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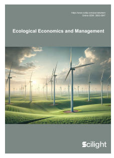

Article

Hydrogen Fuel Cell Vehicles and the Green Logistics Transition in the Beijing-Tianjin-Hebei Urban Agglomeration

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Abstract: As a promising option in the heavy-duty logistics sector, hydrogen fuel cell vehicles are widely applied in freight transport. However, high operating costs, inadequate supporting facilities and technical bottlenecks hinder their large-scale application. This paper takes the Beijing-Tianjin-Hebei urban agglomeration as a qualitative case to explore hydrogen logistics from the perspective of ecological economics and management. Based on existing literature and industrial data, it constructs a conceptual framework and analyzes the mechanism of key influencing factors. The results show that balancing energy supply and freight demand, optimizing incentive and subsidy mechanisms, rationalizing scenario planning, and conducting risk control via standards and data can guarantee the sound development of hydrogen logistics. Different from traditional studies focusing on vehicle substitution, this research takes regional transformation management as the core and enriches relevant studies in this field. For domestic urban agglomerations committed to developing green freight corridors, advancing the sharing of hydrogen refuelling facilities and implementing efficiency-oriented support policies, the proposed management suggestions are informative and practical.

Keywords: hydrogen fuel cell vehicles; green logistics; ecological economics; Beijing-Tianjin-Hebei; conceptual framework; sustainability transition

1. Introduction

Decarbonizing freight transport requires coordination of ecological, economic and governance systems, posing considerable challenges. The logistics sector, a key driver of production and trade, suffers from excessive diesel use, compact facility layout and high energy consumption. Environmental policies force enterprises to reduce emissions, while logistics operators need to strictly abide by delivery timeliness, loading standards and cost targets. To meet various requirements, relying solely on environmental protection technology is far from enough. Only by adopting mature business models, stabilizing infrastructure and improving governance can we truly realize the transformation. Hydrogen fuel cell vehicles are deeply involved in this contradiction. They have the advantages of zero emission and rapid refuelling, but face high upstream costs and challenges in cross-regional collaborative layout. Hydrogen has received growing attention in studies of low carbon economic transition because it can connect renewable electricity, industrial decarbonization, transport applications, and energy storage [1]. In China, clean hydrogen is also recognized as a potential route for addressing hard to abate sectors, including heavy industry and freight transport [2]. However, whether hydrogen energy is environmentally friendly cannot be proved by the operation of vehicles. From hydrogen production, storage and transportation to the actual use of vehicles, each link will affect the final environmental protection effect of hydrogen energy. Accordingly, the analysis of hydrogen energy logistics needs to be based on the regional comprehensive system, rather than looking at this technology in isolation.

Existing research has made important progress in explaining the technical and economic promise of hydrogen. Studies have reviewed hydrogen society pathways, production routes, supply and demand drivers, and clean hydrogen cost competitiveness [3]. Other work has examined hydrogen supply chains, business models, and subsidy design [4]. Despite their contributions, existing works rarely address how hydrogen can be deployed in the logistics networks of large urban agglomerations. Furthermore, the industry is plagued by unequal benefit and cost allocation between upstream and downstream participants, making cross-stakeholder collaboration difficult. As a major research topic in ecological economics, inter-agent coordination reveals that environmental goals cannot be achieved without robust institutional and market support.

The Beijing-Tianjin-Hebei Urban Agglomeration is adopted as the research case for this study. Pure electric trucks have been deployed at Tianjin Port to advance regional emission reduction. During the service period, the pure electric truck is suitable for short distance and port operation, but it is difficult to cope with regional long-distance heavy haul transportation, and the endurance, load and energy replenishment time are significant challenges. This context provides a unique opportunity to examine hydrogen fuel cell vehicles (HFCVs) as a complementary technology that may address the limitations of battery electrification in the most demanding freight scenarios [5]. From the perspective of advantages, the Beijing-Tianjin-Hebei region is full of freight trunk lines, key industrial zones, ports, airports and urban distribution networks, and the surrounding renewable energy reserves are rich. At the same time, regional air pollution control and low-carbon development pose arduous tasks. Local scenarios including port logistics, airport freight and intercity heavy haul show high compatibility with hydrogen fuel cell vehicles. The region also needs to advance intercity infrastructure coordination, mitigate pressures from high hydrogen prices and vehicle procurement costs, enforce safety supervision, and turn demonstration projects into regular logistics operations.

From the perspective of regional planning, this paper explores the specific path of the development of hydrogen fuel cell vehicle enabling green logistics. To fully explain this issue, it is necessary to take into account the policy environment, economic incentives, technical routes and management mechanisms, which dominate the investment direction, enterprise selection, application scenarios and daily operations respectively. These elements are often analyzed separately, but logistics transition requires them to be examined together [6].

This study constructs a multi-dimensional conceptual framework for hydrogen energy logistics covering ecological, policy, economic, technological and managerial dimensions to support sustainable development. Based on literature synthesis, policy interpretation and project analysis, this qualitative research applies the framework to the Beijing-Tianjin-Hebei Urban Agglomeration to explore the practical governance logic of low-carbon logistics transformation. This research further situates hydrogen logistics within the interdisciplinary perspective of transformation governance, integrating environmental, industrial and governance factors to systematically analyze the practical obstacles and developmental paths of regional hydrogen freight development [7].

2. Literature Review

Extant investigations into hydrogen energy green transition firstly focus on environmental performance, laying a basic analytical foundation for industrial application. Existing research initially focuses on the environmental adaptability of hydrogen in modern energy systems, and has subsequently shifted focus to the economic constraints limiting its large-scale industrial application. Evaluations of business models indicate that hydrogen systems require integrated planning aligning application scenarios with investment structures. Subsequent analyses focus on operational decision-making among logistics enterprises as end-users of hydrogen facilities. Ultimately, existing work explores institutional frameworks and governance mechanisms required to support the rollout of hydrogen-related industries. In terms of ecological sustainability and energy system transformation, green hydrogen is widely recognised as a medium linking renewable electricity to sectors that are difficult to electrify directly. Analyses of hydrogen generation reveal that hydrogen can be produced from fossil fuels, industrial byproducts or renewable electricity, yet these generation routes feature marked differences in carbon intensity and costs. Hydrogen generates ecological benefits only when low-carbon energy supports its generation and deployment alongside high facility utilisation rates. Relevant literature thus highlights that hydrogen logistics cannot deliver inherent environmental advantages unless such preconditions are fully satisfied [8,9].

Based on environmental research outcomes, extant studies further explore economic constraints restricting the large-scale promotion of hydrogen energy. Even if hydrogen satisfies environmental requirements, its widespread uptake is constrained by economic factors. Regarding economic transition and cost structures, hydrogen adoption involves expenditures covering production, storage, delivery, refuelling infrastructure, vehicle components, maintenance and operational downtime. Assessments of hydrogen cost competitiveness reveal that green hydrogen still faces substantial economic barriers across most application scenarios, particularly amid fragmented market demand and underutilised infrastructure. Analyses focusing on cost reduction and market demand in China also indicate that scale expansion, learning effects and policy support facilitate cost declines over time, though progress remains uneven [10,11]. In this context, evaluating hydrogen logistics solely by purchase subsidies lacks comprehensiveness. The core economic challenge lies in whether regional stakeholders can improve resource utilisation, share operational risks and formulate solutions to cut overall operating costs.

To address economic cost dilemmas, current studies turn to exploring feasible supply chain and business model optimisation strategies. Against such cost constraints, researchers have probed feasible operational frameworks for industrial promotion. From the perspective of hydrogen supply chains and business models, hydrogen logistics encompasses the complete chain of production, storage, transportation, refuelling station operation, vehicle scheduling, maintenance and safety management. Supply chain analyses confirm that the delivered cost of hydrogen is highly responsive to transportation distance, pressure levels, storage technologies and station throughput. Analyses of business models suggest that hydrogen systems require integrated planning that aligns application scenarios with investment structures. Studies on digital supply chains and industrial practice further highlight that efficient information exchange and rigorous evaluation of application prospects form the foundation of industrial development. Such insights are highly applicable to freight transport, where fleets operate along fixed routes and rely heavily on integrated refuelling networks. Even with technically mature equipment, refuelling layouts mismatched with freight flows will compromise operational performance. Accordingly, academics advocate scenario-oriented planning as well as collaborative partnerships between infrastructure investors and logistics operators.

Reasonable supply chain design requires matched enterprise operation management to achieve practical industrial effects. They conduct holistic assessments covering vehicle reliability, route adaptability, fuel accessibility, driver training, maintenance services, residual asset value and shipper demand for low-carbon logistics services. Small and medium-sized logistics enterprises face notable financial and operational risks. Analyses of subsidy policies for green hydrogen generation confirm that targeted policy design can accelerate industrial deployment, yet support schemes should be tied to operational performance and market learning rather than independent capital grants. Within the logistics sector, operation-linked incentives, equipment leasing, shared infrastructure and service contracts outperform one-off purchase subsidies due to their tight connection with daily operational activities.

Beyond micro-level enterprise operation, macro institutional governance acts as the fundamental guarantee for sustainable hydrogen logistics development. Corporate efforts to promote hydrogen logistics are often limited without systematic institutional support. With respect to policy environments and governance issues, national hydrogen strategies assign different priorities to industrial development, environmental targets, energy security and export potential [12]. Global studies of hydrogen deployment show that supply and demand dynamics are shaped by policy signals, infrastructure coordination and sectoral development priorities. Effective governance carries particular significance for urban agglomerations such as the Beijing-Tianjin-Hebei region. Hydrogen production, freight demand, infrastructure approval and vehicle manufacturing are regulated by distinct administrative authorities. Such administrative segmentation hinders cross-department coordination, which easily leads to duplicated investment and fragmented refuelling networks lacking continuous coverage.

3. Conceptual Framework

This research adopts five analytical dimensions. They include ecological pressure, policy environment, economic incentives, technological pathway, and management practices. These dimensions are widely applicable to various green technologies. This study modifies the framework to match hydrogen logistics. Hydrogen logistics has two distinctive traits, generating unique barriers during the low-carbon transition. The technological pathway brings considerable complexity. Upstream carbon intensity varies greatly across hydrogen production routes. Hydrogen stands apart from biofuels and grid electricity. Its carbon footprint differs drastically. The gap stems from production sources. Grey hydrogen comes from fossil feedstocks, whereas green hydrogen is produced using renewable electricity. This source-based categorization enable continuous monitoring and certification covering the full hydrogen supply chain.

Economic incentives are further constrained by the throughput threshold of supporting infrastructure. Hydrogen refuelling stations (HRS) require a high minimum utilisation rate to be economically viable, creating a structural mutual dependency dilemma. This is distinct from Battery-Electric Trucks (BETs), where charging infrastructure can be deployed incrementally at depots. Consequently, the policy environment dimension plays a vital role in consolidating demand along dedicated transport corridors to overcome this economic threshold.

The conceptual framework is developed based on the foregoing literature review and practical features of hydrogen freight deployment. The central assumption is that sustainability outcomes are produced through the interaction of ecological pressure, policy environment, economic incentives, technological pathway, and management practices. They function as analytical dimensions supporting the interpretation of case evidence involving multiple stakeholders and diverse sources of information.

Ecological pressure denotes the requirement to cut greenhouse gas emissions and local pollutants from freight transport while preserving the operational capacity of regional logistics systems. The policy environment includes strategic targets, demonstration programs, safety standards, infrastructure approval, and coordination mechanisms. Policy frameworks can reduce uncertainty, but they can also create fragmentation if different jurisdictions set incompatible priorities. Economic incentives cover vehicle acquisition costs, hydrogen prices, refuelling station utilisation, financial subsidies, leasing schemes and risk-sharing arrangements. These factors determine whether logistics firms can translate environmental objectives into practical procurement and operational decisions.

The technological pathway refers to the configuration of hydrogen production, storage, refuelling infrastructure, fuel cell systems, and vehicle application scenarios. Importantly, the technological pathway for hydrogen logistics differs from battery electric alternatives owing to intrinsic safety constraints. HRS, involving high-pressure storage, are typically restricted to peri-urban safety zones or industrial peripheries to minimize urban risk. This requires coordinated management of operational corridors. This dimension shapes the capacity of hydrogen to satisfy the operational demands of freight transport. Management practices refer to the organizational arrangements that make technology usable, including route selection, fleet scheduling, maintenance service, data reporting, station sharing, and cooperation among stakeholders. Sustainability outcomes encompass emission reduction potential, industrial learning effects, cost optimization and governance capacity. Figure 1 presents the relationship among these constructs.

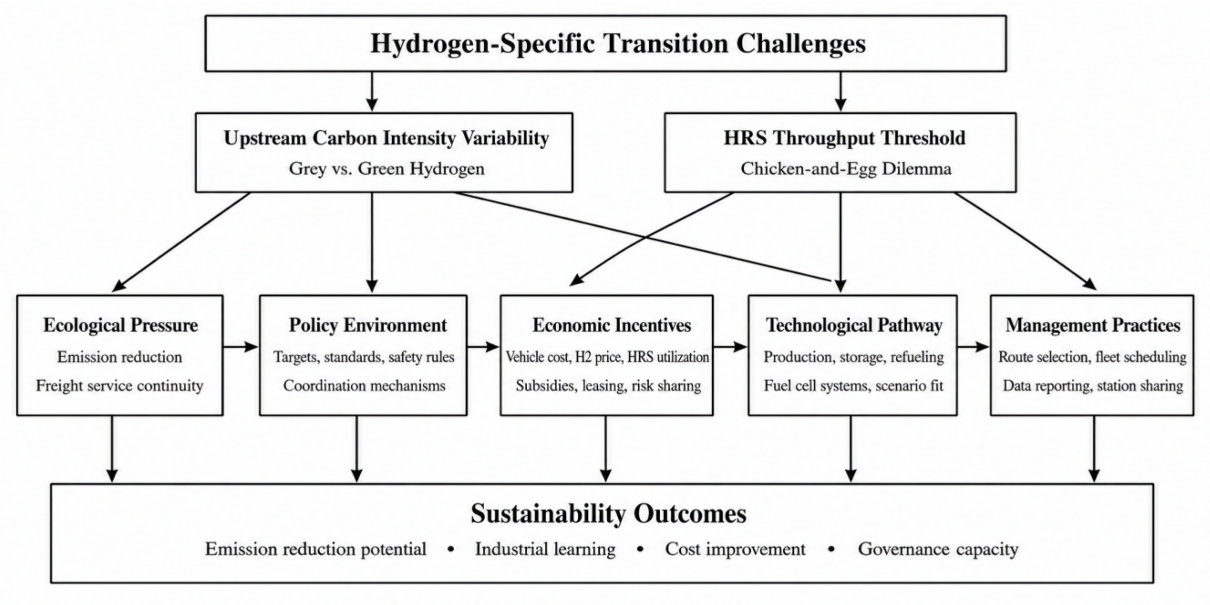

Figure 1. Conceptual framework.

4. Research Design

4.1. Case Selection and Research Orientation

This study focuses on the application of hydrogen fuel cell vehicles in the logistics sector of the Beijing-Tianjin-Hebei urban agglomeration. This region is chosen for its intensive freight volume, strict environmental governance objectives, sound manufacturing base, available renewable energy, and notable difficulties in cross-administrative coordination. Different from private passenger transport, the analysis targets commercial logistics scenarios covering port logistics, airport freight, industrial park transportation, cold chain distribution and intercity heavy-duty freight. Qualitative analysis is adopted for these scenarios to uncover the practical interactions among vehicle technology, refuelling infrastructure, logistics organisation and policy support.

Reliable fleet-level datasets required for formal statistical modelling remain unavailable, making a qualitative design more suitable and transparent. Such an approach enables an investigation into the organisational mechanisms of hydrogen logistics without introducing unsubstantiated quantitative assertions. Although the case is geographically bounded to this region, the analysis prioritises generalisable mechanisms that offer insights for other freight-concentrated urban agglomerations developing nascent hydrogen infrastructure.

4.2. Data Sources and Analytical Strategy

This study builds on three foundational research inputs. Core empirical content is derived from internal regional case materials for hydrogen logistics in the Beijing-Tianjin-Hebei region, which elaborates on policy orientation, infrastructure bottlenecks, hydrogen production systems, industrial chain progress, and typical logistics scenarios across the Beijing-Tianjin-Hebei region. The study also integrates existing academic literature concerning hydrogen production, supply chain operation, cost evolution, commercial models, national hydrogen strategies, clean hydrogen economics, and hydrogen deployment in transportation. The third input is the conceptual framework developed in Section 3, which synthesises the literature and the practical characteristics of hydrogen freight deployment into five analytical dimensions—ecological pressure, policy environment, economic incentives, technological pathway, and management practices—and provides the structure for organising and interpreting the case evidence.

The analytical framework proceeds through four sequential stages. A review of relevant literature is conducted to derive a set of analytical dimensions. The subsequent step maps the case evidence onto those dimensions, focusing on ecological pressure, policy environment, economic incentives, technological pathway, and management practices. Evidence obtained from different logistics scenarios is then compared to identify recurrent operational mechanisms and implementation barriers. The final stage links these identified mechanisms back to the core research questions and generates findings to support theoretical inference and practical policy discussion. Figure 2 summarizes this procedure, and Table 1 defines how each analytical dimension is operationalized in the study. During the mapping process, the analysis specifically screened for hydrogen-specific spatial constraints. We examined how the location of HRS, dictated by safety regulations, shapes the formation of logistics corridors. This allowed us to differentiate the hydrogen transition mechanism from generic green logistics models.

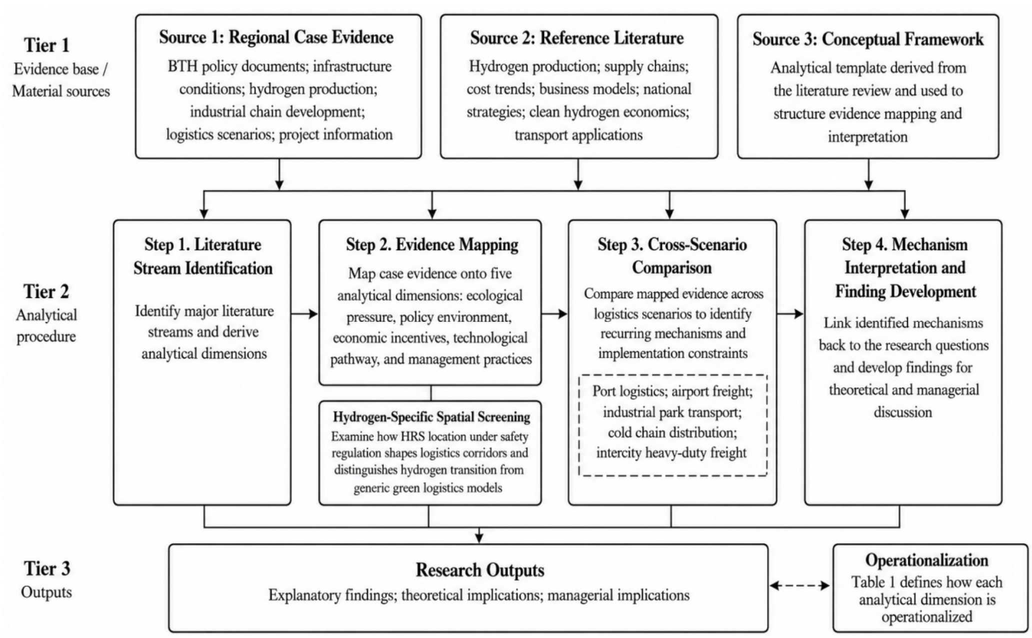

Figure 2. Research design and analytical procedure.

Table 1. Definition of analytical dimensions.

Analytical Dimension	Operational Meaning	Evidence Source	Related Research Question
Ecological pressure	Need to reduce freight emissions while maintaining logistics service capacity	Original manuscript background and hydrogen transition literature	Why hydrogen logistics is relevant to sustainability transition
Policy environment	Targets, standards, demonstration arrangements, safety rules, and regional coordination	Original manuscript policy discussion and hydrogen strategy literature	How institutions shape deployment conditions
Economic incentives	Vehicle cost, hydrogen price, station utilisation, subsidies, leasing, and risk-sharing	Cost studies, business model literature, and case findings	How enterprises adapt under cost uncertainty

Table 1. *Cont*.

Analytical Dimension	Operational Meaning	Evidence Source	Related Research Question
Technological pathway	Production, storage, refuelling, fuel cell systems, and route suitability	Hydrogen production and supply chain literature plus case scenarios	Where hydrogen vehicles are most operationally credible
Management practices	Fleet scheduling, station sharing, maintenance, data reporting, and stakeholder cooperation	Case findings and management oriented interpretation	How transition is organized beyond technology adoption

5. Findings

5.1. Institutional Coordination and Regional Sustainability Transition

Drawing upon regional policy documents, logistics-sector statistics and contextual evidence collected for this study, this section examines core forces steering hydrogen-based freight logistics across the Beijing-Tianjin-Hebei territory. The analysis reveals that hydrogen logistics in Beijing-Tianjin-Hebei is shaped first by cross-regional institutional coordination. Freight emissions and air pollution transcend municipal boundaries, which means ecological pressure constitutes a shared challenge across the region. At the same time, resources supporting hydrogen transition are distributed unevenly. Renewable energy resources and potential hydrogen production bases are concentrated in some areas, major logistics demand appears around Beijing and Tianjin freight nodes, and industrial capabilities are distributed across vehicle manufacturers, component firms, and research institutions. Such spatial distribution renders institutional coordination a prerequisite for advancing sustainability rather than a subordinate administrative concern.

Institutional coordination plays a vital role given the demand for synchronous decision-making in hydrogen logistics. Expanding hydrogen production without matching freight demand sustains high supply costs and unstable facility utilisation. Logistics enterprises that adopt hydrogen vehicles ahead of adequate refuelling infrastructure face vehicle downtime and route limitations, which erode market confidence. If stations are planned only by local administrative units, the network may fail to support cross-city freight corridors. Accordingly, the transition challenge exhibits an inherently regional structure. Hydrogen can serve logistics only when production, station location, vehicle routes, and safety supervision are designed around the same operational geography.

This finding responds directly to the research question by showing that hydrogen fuel cell vehicles cannot be evaluated as isolated assets. Their decarbonization value hinges on institutional arrangements that align environmental targets with infrastructure construction and industrial organisation. The Beijing-Tianjin-Hebei case indicates that port logistics, airport freight, industrial park transport, and intercity corridors each require a different form of coordination. Port logistics takes advantage of concentrated transport routes and predictable refuelling demand. Airport logistics prioritises operational reliability and punctuality. Industrial park operations demand strict safety management and alignment with manufacturing schedules, while intercity freight relies on continuous corridor connectivity. A regional transition strategy must therefore combine shared goals with scenario-specific planning.

The mechanism is also relevant to ecological economics. Institutions generate environmental value by lowering transaction costs and enabling clean technologies to operate at viable scales. Without coordination, stakeholders fall into passive waiting behaviour. Energy firms may wait for fleet demand, logistics firms may wait for station coverage, and governments may wait for evidence of commercial viability. This waiting pattern can slow transition even when all actors accept the need for decarbonization. Institutional coordination can break the pattern by defining demonstration corridors, clarifying standards, aligning subsidies with actual operation, and creating channels for data feedback. Regional governance is consequently more than a contextual policy condition; it acts as an active productive component of the hydrogen logistics system.

The finding also clarifies why the Beijing-Tianjin-Hebei case is useful for management research. Most clean freight technologies struggle to scale from pilot schemes to regular commercial operation, and hydrogen logistics introduces additional complexity due to the interdependent development of hydrogen production, vehicle deployment and refuelling infrastructure. The case indicates that the early stage should prioritize scenarios where actors can coordinate with limited uncertainty, such as ports, airports, and large industrial parks. These sites provide stable demand and allow operational data to be collected. Such data can then support corridor expansion and policy refinement. Institutional coordination accordingly serves as the connecting mechanism linking ecological pressure to tangible low-carbon transition.

5.2. Economic Incentives and Managerial Adaptation

Hydrogen logistics will not scale simply because policy declares it desirable. Logistics operators work under narrow profit margins and require vehicles capable of fulfilling service commitments at affordable costs. The cost challenge includes vehicle purchase price, hydrogen price, maintenance service, driver training, station access, and residual-value uncertainty. Empirical examinations of hydrogen cost competitiveness suggest such obstacles will persist until relevant supply chains mature and facility utilisation rises [13,14]. Accordingly, the case evidence highlights the value of incentive frameworks that mitigate risks while encouraging practical operational activities.

Distinct subsidy forms induce divergent corporate behaviours. Purchase subsidies lower upfront vehicle expenses yet fail to guarantee high utilisation or tangible emission reductions. By contrast, operational support, leasing mechanisms, joint investment in refuelling facilities and integrated service contracts align incentives more closely with logistics performance. For example, a leasing arrangement can allow logistics firms to test hydrogen vehicles without carrying the full asset risk. Joint investment in refuelling infrastructure eases burdens for individual operators and improves facility throughput. Service contracts that combine vehicle provision, fuel supply, and maintenance can reduce uncertainty for fleet managers. Such arrangements connect economic incentives with daily management decisions.

The evidence also points to the need for a gradual shift from demonstration finance to market formation. Early-stage subsidies are justified when they facilitate industrial learning, mitigate local pollution and accumulate information regarding route suitability and facility utilisation. However, if support remains detached from performance, the transition may depend on fiscal spending rather than operational value. This risk is particularly prominent in logistics sectors. Firms may purchase hydrogen vehicles for demonstration purposes yet operate them at low intensity if routes and refuelling conditions remain inadequate. Therefore, incentive schemes should reward actual operation, verified service performance and data reporting, distinguishing superficial technology deployment from substantive low-carbon transition. A unique constraint facing hydrogen systems stems from the throughput threshold of refuelling infrastructure. Refuelling facilities carry substantial fixed costs and rely on a sufficient volume of vehicles to attain profitability, generating distinctive spatial-economic tensions across the Beijing-Tianjin-Hebei region. Unlike BETs that support scattered urban charging, hydrogen vehicle operations are shaped by safety and cost limitations. Logistics activities need to form interconnected networks linking ports, airports and industrial parks adjacent to peripheral refuelling facilities. This spatial arrangement constitutes a fundamental prerequisite for aggregating adequate demand to meet minimum throughput thresholds and secure infrastructure economic viability.

Economic incentives further reshape interactions among stakeholders. Energy operators require stable baseline demand to justify investment in refuelling facilities. Vehicle manufacturers need predictable orders and feedback from real operation. Logistics firms pursue predictable costs and reliable service conditions. Financial institutions can help by providing leasing, insurance, and risk-sharing products, but they also require credible information on asset performance. These conditions imply that hydrogen logistics relies on a complete economic ecosystem rather than isolated subsidy programmes. The Beijing-Tianjin-Hebei region possesses both concentrated freight demand and solid industrial capacity, yet the core challenge lies in translating these resources into coordinated commercial cooperation.

This finding responds to the core research question by clarifying how economic incentives mediate between policy objectives and corporate behaviour. Ecological pressure delivers legitimacy for hydrogen adoption, and policy frameworks set development orientations. Even so, firms only implement adaptive adjustments when costs and risks fall within acceptable ranges. Managerial adaptation thereby acts as a core transition mechanism, encompassing route planning, fleet procurement strategies, refuelling arrangements, maintenance management and cooperation with infrastructure suppliers. Beyond conventional financial barriers, the case identifies a fundamental structural constraint: spatial costs exert stronger influences than direct vehicle purchase expenses. Contrary to the common view that high vehicle prices represent the primary obstacle, this analysis demonstrates that land costs and inefficient driving routes, driven by stringent safety regulations, dominate economic constraints for regional logistics enterprises. Safety separation requirements concentrate refuelling facilities in peri-urban zones. Logistics operators consequently face two costly options: relocating depots to expensive fringe land, or accumulating substantial non-revenue mileage to access refuelling services. This spatial-economic tension indicates that corporate adaptation responds weakly to general purchase subsidies and depends more heavily on land-use planning and transport corridor efficiency. The low-carbon transition becomes more sustainable when relevant management practices are backed by operation-targeted incentives.

5.3. Technological Pathways and Scenario-Based Ecological Performance

Restrictions arising from safety risks preclude refuelling facilities within urban core areas, while such infrastructure is predominantly deployed in peri-urban zones to serve as a safety buffer. Freight vehicles operate within interconnected transport networks linking peripheral refuelling sites, ports and industrial parks. This demonstrates that hydrogen logistics is a reconfiguration of the network around safety-constrained refuelling nodes. Scenario analysis demonstrates that hydrogen fuel cell vehicles deliver credible decarbonisation value only when technological pathways are tailored to specific logistics contexts. Hydrogen technology cannot universally replace all freight vehicles, and its strengths emerge in operations requiring long driving ranges, high payload capacity, rapid refuelling and predictable transport routes.

The advantages of hydrogen fuel cell vehicles are evident within the logistics system serving Tianjin Port, where vehicles undertake prolonged shifts with heavy loads. Under such conditions, hydrogen constitutes an effective alternative to both diesel and battery electric vehicles for demanding heavy-duty transport routes. Port logistics, airport freight, industrial park operations, cold chain distribution and selected intercity corridors better match these operational characteristics compared with scattered short-distance delivery tasks. This scenario logic is consistent with hydrogen supply chain research, which emphasizes the relationship between delivered cost, station throughput, and spatial organization. It is also consistent with business model studies advocating application-centred hydrogen planning rather than broad, undifferentiated technology promotion.

Within the Beijing-Tianjin-Hebei region, hydrogen fuel cell vehicles compete with battery electric vehicles already deployed at Tianjin Port. Although battery electric vehicles suit short-distance and terminal transport, HFCVs exhibit distinctive strengths in certain heavy-duty scenarios thanks to superior energy density and refuelling performance. Scaling battery electric vehicles for long-haul transport requires bulky battery packs that reduce allowable payload, alongside prolonged charging times that often necessitate overnight stops. By contrast, HFCVs achieve a more balanced performance profile for high-intensity freight corridors. Technological pathways built around hydrogen complement road electrification for operations with daily travel distances exceeding 300 kilometres, vehicle configurations such as 49-tonne tractor units, and strict turnaround schedules. This distinction establishes practical boundary conditions for hydrogen within regional low-carbon transitions.

Scenario-centred planning reshapes the evaluation framework for ecological performance. Limitations of battery electric vehicles become prominent along long-haul freight corridors connecting Tianjin Port with inland industrial hubs, a vital component of the regional logistics network. These routes typically demand daily ranges above 300 kilometres and full payload utilisation. Equipping battery electric vehicles to satisfy such requirements relies on excessively large batteries, cutting legal payload capacity and undermining transport economic efficiency. HFCVs achieve refuelling durations similar to diesel vehicles, roughly between 10 and 15 min, enabling continuous operation without efficiency losses stemming from slow charging or battery swapping. Moreover, the favourable energy-to-weight ratio of hydrogen preserves high payload capacity over extended distances. While battery electric vehicles are well suited to short-distance terminal transport and intra-port movement, HFCVs better match the operational requirements of heavy-duty trunk transport networks.

A fundamental characteristic separating hydrogen from alternative fuels lies in the separation of emission generation locations and tailpipe emission points. The Technological Pathway must therefore ensure that the hydrogen supply is aligned with low-carbon energy sources. In the Beijing-Tianjin-Hebei region, this requires connecting heavy-duty freight corridors between ports and industrial parks with local renewable energy resources. Without such coordination, hydrogen vehicles, despite zero tailpipe emissions, may fail to deliver expected sustainability outcomes owing to high carbon intensity associated with fossil-fuel-based hydrogen production. Such variations demand rigorous institutional arrangements to verify the low-carbon attributes of supplied hydrogen. Overall ecological performance depends on the volume of diesel displacement and the carbon footprint of hydrogen feedstocks. High-utilisation fleets operating at ports and industrial parks accumulate sufficient mileage to improve local air quality and support stable refuelling facility throughput. By contrast, dispersed operations force vehicles to travel inefficiently for refuelling and reduce operational intensity. Identical vehicle technology can therefore generate divergent sustainability outcomes, determined by route planning, depot layout, refuelling infrastructure arrangement and hydrogen production sources. This illustrates why technological pathways must be analysed alongside logistics organisation models.

The Beijing-Tianjin-Hebei region illustrates the importance of spatial configuration. Surrounding renewable energy resources can support local hydrogen production, whereas Beijing and Tianjin host major freight demand centres. Industrial capabilities in vehicle manufacturing and fuel cell systems can support localization and service response. These resources can form a viable regional technological pathway when connected via hydrogen production bases, refuelling nodes and freight corridors. The pathway becomes weaker if hydrogen is transported over long distances without sufficient demand density or if refuelling stations are placed where logistics vehicles cannot use them efficiently. Technology therefore requires regional matching.

Technological configuration also includes the maturity of fuel cell systems, storage equipment, and maintenance services [15]. Nevertheless, logistics operators assess technology based on practical on-site performance. Fuel cell systems achieving high efficiency under laboratory conditions must endure continuous freight operations, low-temperature environments and long service cycles, while refuelling equipment must maintain stability during peak operational hours. Vehicle manufacturers and service suppliers also need to provide rapid fault response mechanisms. These practical requirements confirm that technological pathways cannot be examined independently of management practices.

This finding contributes to the ecological management dimension of this research. Hydrogen logistics should begin with scenarios where the technology can perform well and where environmental benefits can be measured. Ports, airports and industrial parks are appropriate starting points, as they support closed or semi-closed transport loops, simplify infrastructure planning and streamline data collection. Intercity corridors can follow when node density and station reliability improve. Such phased expansion prevents excessive investment and creates opportunities for operational learning. It also reduces the risk of treating hydrogen as a symbolic technology rather than a practical instrument of freight decarbonization. Technological pathways therefore link ecological performance with operational discipline. To summarize this technological differentiation, Table 2 presents a comparative analysis of HFCVs and BETs across key operational parameters, defining the realistic boundary conditions for hydrogen's application in the Beijing-Tianjin-Hebei transport system.

Table 2. Comparative analysis of HFCVs and BETs in key logistics scenarios.

Operational Parameter	BETs	HFCVs	Best Suited Scenario in Beijing-Tianjin-Hebei
Daily Range	Limited (150–200 km)	Long (300–500 km)	HFCVs: Long-haul intercity corridors
Payload/Weight Ratio	Poor (Heavy batteries reduce cargo capacity)	Good (Lighter storage, full payload)	HFCVs: Heavy-duty freight (40–49 tons)
Refuelling/Charging Time	Long (1–2 h fast charging; overnight ideal)	Fast (10–15 min)	HFCVs: High-intensity, time-sensitive routes
Infrastructure Flexibility	High (Can charge at depots)	Low (Requires dedicated HRS)	BETs: Dispersed urban distribution
Upfront Cost	Lower	Higher	BETs: Cost-sensitive short-haul ops

5.4. Governance Constraints and Implementation Risks

Despite policy emphasis on regional coordination, intercity competition for hydrogen demonstration accreditation has resulted in fragmented investment and redundant construction of industrial facilities. Local governments tend to pursue independent industrial layouts rather than developing scenario-specialised functions, which undermines coordinated institutional arrangements.

A prominent practical issue is that many logistics enterprises adopt hydrogen vehicles primarily to obtain policy subsidies and meet regulatory requirements, rather than responding to actual operational demand. Unfavorable fuel economics, driven by high hydrogen prices and insufficient facility utilisation, compel fleets to maintain only basic operational intensity to sustain policy eligibility. Such operational levels remain far below the threshold required for commercial viability. This phenomenon leads to inactive fleet deployment, in which vehicles are formally registered for demonstration purposes but maintain limited practical transportation functions. This empirical observation captures the inherent tension between top-down policy targets and bottom-up corporate operational rationality, representing an unanticipated governance challenge derived from case evidence.

Even with recognised technological and economic feasibility, hydrogen logistics transitions remain exposed to persistent implementation risks. Key constraints include infrastructure underutilisation, unstable hydrogen pricing, intensive safety supervision pressure, inconsistent industrial standards and inadequate operational data accumulation. These uncertainties weaken market confidence among logistics operators and industrial investors. Without unified evaluation criteria for demonstration projects, public fiscal investment may fail to generate effective decarbonisation returns.

Data governance constitutes a critical yet underemphasised constraint. Public authorities need reliable information on vehicle mileage, hydrogen consumption, refuelling frequency, station utilisation, maintenance records, and estimated diesel displacement. However, logistics enterprises are often reluctant to disclose commercially sensitive operational information, and refuelling facility operators frequently adopt inconsistent data reporting formats. Without standardised data, it is difficult to assess whether hydrogen vehicles are delivering ecological benefits or whether subsidies are supporting low utilisation assets. A standardised regional data mechanism can resolve this issue by unifying evaluation indicators and reporting specifications without compromising commercial privacy, enabling gradual transition toward performance-oriented policy support.

Safety and public acceptance also require careful governance. HRS and high pressure storage systems are technically manageable, but they require strict standards, trained personnel, emergency procedures, and transparent supervision. Logistics safety management must be integrated with depot scheduling, vehicle maintenance, driver training and route planning. Treating safety merely as technical compliance underestimates long-term operational risks, while inadequate public communication may trigger social concerns, delay infrastructure approval and increase construction costs. Effective governance therefore integrates technical specifications with standardised organisational operational routines.

Misalignment between policy demonstration cycles and industrial investment cycles creates additional transition frictions. Governments may prefer visible pilot results, while energy and vehicle firms need longer horizons to recover investment. Logistics firms are willing to participate in preliminary demonstration projects but remain cautious regarding large-scale expansion amid uncertain hydrogen pricing and policy continuity. This mismatch can produce a stop start pattern that limits learning. The literature on national hydrogen strategies and clean hydrogen deployment suggests that stable policy signals are essential for investment confidence. The case supports this argument by showing that regional hydrogen logistics needs predictable rules for station approval, safety supervision, hydrogen pricing support, and vehicle operation incentives.

These findings indicate that implementation risk must be treated as part of the transition mechanism. Figure 3 illustrates the integrated transition mechanism driven by hydrogen-specific constraints. At the top level, upstream carbon intensity variability and refuelling station throughput thresholds act as critical boundary conditions. Within the framework, institutional coordination establishes the regional foundation, while economic adaptation responds to cost structures shaped by these constraints. Technological configuration determines scenario suitability based on storage and range limitations, and governance risk control ensures scalable implementation through dynamic policy adjustment. Together, these dimensions facilitate the shift toward a coordinated regional hydrogen logistics system. Table 3 summarizes these findings and their implications.

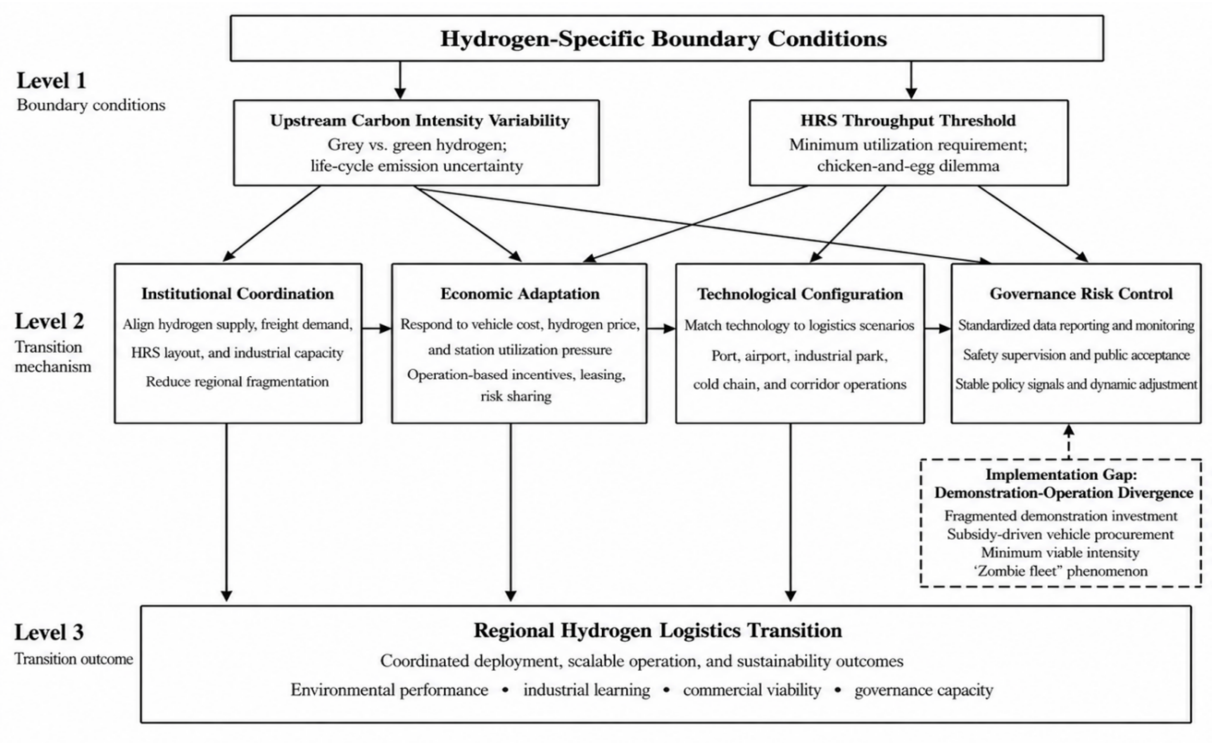

Figure 3. Transition mechanism framework incorporating hydrogen-specific constraints.

Table 3. Summary of findings.

Finding	Key Evidence	Explanatory Mechanism	Theoretical Implication
Institutional coordination	Hydrogen supply, freight demand, infrastructure, and industrial capacity are distributed across the urban agglomeration	Regional coordination reduces fragmentation and links ecological pressure with practical deployment	Sustainability transition depends on governance arrangements
Economic incentives	Vehicle cost, hydrogen price, station utilisation, leasing, and risk-sharing affect enterprise adoption	Incentives become effective when connected with actual operation and user risk reduction	Ecological economics should assess market formation and performance-based support
Technological pathways	Hydrogen is more credible in port, airport, industrial park, cold chain, and corridor scenarios	Scenario matching links vehicle capability with station utilisation and emission reduction	Technology value is produced through operational configuration
Governance constraints	Data gaps, safety standards, price uncertainty, and fragmented planning remain important risks	Risk control enables pilot projects to become transferable management knowledge	Transition management requires monitoring, learning, and policy adjustment

6. Discussion

Evidence from the Beijing-Tianjin-Hebei region confirms that cross-regional institutional coordination connects renewable energy endowments with freight demand distribution, refined incentive mechanisms mitigate operational risks for logistics firms, scenario-oriented technological planning improves practical ecological performance, and robust governance controls scalability risks. Collectively, these results indicate that hydrogen logistics transition constitutes an integrated ecological, economic, and managerial challenge, rather than a purely technical or engineering issue.

Compared with existing hydrogen research, the paper shifts attention from general technical potential to the managerial conditions of application. Analyses of hydrogen generation reveal divergent characteristics between fossil-derived and renewable-based hydrogen [16]. Cost studies explain why green hydrogen needs scale, learning, and supportive policy. Supply chain studies show that infrastructure and delivery costs depend on spatial organization [17]. Policy studies examine subsidies and national strategies [18,19].

The findings also advance ecological economics research by establishing the contingent relationship between technological environmental performance and institutional–organisational arrangements. In many discussions, the environmental value of a technology is treated as a technical attribute. The present analysis suggests that this value is conditional. It depends on hydrogen source, freight route suitability, station utilisation, enterprise behavior, and policy feedback. This conditional view is important because it prevents both technological optimism and premature rejection. Hydrogen logistics can generate substantial emission reduction benefits under high-intensity and well-matched operational scenarios, while mismatched infrastructure layout and blind vehicle deployment may trigger inefficient investment and limited decarbonisation gains. Accordingly, ecological economic evaluation of low-carbon transitions requires integrated consideration of environmental externalities, cost formation mechanisms, industrial learning effects, and multi-level governance capacity.

This study yields targeted managerial and practical implications. Public authorities should focus on corridor- and node-based planning. Energy firms should work with anchor logistics users before investing in refuelling capacity. Vehicle manufacturers should tailor products and maintenance services to scenario requirements. Financial institutions can support the transition through leasing, insurance, and risk-sharing products. These implications are consistent with the paper's framework because each actor contributes to one part of the transition system. None of them can create the transition alone.

The discussion also suggests a cautious approach to policy support. Subsidies can be useful when they create learning and verified emission reduction, but they should gradually move toward performance-based mechanisms. Operation-based incentives, green hydrogen certification, station utilisation targets, and standardised data reporting can improve the credibility of public support. A mature green logistics strategy should allow technologies to compete and specialize according to route distance, payload, energy availability, and infrastructure conditions. Hydrogen has a role, but that role should be defined through evidence and management discipline. Table 4 outlines the phased evolution of the hydrogen logistics transition. Notably, Phase 2 emphasizes large-scale industrial expansion and cost mitigation, which directly addresses the high infrastructure threshold and the structural mutual dependency dilemma unique to hydrogen, distinguishing it from other low-carbon alternatives.

Table 4. Phased evolution of the Beijing–Tianjin–Hebei hydrogen logistics transition.

Phase 1: Early Stage	Phase 2: Transition	Phase 3: Market Maturity
Period: 2021–2025	Period: 2026–2027	Period: 2028–2035
Governance: Government-led (Subsidy-driven)	Governance: Government and Market (Policy-Interaction)	Governance: Market-driven (Profit-driven)
Focus: Infrastructure layout and Pilot projects	Focus: Scaling up and Cost reduction	Focus: System activation and Commercial viability
Analytical Level: Regional System	Analytical Level: Regional and Enterprise	Analytical Level: Enterprise–levelt

7. Conclusions

This research frames the deployment of hydrogen fuel cell vehicles within Beijing-Tianjin-Hebei logistics as a regional sustainable transition issue. These vehicles form only one part of a broader system integrating energy provision, transport demand, industrial capacity and public governance.

This study establishes an integrated conceptual framework connecting ecological pressure, policy settings, economic incentives, technological pathways, operational practices and sustainability outcomes. The framework illustrates how environmental benefits can be realised under appropriate institutional and organisational conditions. The analytical approach offers insights for ecological economics and transition management research by revealing how transition results depend on supporting institutional arrangements. The analysis also generates actionable insights for regions advancing low-carbon freight transport. Hydrogen solutions should first be rolled out in logistics scenarios featuring fixed routes, concentrated refuelling demand and accessible operational data collection. Public support ought to be tied to real operational activity and verified performance. Infrastructure planning should prioritise freight corridors and logistics hubs. Risk-sharing mechanisms covering vehicles, hydrogen supply, maintenance and data feedback also support enterprises in advancing their development. These approaches facilitate the shift of hydrogen logistics from pilot demonstration to stable regional operation.

The analysis draws on published documents and open project data, without access to internal operational datasets from logistics operators. For this reason, precise estimation of life-cycle emissions, hydrogen consumption, maintenance expenditure and refuelling station utilisation remains unavailable. Follow-up work can gather fleet-level operational data to compare hydrogen vehicles with battery electric and diesel trucks under identical route conditions. Cross-case analysis covering other urban agglomerations will further examine whether the framework can be adapted to regions beyond Beijing-Tianjin-Hebei. Empirical evidence from such work can support targeted decision-making for hydrogen deployment within green logistics transitions.

Author Contributions

Conceptualization was completed by J.F. and X.Z. Methodology was developed by X.Z. and Z.W. Literature analysis was conducted by J.C. and J.Z. Writing and revision were completed by all authors. All authors have read and agreed to the submitted version of the manuscript.

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Data Availability Statement

The study draws on published literature, open policy documents and publicly available project information. Supplementary supporting data for analysis can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Doubao AI to assist with manuscript drafting, logical sorting and English language polishing. After using this tool, the authors reviewed, revised and edited all content as needed and take full responsibility for the content of the published article.

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