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EDITORIAL

Journal homepage: www.the-innovation.org/energy-use

Energy Use

INNOVATION PRESS

Energy Use 1 (2026):100038

Contents lists available at INNOVATION PRESS

Commercial Vehicle Battery Swapping: A Pathway to Support Green and Low-Carbon Transport Energy Use

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Received: February 4, 2026; Accepted: March 17, 2026; Published Online: March 25, 2026; https://doi.org/10.59717/ipj.energy-use.2026.100038

Citation: Zhang Z., Hua H., Peng Q., et al. (2026). Commercial Vehicle Battery Swapping: A Pathway to Support Green and Low-Carbon Transport Energy Use. *Energy Use* **2**:100038.

Promoting transport electrification is a direct and effective pathway to improve end-use energy efficiency and reduce carbon emissions.[1] Commercial vehicles, which underpin freight logistics and construction activities, are typically operated at high utilization rates and thus display much higher emission intensity than passenger vehicles. Despite accounting for only around 12% of the national vehicle fleet, they produce more than 55% of transport-related carbon emissions.[2] Therefore, in the pursuit of the carbon peaking and carbon neutrality targets, accelerating new-energy adoption in commercial vehicles constitutes a key breakthrough for greening transport energy use.

Progress in Electrification and Core Bottlenecks

Data released by the China Association of Automobile Manufacturers (CAAM) in January 2025 indicate that domestic sales of new energy commercial vehicles reached 532,000 units, corresponding to a market penetration rate of 17.9%.[2] This is substantially lower than the 47.6% penetration rate of new energy passenger vehicles, underscoring the need to accelerate commercial-vehicle electrification. Unlike passenger mobility, however, commercial fleets operate under stricter requirements for high uptime, predictable energy replenishment, and low total cost of ownership, making the transition both technically and economically more demanding.

Among these constraints, high upfront cost and energy replenishment concerns remain particularly binding. New energy commercial vehicles are typically 30–50% more expensive than comparable conventional fuel vehicles, and key components such as batteries and fuel cell stacks account for more than 60% of total cost.[2] In addition, energy replenishment is significantly slower than refueling: under direct-current fast charging, fully charging a heavy-duty electric commercial vehicle typically requires 1.5–2 hours, while slow charging requires 6–7 hours. Such extended downtime disrupts dispatch schedules, reduces asset utilization, and can translate directly into revenue losses in time-sensitive freight and construction operations. Consequently, operational reliability and service availability often outweigh nominal energy-cost savings in users' decision-making, raising the bar for infrastructure coverage and service quality.

EFFICIENCY AND COST-REDUCTION ADVANTAGES OF BATTERY SWAPPING

Battery swapping offers an operationally competitive alternative. Compared with charging, swapping can complete replenishment in approximately 3–5 minutes, effectively alleviating replenishment concerns. For electric heavy-duty trucks, a swap can be completed in about 5 minutes, roughly an 18-fold improvement compared with typical 1.5-hour DC fast charging. This ultra-fast replenishment can materially improve fleet utilization and route feasibility, especially for high-mileage corridors and closed-loop logistics.

Swapping also enables a vehicle–battery separation (VBS) model that reduces upfront purchase cost. Users can deduct the battery price at purchase and pay a monthly battery leasing fee during operation, thereby lowering the initial capital burden and smoothing cash flow. At the same time, VBS can transfer battery residual-value and degradation risks to professional asset operators, relieving fleet users from concerns about battery aging, technology iteration, and resale uncertainty. If governed well, this "asset professionalization" can improve lifecycle management and accelerate market adoption.

Key Challenges for Large-Scale Deployment

Despite these advantages, large-scale deployment of commercial-vehicle battery swapping is constrained by three core challenges.

First, station supply remains insufficient and spatially uneven. Deployment is relatively weak in many logistics parks and remote corridors, which prevents long-haul fleets from accessing timely swapping services and undermines route reliability. Limited coverage also weakens network effects and user confidence, as commercial fleets typically require predictable service availability along key operating routes.

Second, high investment intensity and long payback periods suppress infrastructure roll-out. The construction cost of a heavy-duty truck battery swapping station is approximately 4.2 million yuan.[3] Beyond station construction, operators must also bear battery asset investment and grid connection and line-upgrade costs, and in some areas deployment is further constrained by transformer capacity, feeder limits, site availability, and permitting timelines—factors that collectively raise the true cost and extend the investment recovery horizon. High upfront expenditure coupled with uncertain utilization often exceeds enterprises' risk tolerance.

Third, a lack of unified standards and a limited profitability model hinder scalability and sustainability. Significant differences persist in battery specifications, interface protocols, and communication protocols, preventing cross-

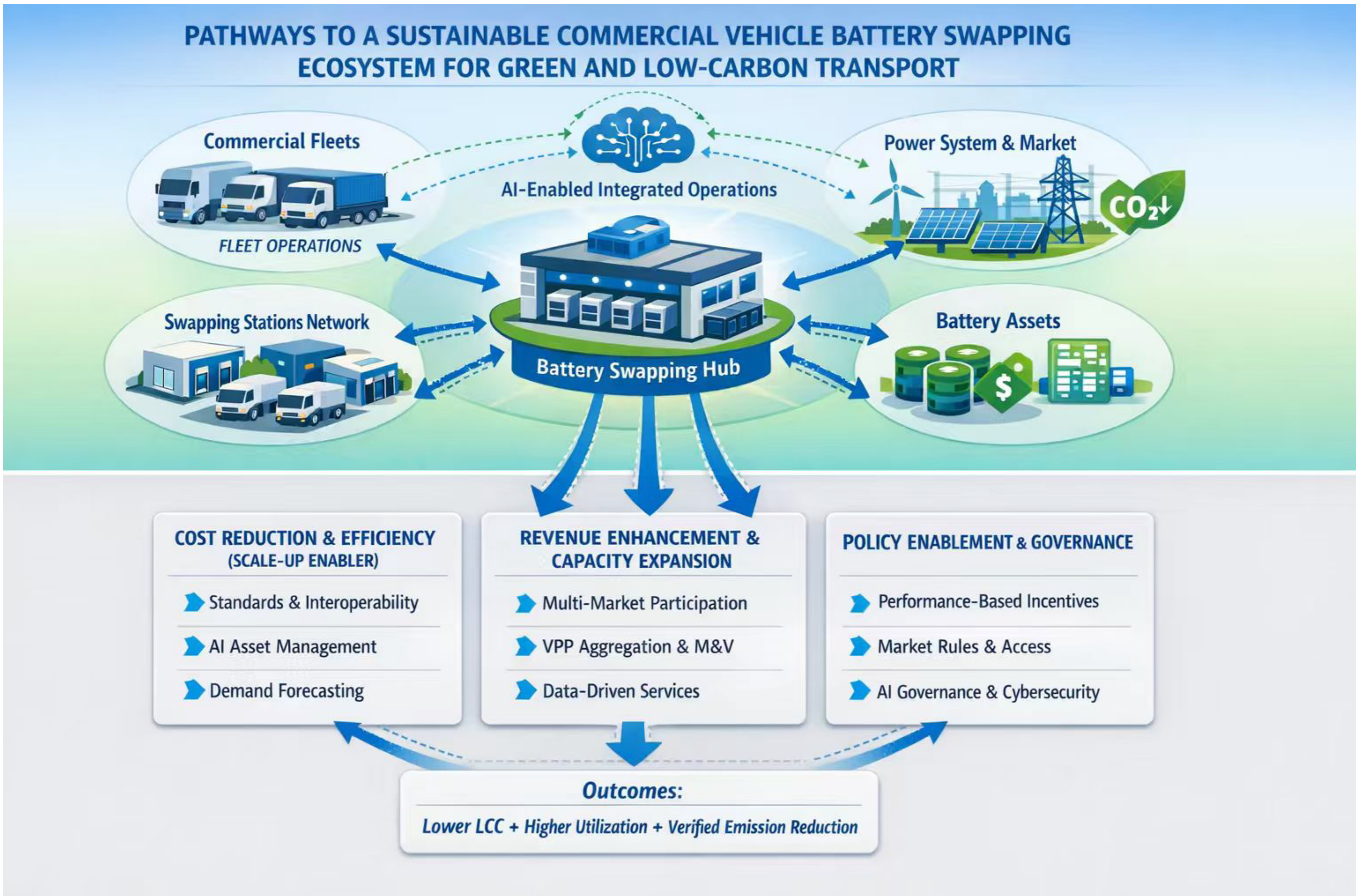

Figure 1. Pathways to sustainable commercial vehicle battery swapping ecosystem for green and low-carbon transport

brand interoperability. This fragmentation is amplified by the diversity of commercial vehicle types (e.g., tractor trucks, dump trucks, mixer trucks, and sanitation vehicles) and heterogeneous battery suppliers (e.g., CATL, Gotion High-Tech, BYD), which are generally not interoperable. While CATL has attempted to standardize passenger-vehicle swapping through its Choco-SEB solution, a broadly applicable solution for commercial vehicles remains absent. Meanwhile, revenues largely rely on swapping service fees and battery leasing, but techno-economic evidence suggests that swap-based truck energy-supply services become financially viable only at relatively high facility utilization, whereas observed utilization in practice is often lower.[3] Although idle battery resources could, in principle, participate in ancillary services such as peak shaving and frequency regulation, the value of swapping stations as distributed energy storage has not been effectively activated.

AI-Enabled Opportunities and Pathways Forward

With the rapid advancement of artificial intelligence, commercial-vehicle battery swapping systems are entering a new window of opportunity. AI has shown distinctive advantages in battery health management, intelligent scheduling, vehicle routing optimization, market transaction forecasting, and user behavior modeling.[3] These capabilities provide renewed technical support for addressing cost pressure, facilitating standard coordination, and enabling business model innovation, thereby reducing lifecycle costs, improving asset and station utilization, and enhancing operational reliability. More importantly, by integrating battery asset management, station dispatch, fleet routing, and power procurement into a unified operational framework, AI can reduce inefficiencies caused by fragmented decision-making. Consequently, deeply embedding AI into the battery swapping system is expected to become a key driver for accelerating the adoption of new energy commercial vehicles and promoting the sustainable development of battery swapping.

COST REDUCTION AND EFFICIENCY IMPROVEMENT: BREAKING SCALE-UP BOTTLENECKS

Standardization should be prioritized as a prerequisite for scale. A full-chain standards framework should specify swapping interfaces, battery pack dimensions, safety requirements, communication protocols, and data formats, with interoperability and safety as core objectives. Upgrading recommended standards into enforceable national standards, or ensuring compliance through policy instruments, can reduce fragmentation and prevent incompatible ecosystems. For high-frequency heavy-duty operation, safety-oriented standards remain essential, including thermal management, insulation protection, fault diagnosis, emergency response, and cybersecurity requirements for connected equipment.

In parallel, battery asset operations should be digitalized and optimized through AI-enabled lifecycle management. A unified battery asset management platform, supported by real-time monitoring and data integration across vehicles, batteries, and stations, can deploy intelligent algorithms for state-of-health estimation, remaining-life prediction, degradation risk early warning, and predictive maintenance. These capabilities improve asset utilization, extend service life, and increase residual value, thereby strengthening vehicle-battery separation and leasing models. For station operators, AI-driven forecasting of swap demand and battery circulation can reduce standby inventory, mitigate congestion, and improve service reliability. At end-of-life, intelligent sorting, automated dismantling, and material identification can improve recycling efficiency and economic viability, reduce reliance on primary raw materials, and support circular-economy objectives.

REVENUE ENHANCEMENT AND CAPACITY EXPANSION: EXTENDING DIVERSIFIED VALUE CHAINS

To strengthen station economics, swapping stations should pursue multi-market participation and diversified revenue models. If permitted to participate in electricity market transactions directly or via aggregators, stations can use AI to forecast prices and local loads, optimize charging schedules, and capture arbitrage opportunities under time-of-use price differentials while respecting operational constraints. Stations can also provide demand response and ancillary services through AI-based coordination of charging and discharging, allowing distributed swapping assets to deliver grid support without compromising fleet service quality.[4]

A practical case indicates feasibility. The aggregation platform operated by State Grid Jibei Clean Energy Vehicle Company integrated 11 electric heavy-duty truck charging and swapping stations in Tangshan. Over five months, the heavy-duty-truck virtual power plant delivered 786,600 kWh of effective peak-shaving response, and station operators received total revenue of 364,500 yuan. This case illustrates that the combined value proposition of mobility infrastructure and grid services can be viable when dispatch, telemetry, and measurement and verification capabilities are in place. AI plays a central role in this linkage by improving forecasting accuracy, enabling real-time scheduling, and supporting auditable performance verification.

Data-driven services can further expand value. Swapping networks generate high-frequency operational data, including swap demand, charging windows, battery availability, and energy consumption patterns. AI-based modeling can support fleet dispatch optimization, route planning, energy-efficiency analytics, and service personalization, helping transport enterprises reduce costs and improve service quality. With standardized data interfaces and appropriate privacy protection, these data products can also support traffic governance and emissions monitoring, creating broader public value and additional service revenue streams.

POLICY ENABLEMENT: BUILDING AN INCENTIVE-COMPATIBLE MECHANISM

Policy design should build an incentive-compatible mechanism. Fiscal support can shift toward performance-based subsidies tied to verified service volumes, reliability metrics, and emissions reduction outcomes,[5] improving the efficiency of public spending and encouraging operational excellence rather than simple capacity expansion. For high-capex early-stage networks, policy tools can also include low-interest financing, risk-sharing mechanisms, and corridor-oriented deployment packages to reduce first-mover disadvantages.

Electricity market rules should be refined to unlock grid-value realization. Clear entry requirements for swapping stations, transparent trading mechanisms, and benefit-allocation rules can provide predictable returns for stations delivering grid services. For AI-enabled virtual power plants, dedicated governance rules are needed to address risks related to algorithmic opacity and data monopolization, while ensuring cybersecurity and data protection. National pilots in representative logistics corridors, port transport channels, and industrial parks can validate business models, consolidate replicable practices, and support progressive scale-up toward a unified national intelligent swapping ecosystem.

CONCLUSION

Battery swapping is a practical pathway to address replenishment constraints for new energy commercial vehicles, but large-scale deployment is hindered by high costs, insufficient standardization, uneven coverage, and limited revenue structures. AI can reduce lifecycle costs, improve station scheduling and battery asset utilization, enable market participation, and unlock data-driven services. As illustrated in Figure 1, with coordinated progress in standardization, digital operations, intelligent enablement, and policy support, China can accelerate the adoption of new energy commercial vehicles and strengthen a resilient, efficient, and low-carbon transport energy system.

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FUNDING AND ACKNOWLEDGMENTS

This work was supported in part by the National Key Research and Development Program of China under Grant 2022YFE0140600; in part by the National Natural Science Foundation of China under Grant 52377093; in part by funding of Russian ministry of science and higher education No. FWEU-2026-0015.

DECLARATION OF INTERESTS

The authors declare no competing interests.