery circular utilisation through top-level industrial design—reflecting NIO's forward-looking ambition to evolve from managing its own assets to shaping the rules of the circular industrial ecosystem.

In summary, NIO's BaaS model has established the foundation for asset-based operations through property rights restructuring, and has used this incentive to drive a full-chain, circular-oriented transformation of corporate behaviour spanning battery design, operations, and end-of-life management. The 2024 evidence demonstrates that the model has transcended commercial innovation per se and, through infrastructure sharing, data-intelligent management, and ecosystem alliance construction, is substantively advancing the evolution of both NIO and the broader industry toward a traction battery full life-cycle circular system.

5. Discussion and mechanism elaboration

5.1. Reconfirmation of the core driving mechanism

The practice of NIO's BaaS model validates the effectiveness of the "Property Rights–Incentives–Behaviour" framework. Its core logic lies in internalising environmental externalities through property rights restructuring, generating incentive compatibility between commercial value and environmental value. Property rights centralisation serves as the prerequisite: the BaaS contract converts dispersed, privately held consumer assets into centrally managed corporate assets. The Weineng asset pool—reaching a scale of tens of GWh—provides the physical infrastructure for circular management and resolves the absence of circular incentives inherent in the conventional model. Incentive compatibility serves as the core driver: the imperative to "maximise full life-cycle asset value" motivates the firm to make circular-oriented decisions across the design, operations, and end-of-life chain—activities such as long-life battery R&D and swapping network construction are co-products of commercial rationality and environmental benefit. Behavioural transformation serves as the implementation pathway: the firm reorients from "product-centric" to "asset-centric", producing systemic behaviour characterised by eco-design on the supply side, high efficiency in operations, and closed-loop management at end-of-life. Through battery life extension (target: < 20% degradation over 12 years), cascade utilisation, and materials regeneration, NIO's BaaS model effectively reduces the life-cycle carbon emissions of traction batteries. NIO's 2023 ESG Report [12] discloses that the carbon footprint of its 75 kWh battery pack has reached the industry benchmark of 49 kg CO_2e/kWh, validating the feasibility of the proposed mechanism.

5.2. Multiple implications for circular industry development

First, the circular industry can achieve market-driven momentum through business model innovation. The BaaS model does not rely on policy subsidies; rather, it creates an endogenous "circularity-as-profit" mechanism through property rights and service innovation. This offers a reference point for circular transitions in sectors such as electronic waste and industrial solid waste, and aligns with China's policy direction for constructing a circular economy standards system (State Administration for Market Regulation, 2024 data). Second, infrastructure-led investment is critical for achieving scale. Although NIO's swapping network investment of over CNY 30 billion creates short-term financial pressure, the resulting centralised management node network—combined with the formation of a swapping alliance with eight automakers, enabling procurement scale efficiencies and shared operational resources—has led to substantial reductions in per-station operating costs. This suggests that the circular industry needs to strengthen investment in infrastructure such as inspection centres and material regeneration facilities. Third, ecosystem openness and standards unification improve circular efficiency. The swapping alliance promotes standardisation of battery specifications and interfaces, which can address the low disassembly efficiency caused by specification fragmentation in current traction battery recovery, providing a "standards-led, alliance-driven" practical pathway for circular industry ecosystem collaboration.

5.3. Challenges and sustainability considerations

The model's sustainability still faces three core challenges. First, financial pressure: according to NIO's 2024 Annual Report, net cash flows from investing activities were −CNY 4.958 billion, the debt-to-asset ratio rose to 87.3%, and battery assets valued at hundreds of CNY billion impose significant annual depreciation and impairment pressures. Second, technology iteration risk: the evolution of Cell-to-Chassis (CTC) technology and semi-solid-state batteries conflicts with the existing standardised swapping system; retrofitting the existing stock of approximately 3,100 swapping stations would cost over CNY 15 billion, and asset lock-in risk is pronounced. Third, ecosystem coordination barriers: the significant differences in technology roadmaps and commercial interests among alliance member automakers, combined with the high costs of coordinating standards unification and benefit distribution, mean that only framework agreements were signed in 2024, leaving implementation outcomes to be observed. Furthermore, the proliferation of 4C ultra-fast charging technology has eroded the convenience advantage of battery swapping: the proportion of BaaS users relying on high-frequency swapping has fallen to 41% (NIO 2024 user data), and intensifying external competition further exacerbates sustainability pressures. Future progress will require efficiency improvements, technological adaptation, and alliance mechanism optimisation to overcome these obstacles.

6. Conclusion and outlook

6.1. Research conclusions

Taking NIO Automotive's "Battery-as-a-Service" model as its case, this study provides an in-depth analysis of the intrinsic mechanism through which PSS drives circular industry development. The research finds that the core driving force of deep servitisation models such as BaaS originates from the chain reaction of "property rights restructuring → incentive reshaping → behavioural transformation". By converting batteries from sold commodities into long-term assets held and operated by the firm, business model innovation fundamentally establishes "maximising the total life-cycle value of battery assets" as the firm's core economic incentive. Under this incentive, the firm spontaneously evolves from a product manufacturer into a key actor in the

circular industrial ecosystem: as an eco-designer, it invests in long-life, standardised, and easily recyclable battery products; as an intelligent operator, it achieves dynamic asset dispatching, real-time monitoring, and health management through a capital-intensive swapping network, maximising in-service utilisation efficiency; and as a closed-loop integrator, it proactively lays out cascade utilisation and materials regeneration pathways to capture the ultimate residual value of its assets.

Operational data from 2024 demonstrate that this model has generated considerable asset operational scale and nascent network effects. The case evidence demonstrates that a well-designed business model can systematically embed life-cycle management principles into the firm's daily operations and strategic decision-making, providing compelling real-world evidence that "market mechanisms and commercial innovation can drive circular industrial transformation".

6.2. Limitations and future research directions

As an exploratory case study focused on a pioneering firm, the generalisability of this study's conclusions requires testing in broader industry contexts. While this study reveals the intrinsic mechanism by which PSS drives circular industry development, whether and how findings based on the NEV sector apply to industries with markedly different product values, technological characteristics, and market structures—such as consumer electronics, industrial equipment, or construction—remains to be validated through subsequent cross-case comparative research. Moreover, the data and materials drawn upon in this study are sourced primarily from firms' public disclosures and industry analysis reports; the specific internal financial models, operational cost structures, and detailed environmental benefit data lack the depth of primary data verification. This limits the study's conclusions largely to the level of mechanistic explanation and trend assessment, without enabling a precise quantitative evaluation of the model's economic and environmental performance.

Looking ahead, as China's first wave of large-scale, commercially deployed traction batteries reaches retirement, the circular pathways constructed by business models such as NIO's BaaS will face a comprehensive practical test. This represents not only a test of the commercial resilience of a single firm, but also a real-world evaluation of a circular economy development paradigm led by market forces and powered by business model innovation. The evolution of this process, the responses to its challenges, and its ultimate outcomes will provide an exceptionally valuable Chinese practical sample and theoretical deepening scenario for the global exploration of pathways to operationalise the circular economy.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Both authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Jie Ma. The first draft was written by Jie Ma and Hehua Li commented on previous versions. Both authors read and approved the final manuscript.

Data availability

All data supporting the findings of this study are derived from publicly available corporate reports, official announcements, and industry databases as cited in the reference list. No new primary datasets were generated.

References

[1] Frank, G. A., Mendes, H. G., Ayala, F. N., & Ghezzi, A. (2019). Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. *Technological Forecasting and Social Change, 141*, 341–351. https: //doi.org/10.1016/j.techfore.2019.01.014

[2] Feng, C., Gao, X., & Qi, K. (2025). Business model innovation and evolution during manufacturing enterprise servitisation: A longitudinal case study of Haier [in Chinese]. *Science and Technology Progress and Policy, 42*(22), 140–149.

[3] Zhang, Y., Zhou, M., & Zhou, Y. (2022). The mechanism of value creation in servitising manufacturing firms from a life-cycle perspective: A multi-case study [in Chinese]. *Management Case Studies Review, 15*(5), 563–581.

[4] Hu, Z., Yang, F., & Linghu, K. (2025). The mechanism by which value proposition influences firm performance during servitisation: A case analysis of three domestic manufacturing enterprises [in Chinese]. *Enterprise Economy, 44*(10), 56–66.

[5] Liu, T., Zheng, Y., & Han, L. (2025). Research on the effect of intelligent transformation on manufacturing servitisation [in Chinese]. *Shanghai Finance,* (9), 44–56.

[6] Hu, Y., & Han, Q. (2021). Evolutionary game analysis of value co-creation in product-service systems [in Chinese]. *Management Review, 33*(6), 242–254.

[7] Wang, S., Liu, F., & Guo, R. (2025a). Temporal–spatial evolution of factor allocation efficiency for technological innovation from a full life-cycle perspective [in Chinese]. *Statistics and Decision, 41*(16), 60–65.

[8] Wang, Y., Zhu, M., Zhang, Y., & Chen, L. (2025b). Optimal charging dispatch strategy for battery-swapping stations considering electricity market–renewable energy coupling [in Chinese]. *Electric Power Construction, 46*(6), 38–48.

[9] Wei, L., & Wang, C. (2024). Pricing and promotion strategy research on NEV charging and swapping modes [in Chinese]. *Systems Science and Mathematical Sciences, 44*(10), 3040–3053.

[10] Wu, J., Hao, M., & Huang, J. (2021). Research on the construction of enterprise innovation ecosystems in the "Internet+" environment: Taking NIO as an example [in Chinese]. *Soft Science, 35*(5), 70–77.

[11] NIO Inc. (2025). NIO power 2024 annual development and data report. NIO Inc.

[12] NIO Inc. (2024). Environmental, social and governance report 2023. NIO Inc.