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Integration of electric freight logistics and energy communities: a system - level operating model

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Abstract: The electrification of road freight transport is a priority objective of European decarbonisation policy; however, its large-scale implementation remains constrained by charging infrastructure availability, electricity grid capacity limits, and the specific energy demand profiles of freight transport operations. From a logistics perspective, this transition requires coordinated management of material, information, and energy flows within increasingly complex transport systems. The aim of this research is to examine how electric freight vehicles can be integrated into future logistics networks through operating models based on energy community principles. The study is grounded in a systematic review of relevant literature published between 2020 and 2025, focusing on technological trends, electric road freight vehicles, and energy supply configurations. The analysis indicates that existing research predominantly addresses route optimisation, infrastructure development, and capacity management, while system-level cooperation between energy communities and electric freight transport remains underexplored. The study proposes a conceptual model based on replaceable high-capacity energy storage units and decentralised charging infrastructure, enabling improved coordination between transport flows and energy flows. The framework supports more efficient utilisation of renewable energy and enhanced economic and network performance and is positioned relative to prevailing logistics and operational paradigms.

1 Introduction

Electrification of the transport sector is widely recognised as a key instrument of European decarbonisation policy. In the context of road freight logistics, however, electrification does not represent a simple technological substitution, but a structural transformation affecting transport operations, infrastructure planning, and supply chain coordination. The transition introduces additional constraints related to charging time, battery capacity, and grid integration, which directly influence transport flow management and network performance.

Recent studies [1] and [2] underline the increasing charging demand of heavy-duty vehicles and the resulting pressure on electricity distribution networks. At the same time, advances in energy storage integration and vehicle-to-grid (V2G) applications [3-5] suggest that electric freight vehicles may play a broader role within decentralised energy systems. Despite these developments, current research remains largely centred on route optimisation and charging infrastructure placement, with limited attention given to the integrated coordination of logistics networks and energy community structures.

Against this background, the present study develops a system-level perspective that connects freight transport operations with decentralised energy community frameworks.

2 Systematic literature review on logistics energy system integration

To ensure a comprehensive and methodologically rigorous examination of the topic, a systematic literature review (SLR) methodology was applied (Figure 1).

1. Description of motivation: The aim of the current research is to explore new opportunities for a two-way cooperation model between energy communities and electric vehicles after analysing the relevant literature on the electrification of road transport vehicles.

2. Formulation of research questions: The research aimed to answer the following questions:

- What are the development trends in the operation of electric road transport vehicles?
- What are the current operating models for electric road freight transport?

3. Defining keywords and their combinations: In order to answer the specific questions, publications were identified in the Scopus database using the following keywords: electric vehicle, logistics, freight transport, renewable energy, energy community.

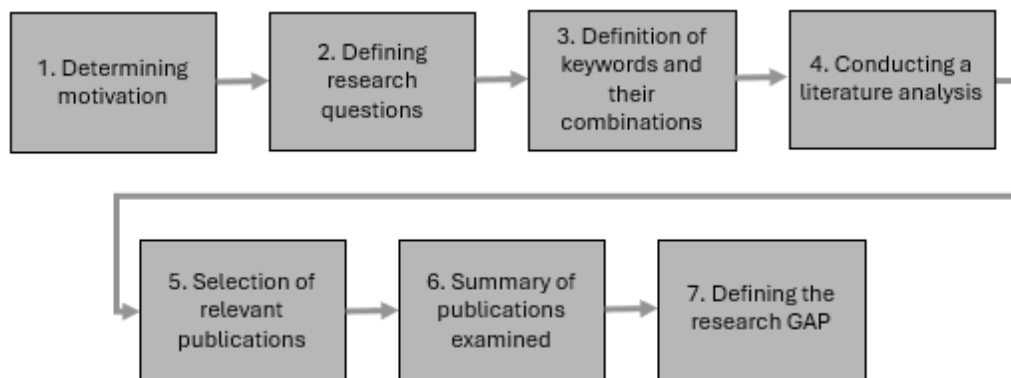


Figure 1 Steps of the systematic literature review [self-edited]

The following search string was used, which identified 223 documents:

(electromobility OR "electric vehicle" OR "electric freight" OR e-mobility) AND (logistics OR freight OR "urban logistics" OR "transport system*") AND ("energy community" OR "local energy community" OR "renewable energy community" OR "energy sharing" OR "microgrid" OR "smart grid" OR "vehicle-to-grid" OR "V2G" OR "distributed energy resource*" OR "DER integration")*

In order to focus on the most relevant publications, the number of articles was narrowed down as shown in Figure 2:

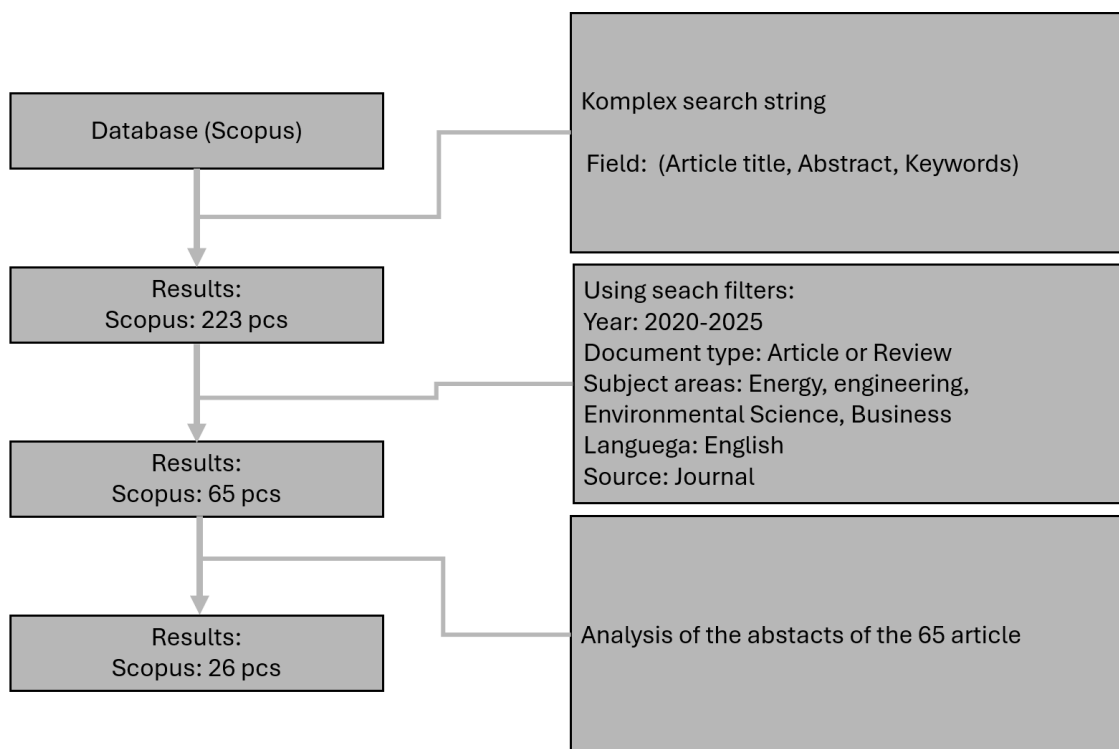


Figure 2 Process of literature analysis [self-edited]

4. Conducting a Literature Analysis

Based on the complexity of the search string, the filters applied, and a preliminary review of the titles of the results, the resulting sample of 65 publications was considered sufficient for in-depth thematic analysis, so no further narrowing was applied.

5. Selection of relevant publications

Abstract-level screening revealed that numerous studies deal with fleet-level electromobility and logistics vehicles in terms of urban freight transport, road transport, and last-mile delivery. The sample was subsequently narrowed down to 26 relevant studies focusing specifically on road freight transport, alternative energy production, energy communities, and the research questions formulated in Section 2.

6. Summary of publications examined

Current research and development trends:

In order to review current research trends in electric road freight transport, a detailed analysis of the relevant literature was conducted. The aim of the analysis was to identify which vehicle categories, technological solutions and operating concepts are currently the focus of scientific research. Table 1 summarises the key development trends, with a particular focus on vehicle technology, charging infrastructure optimisation and solutions for integrating electric freight transport into the energy system.

Table 1 Research and development trends [self-edited]

Areas under investigation	Main findings/direction	Application context	Related references
Main vehicle categories	Dominance of electric trucks and light commercial vehicles	Urban and long-distance freight transport	[1,2,4,9,21-23]
Infrastructure development direction	Optimisation of charging infrastructure location and sizing	Depot charging, public charging network	[10,15,16]
Digital and optimisation tools	Smart charging stations, IoT-based data collection, MILP models	Fleet management, energy demand forecasting	[24,25]
Location optimisation of charging points	Reducing network losses and increasing security of supply	Electricity distribution networks	[6,7]
Vehicle technology trends	Comparison of BEV and FCEV systems	Short- and long-distance freight transport	[2,28]
Energy system integration	Application of V2G technology	Reducing peak grid loads, cost optimisation	[3-5,11,27,28]
Sustainability and operational performance in road freight	Link between environmental sustainability and logistics operational efficiency	Road freight sector	[29,30]

Current models of electric road freight transport

Scientific work on electrified road transport focuses mainly on optimising traditional transport, route planning, and charging habits. Early studies on smart grids primarily interpreted electric vehicles as controllable loads within the energy system, focusing on demand management rather than their potential role as active elements of decentralized energy systems [8]. Some of the research is based on integrated logistics-energy models that examine the joint optimization of heavy goods vehicle fleets, charging infrastructure, and distributed energy generation (DER) at the regional or terminal level [9,10]. While advanced charging control strategies, such as priority-based or fuzzy logic approaches, improve the performance of local networks, they are typically implemented at the level of individual vehicles or stations and do not take into account coordination mechanisms within the energy community [11]. Several studies analyse the integration of photovoltaic power generation and fast charging infrastructures based on demand and energy forecasts; however, these solutions are typically based on stationary storage concepts and fixed charging locations [12]. Another group of publications presents fleet operation and charging management models, where the focus is on route planning [13] and the coordination of depot and public charging [14-16]. These approaches aim to implement an electrified version of traditional freight transport logic. Table 2 contains only studies that present specific electric freight transport operating models and are directly related to fleet operation, charging decisions, route planning, or freight transport logistics costs. General energy system, smart city, or autonomous transport models have been deliberately excluded.

Table 2 Current models of road freight transport [self-edited]

Model type	Focus / operating logic	Ref.
Integrated logistics–energy model	Heavy goods vehicle fleet, micro-network, DER, TCO-based optimisation	[9]
Terminal-level integrated model	Joint planning of fleet, charging infrastructure and energy storage	[10]
Fleet-level energy management	Operation of EV fleet as an aggregated energy storage system	[14]
Fleet operation model	Coordination of depot and public charging	[15]
Route and charging scheduling model	Optimisation of logistics costs and energy requirements	[16]

In general, the analysis indicates that the aim of the models examined is to achieve the smallest possible deviation from traditional transport, as illustrated in Figure 3, taking into account the charging limitations of the vehicles.

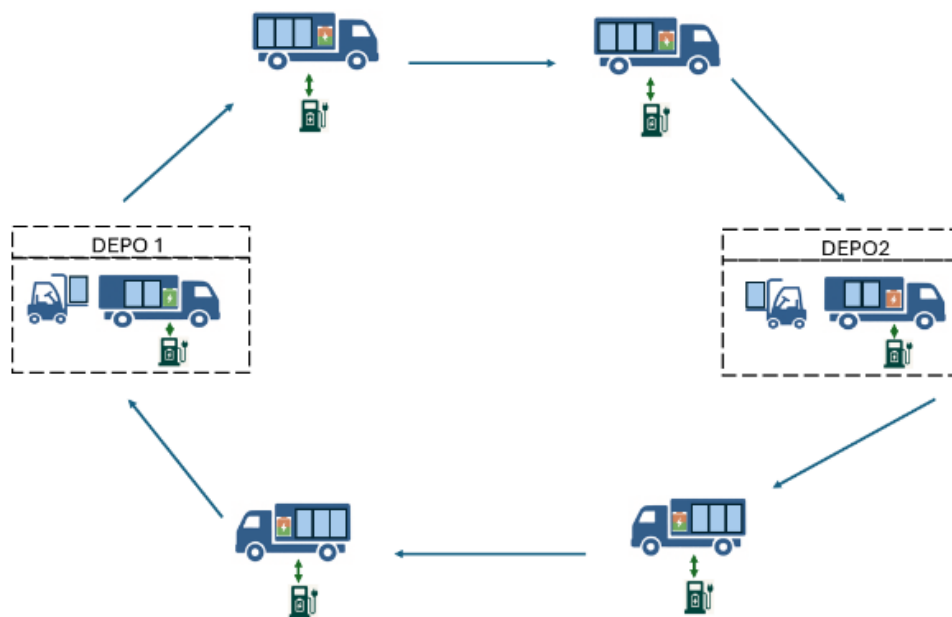


Figure 3 Traditional model [self-edited]

A common feature of the operational models presented is that they interpret electric road freight transport as an electrified version of traditional transport logic. In all cases, the main objective is to achieve the smallest possible deviation from traditional freight transport operations, even with the range and charging limitations of the vehicles. Industrial pilot projects and strategic partnerships between logistics service providers and vehicle manufacturers demonstrate the growing interest in electrified long-distance freight transport, although these initiatives are still largely based on traditional charging paradigms [17]. Integrated logistics-energy models examine the operation of heavy goods vehicle fleets, charging infrastructure and distributed energy resources (DER) at regional or terminal level within a common optimisation framework.

In the case of terminal-level integrated models, logistics hubs – such as distribution centres or depots – become the central units of analysis. These approaches jointly plan fleet size, the number and location of charging points, and energy storage capacities. Here, too, the operating logic is strongly linked to depot-based freight transport, where vehicles are charged at specific locations and time slots.

Fleet-level energy management models treat electric vehicle batteries as aggregated energy storage devices and focus primarily on reducing energy costs and optimising network charges. Although this approach is closer to integration with the energy system, vehicles are still treated as units with fixed energy storage.

Fleet operation and route and charging scheduling models are most directly related to daily freight transport practices. Their aim is to coordinate routes, charging times and charging locations in order to minimise logistics costs and energy consumption. The models typically operate in deterministic or limited stochastic environments and treat electric vehicles as functional equivalents of conventional fleets.

Similar challenges in system-level coordination were also found in other areas of transport, for example in maritime logistics, where a joint optimization of logistics planning and energy management is required to ensure operational flexibility [18].

Overall, the analysis indicates that most operational models conceptualise electric road freight transport primarily as an adaptation of conventional logistics structures, in which the characteristics of electric propulsion must be adapted to existing logistics structures. Although some approaches already apply an integrated logistics-energy perspective, system-level concepts integrating mobile, replaceable energy storage within energy community frameworks remain insufficiently developed.

7. Defining research gap in logistics–energy system coordination

Although numerous studies analyse the coordination of electric transport systems and decentralised energy resources within smart city environments, limited attention has been given to the specific logistics requirements of road freight transport and the integrated management of material and energy flows in supply chain networks [19]. Existing research primarily interprets electrification as an adaptation of conventional logistics processes, treating electric vehicles as energy-constrained transport units with fixed storage capacity. Consequently, the potential role of swappable energy storage systems and the system-level integration of freight transport into energy community frameworks remain insufficiently explored.

This gap is particularly relevant from a logistics perspective, where the coordination of transport flows, energy flows, and infrastructure capacity determines operational efficiency and network stability. The scientific novelty of this study lies in proposing a system-level operating model that repositions electric freight transport as an active, mobile energy storage component within decentralised energy communities.

3 Results - presentation of the new model

Based on the identified research gap, a system-level redesign of the charging concept is proposed for energy storage devices in road vehicles. The operational efficiency of a community aimed at optimising electrified road transport is based on the functional selection of participants. These actors are located at different points in the energy production, distribution, consumption and services chain. However, they can also perform multiple functions within the energy community. Transport companies, for example, can also be participants in the system through the production, use and transport of energy via their vehicle batteries. Production companies represent the customer side of the logistics chain, but at the same time they are also potential producers and consumers of energy. Electricity suppliers provide the basis for the stable operation of the system, but the management of energy produced by local energy producers in a constantly changing manner is a challenge for them.

The hierarchical structure of the model:

1. Energy producers (PV systems)
2. Energy suppliers
3. Transport companies, consumers and mobile energy storage facilities
4. Manufacturing companies
5. Coordinating integrator (central BMS server operator)

High penetration of distributed PV systems introduces significant balancing challenges for electricity suppliers due to the network load caused by production peaks. A new energy community model (Figure 4) offers an effective solution for capturing and redistributing surplus energy over time without overloading the grid. By operating transport vehicles with replaceable energy storage devices, it enables the creation of a circular logistics process with the following objectives:

1. Replacing the storage units of vehicles arriving at the depot or loading area (battery swap)
2. Transporting depleted storage units to a charging point
3. Charging of storage units
4. Transporting the charged storage units to the battery swap area
5. Loading the vehicle in parallel with or after the storage swap.
6. Continuous execution of the operational cycle

The operation of the system is coordinated by an organisation that acts as a coordinator and integrator, operating the central BMS (Battery Management System) server and responsible for optimising energy and information flows, scheduling charging and replacement processes, and settling accounts between the market participants involved.

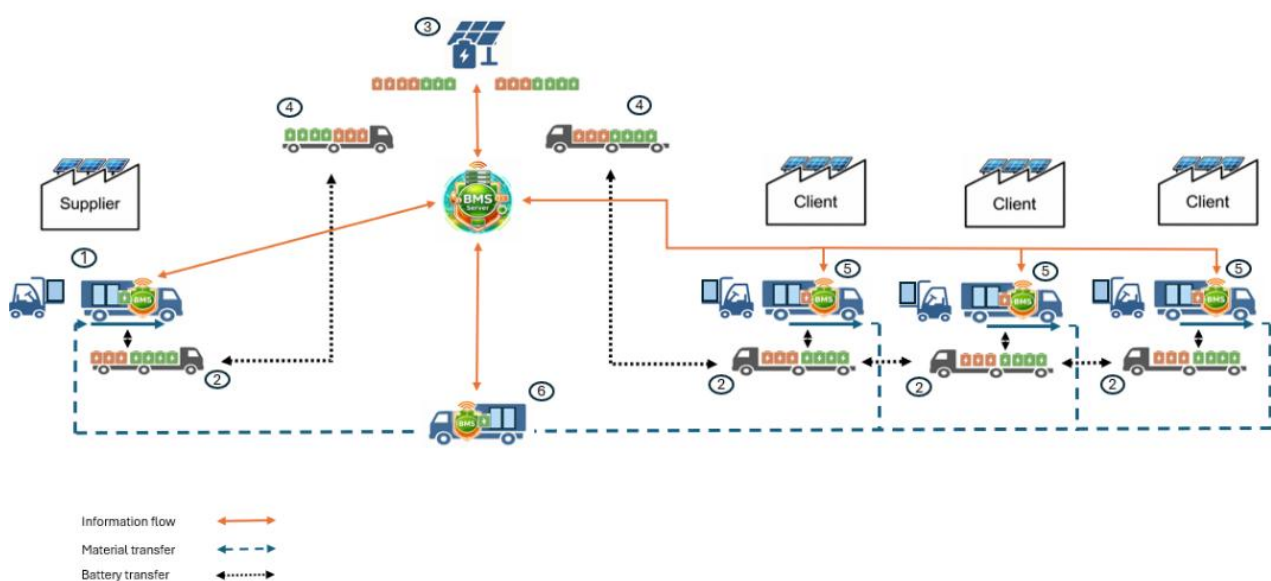


Figure 4 New model [self-edited]

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There are several approaches to settlement within energy communities, but the organised spot market structure applied by HUPX is particularly compatible with the proposed operational framework (Figure 5). HUPX's day-ahead and intraday markets provide transparent, market-based reference prices that are suitable as a basis for energy allocation and settlement within the energy community. The system is based on a battery swap logistics cycle, which is controlled by the central BMS server using a charging strategy aligned with HUPX spot market prices. Charging and replacement processes are optimised at 15-minute intervals, taking into account day-ahead and intraday market prices and available solar production. Settlement within the energy community is linked to the HUPX reference, supplemented by operational and flexibility components, ensuring transparent and auditable cost sharing and supporting operational cost allocation within freight logistics networks. Interchangeable energy storage devices provide physical flexibility, reducing the risks associated with balance group deviations while contributing to the smoothing of network loads.

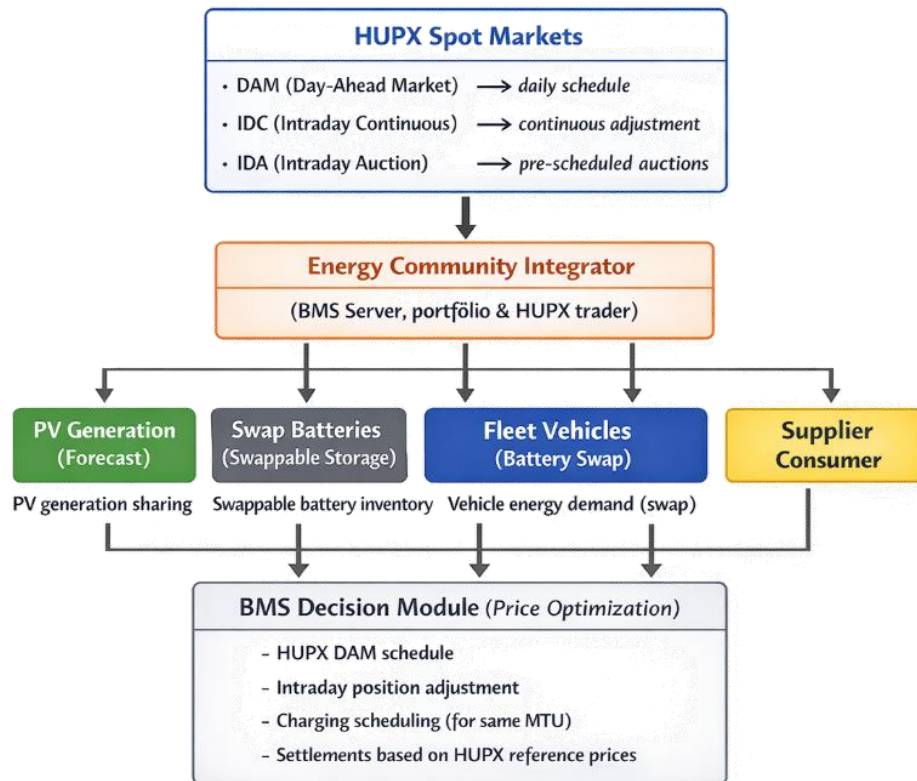


Figure 5 HUPX-based energy community optimisation framework [self-edited]

The model's operation is consistent with the data reporting and market compliance requirements of organised electricity markets, ensuring the system's long-term scalability and market integration. Table 3 shows a comparison between the proposed system model and the traditional operating model.

Table 3 Comparison of operating approaches [self-edited]

Aspects	Traditional approach	Energy community-based approach
Conceptual approach	Preserves traditional freight transport logic with minimal deviation using electric propulsion	System-level redesign integrating transport and energy systems within an energy community
Role of the vehicle	Primarily an energy consumer with a fixed onboard battery	Energy consumer and mobile energy storage unit
Energy storage type	Fixed, non-swappable battery	Swappable battery (battery swapping concept)
Charging concept	Direct vehicle charging at fixed or high-power charging stations	Decoupled charging of batteries optimised in time and location
Renewable energy integration	Limited and mostly indirect	Direct and active integration within the energy community

Handling of PV peak production	Not addressed at system level	Excess energy absorbed and temporarily shifted via storage
V2G applicability	Limited, vehicle-level implementation	System-level, business-oriented V2G integration

The comparison highlights that while the traditional approach essentially preserves the classic transport logic and treats electric propulsion primarily as an alternative energy source, the energy community-based model implements a system-level redesign that integrates transport and energy subsystems within an integrated system framework. For transport companies, the model offers significant cost-cutting opportunities, such as reduced transport and maintenance costs and the use of V2G technology, which allows the battery capacity of transport vehicles to become a source of revenue in the free-market energy trade. For manufacturing companies, it offers reduced logistics costs and increased energy stability, which provides a competitive advantage in the market. For electricity suppliers, decentralised energy storage reduces the peak effects of PV systems, enabling network development cost reductions and optimal scheduling. For renewable energy producers, it ensures stable returns and business stability. Overall, energy efficiency increases across the entire energy community, system-level instability decreases, and positive economic effects are expected, such as a reduction in import energy demand.

4 Discussion

The proposed framework suggests that electric road freight transport should be interpreted not merely as an electrified extension of conventional logistics systems, but as an integrated element of decentralised energy communities embedded within supply chain networks. By positioning electric freight vehicles as mobile energy storage units, the model expands the prevailing research perspective, which has predominantly focused on route optimisation, charging infrastructure placement, and fleet-level energy management.

The spatial and temporal decoupling of battery charging from vehicle operation introduces additional flexibility into transport flow management and supports improved coordination between material flows and energy flows. Such system-level integration is particularly relevant in logistics environments characterised by infrastructure constraints and high penetration of renewable energy sources. The incorporation of organised electricity market mechanisms, including HUPX pricing structures, further connects logistics decision-making with market-based energy signals, strengthening the economic feasibility of coordinated logistics–energy operation.

These findings indicate that enhanced synchronisation of transport operations and decentralised energy management may represent a decisive factor in the long-term development of electric freight logistics.

5 Conclusion

The electrification of road freight transport has become a key area of research in sustainable logistics in recent years. Based on the literature review, current scientific approaches primarily focus on the electrification of traditional logistics operations, with particular emphasis on route optimisation, charging infrastructure placement, and vehicle fleet energy management, while less attention is paid to the integrated coordination of logistics and energy systems. In response to this shortcoming, this study presents a model that interprets electric freight vehicles as active, mobile energy storage elements of energy communities. The use of replaceable, high-capacity energy storage devices allows the charging process to be separated spatially and temporally from vehicle operation, reducing downtime and facilitating the more efficient integration of renewable energy sources. From a logistics perspective, this approach supports improved coordination of material flows and energy flows within transport networks. The energy community-based model offers a solution to logistical, energy and economic challenges at the same time: decentralised energy storage reduces peak grid loads, enhances system stability, and creates additional business opportunities through V2G-based services. The findings indicate that the future development of electric freight transport depends increasingly on the systemic integration of logistics operations and decentralised energy management. Future research should prioritise quantitative modelling, simulation-based validation, and pilot-scale implementation studies, in order to identify the economic and operational conditions required for broader application.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process: During the preparation of this manuscript, the author used ChatGPT (OpenAI) to improve language clarity and stylistic quality. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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Review process

Single-blind peer review process.