Net-Zero Global Logistics by 2050: Pathways, Technology Mix and Systemic Barriers

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Abstract

This study evaluates technologically feasible and practically implementable pathways for achieving net-zero emissions in the global logistics sector by 2050, emphasizing how energy system decarbonization, advanced vehicle technologies, modal diversification, digital optimization, and infrastructure transformation collectively drive emissions reductions. Using a systems-based analytical framework, logistics emissions are decomposed by transport mode and scope, and multiple decarbonization levers—including electrification, hydrogen and fuel-cell deployment, sustainable and synthetic fuels, modal shift strategies, and operational efficiency improvements—are analyzed using secondary data from international agencies, academic literature, and industry reports. Findings reveal that no single technology or intervention can achieve full decarbonization; instead, sustained and coordinated progress across clean energy generation, low-carbon fuels, technology deployment, intermodal transport networks, and digital fleet optimization is required. Electrification offers the strongest near- to mid-term decarbonization benefits for road logistics, whereas hydrogen and e-fuels are essential for aviation and deep-sea shipping. However, large-scale transformation is constrained by slow grid decarbonization, limited low-carbon fuel production, fragmented global technical standards, infrastructure gaps, high capital and financing needs, and inadequate policy certainty. The study provides strategic insights for policymakers, multilateral financiers, and logistics operators by identifying priority investment areas, technology combinations, institutional reforms, and cross-sector collaboration models required to accelerate the transition. The research adds value by integrating engineering, policy, infrastructure, and market readiness perspectives into a unified decarbonization model that demonstrates not only what solutions are

technologically possible, but also the enabling conditions that must exist for net-zero logistics to be realistically achievable by 2050.

Keywords: Digital optimization, Freight decarbonization, Low-carbon fuel, Modal shift, Net-zero logistics, Sustainable transport systems.

1. Introduction

1.1 Background

Global logistics—which includes road freight, rail transport, aviation, maritime shipping, warehousing, and last-mile delivery—forms the backbone of world trade and economic activity. However, the sector relies heavily on fossil fuels and significantly contributes to global greenhouse gas emissions. Rapid growth in the global supply chains, the expansion of e-commerce, rising consumer expectations for fast delivery, and continued industrialization in emerging economies are increasing freight activity and associated emissions. As nations commit to achieving carbon neutrality by 2050, the logistics sector must undergo a deep, system-wide transformation involving new energy sources, technologies, infrastructure investments, and operational redesign.

The transition toward net-zero emissions in global logistics requires a fundamental restructuring of transport systems, energy inputs, and operational practices. Figure 1 illustrates the conceptual structure underpinning this transformation, showing how four major decarbonization pathways—energy system decarbonization, modal shift, digital optimization, and infrastructure transformation—interact with emerging low-carbon technologies such as electrified vehicles, hydrogen and synthetic fuels, and advanced maritime and aviation systems. However, as the diagram highlights, the full-scale transition is constrained by systemic barriers including slow power grid decarbonization, insufficient production capacity for low-carbon fuels, fragmented global regulatory frameworks, and persistent infrastructure investment gaps. This integrated view reflects the sector-wide challenge that achieving net-zero logistics is not solely a technological issue, but a system-wide coordination problem requiring synchronized progress across energy, policy, finance, and digital ecosystems. The diagram therefore provides the foundational context for this research, which aims to analyze the interdependencies between pathways, assess the feasibility of technology deployment, and identify the systemic conditions necessary to align global logistics with 2050 climate targets.

Sources: Author's own creation

Figure 1: Conceptual Overview of Net-Zero Global Logistics by 2050

This diagram illustrates the integrated framework connecting decarbonization pathways, technology mix, and systemic barriers in achieving net-zero emissions in global logistics by 2050. The left section shows core transformation pathways (energy system decarbonization, modal shift, digital optimization, and infrastructure transformation), the center highlights technological solutions (electrification, hydrogen and e-fuel adoption, and low-carbon transport technologies), while the right section displays systemic constraints such as slow grid decarbonization, low-carbon fuel production limitations, fragmented international standards, and high capital and infrastructure requirements.

Existing research identifies multiple pathways for decarbonizing logistics. Scholars point to electrification of urban and regional freight, the role of hydrogen and synthetic fuels in long-distance trucking, aviation and maritime shipping, modal shift toward lower-emission rail and short-sea shipping, and digital optimization for route planning and load management. While these studies provide valuable insights into individual decarbonization levers, the literature remains fragmented. Most analyses focus on single modes of transport or specific technologies rather than assessing integrated global pathways. Additionally, non-technological transition challenges—such as policy uncertainty, fragmented international regulations, high infrastructure costs, supply-chain misalignment, and workforce capability gaps—are often overlooked. This gap underscores the need for holistic, cross-sector assessment of technology mixes and systemic constraints affecting the feasibility of net-zero logistics.

1.2 Problem Statement

Despite growing technological maturity and stronger climate commitments, the global logistics system is not on track to reach net-zero emissions by 2050. Transition progress is obstructed by a combination of structural challenges: limited charging and refueling infrastructure, insufficient large-scale production of hydrogen and e-fuels, uncertain business cases for private investors, lack of alignment among policymakers and logistics operators, and inadequate skills and institutional readiness. Without a comprehensive understanding of how these technological and systemic factors interact, stakeholders risk underestimating the scale, timing, and coordination required for deep decarbonization.

1.3 Research Questions The study explores the following questions:

i. What technology and fuel mix can deliver net-zero emissions in global logistics by 2050?
ii. How do alternative decarbonization scenarios—current policy, accelerated action, and transformational change—differ in emissions reduction potential, cost, and implementation feasibility?
iii. What economic, operational, regulatory, and institutional barriers hinder the scaling of low-carbon logistics solutions?
iv. What policy, investment, and market interventions are required to align the logistics sector with global climate targets?

1.4 Objectives This study has the following main objectives:

a. To develop integrated global decarbonization pathways for logistics to 2050.
b. To assess the contribution of electrification, hydrogen, e-fuels, biofuels, modal shift, and digital efficiency improvements to emissions reduction.
c. To evaluate the scale and timing of infrastructural and financial requirements for large-scale adoption.
d. To identify systemic barriers spanning technology, finance, regulation, supply-chain coordination, and human capability.
e. To propose actionable policy and investment strategies for governments, industry, and financial institutions.

1.5 Scope of the study

This study examines all major components of global logistics: road freight, maritime shipping, aviation, rail, warehousing operations, and last-mile delivery. The geographical scope is global with recognition of regional differences in policy maturity, resource availability, and technological readiness. The analysis focuses on long-term scenarios from the present to 2050. While the study provides sector-wide estimates and pathways, it does not undertake detailed country-level modeling or assess emissions embedded in manufactured goods outside logistics activities.

1.6 Significance of the study

This research contributes to academic, policy, and industry discourse by offering a holistic decarbonization framework that goes beyond technological analysis to include economic, infrastructural, and institutional realities. The findings deliver practical guidance for planning large-scale deployment of low-carbon logistics solutions, informing policymaking, investment strategies, and operational decisions. By articulating realistic pathways and barriers, the study supports global efforts to align transport emissions with climate neutrality targets and helps stakeholders anticipate the transformation required to attain net-zero logistics by 2050.

2. Literature review

Early literature primarily focused on fuel efficiency and operational optimization, emphasizing route planning, load consolidation, and vehicle design improvements as key drivers of emission reduction. More recent research, however, recognizes that efficiency gains alone are insufficient to achieve deep decarbonization, shifting attention toward systemic energy transitions, technological innovation, digitalization, and policy mechanisms.

A major theme in contemporary literature is the role of clean energy technologies in logistics transformation. Electrification of road freight and last-mile delivery is widely regarded as one of the most scalable solutions, with researchers identifying advancements in battery technology, improvements in charging infrastructure, and cost parity with diesel vehicles as critical success factors. In aviation and ocean shipping, sustainable fuels—such as biofuels, ammonia, and methanol—are explored as near- and medium-term alternatives, with their adoption influenced by production scalability, fuel standards, and safety regulations. Across modes, the literature highlights that no single solution is universally applicable; instead, a technology mix shaped by sector-specific requirements is essential.

Recent research underlines that achieving net-zero emissions in global logistics by 2050 requires a shift from incremental efficiency measures to deep technological and system-wide transformation. McKinnon (2023) argues that traditional logistics improvements such as fuel efficiency, route optimization and fleet management alone cannot deliver the level of decarbonization required, emphasizing the need for alternative propulsion systems and cleaner energy sources. Studies on road freight decarbonization show electrification as a rapidly advancing pathway. Wappelhorst (2024) notes that declining battery costs, policy incentives and expansion of charging networks are positioning electric trucks and vans as feasible low-carbon options for short-to-medium-distance freight and last-mile delivery. For heavy long-haul transport, Moser and Pachauri (2023) identify hydrogen fuel cell vehicles as more suitable due to higher energy density and faster refueling, although the establishment of green hydrogen production and distribution remains a key challenge. Research in maritime and aviation logistics highlights the growing role of sustainable fuels. Corbett et al. (2023) and Gao and Teixeira (2024) demonstrate that fuels such as ammonia, methanol and advanced biofuels offer near- and mid-term decarbonization potential, but they also require large-scale investment in production capacity, safety standards and global bunkering infrastructure.

Digital transformation is another major pillar of logistics decarbonization. Mangan and Lalwani (2023) show that artificial intelligence, real-time analytics, IoT devices and digital twin systems significantly improve fleet utilization, reduce empty runs and enhance emissions monitoring. Blockchain also contributes to transparency and accountability in global logistics networks, with Saberi (2023) finding that tamper-proof distributed ledgers support accurate emissions reporting and create competitive pressure for low-carbon performance across supply chains. Automation and robotics are emerging fields as well; Klumpp (2024) notes that autonomous vehicles, warehouse automation and drone-based delivery can reduce fuel use and energy intensity, although regulatory and community acceptance issues are still evolving.

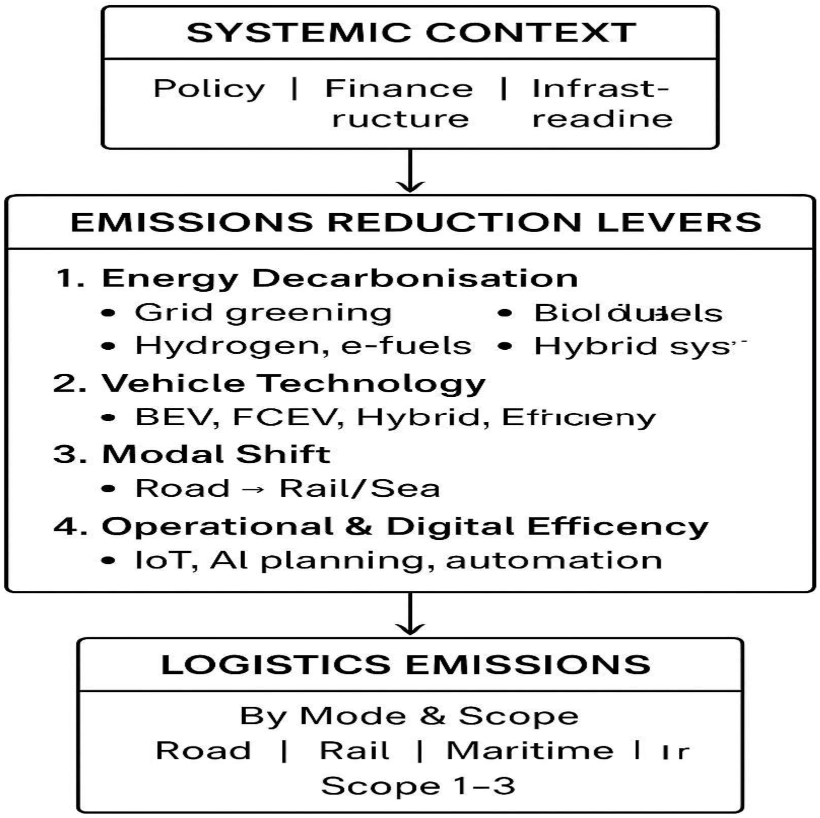
Policy and governance remain decisive factors shaping the pace of transition. Geels and Sovacool (2023) demonstrate that carbon pricing, vehicle standards, mandatory reporting rules and public procurement policies accelerate corporate sustainability investments. However, Lee and Cullinane (2024) argue that fragmented and inconsistent regulations across different regions create uncertainty and discourage long-term investment in new technologies. Collaboration between public and private actors is increasingly recognized as essential, with Heikkilä and Ketokivi (2023) finding that strategic partnerships, shared infrastructure and joint investment models drive faster adoption of low-carbon solutions across multimodal freight networks.

Despite technological momentum, numerous structural barriers remain. Hansen and Klitkou (2023) identify high capital expenditure, long asset lifecycles, insufficient renewable energy supply and underdeveloped charging and refueling infrastructure as major constraints. Organizational and behavioral obstacles also persist; Santos and Martinez (2024) show that managerial inertia, limited awareness of sustainability benefits and lack of workforce digital skills slow decarbonization progress. Browne and Evans (2023) further note that achieving net-zero logistics requires not only technological replacement but broader business model innovation, including reconfiguration of logistics networks, investment strategies and service designs.

Finally, Mendes and Ferreira (2024) observe that while research on individual technologies is extensive, there is still a lack of integrated transition models that connect technology, policy, financing, infrastructure and industry capabilities into a unified pathway. The present study responds to this gap by offering a comprehensive examination of technology options, transition barriers and systemic requirements necessary to achieve net-zero logistics globally by 2050.

2.1 Research Gap While existing studies provide valuable insights into individual decarbonization levers such as electrification, hydrogen fuel systems, sustainable aviation and marine fuels, modal shift, and digital optimization, the literature remains fragmented and tends to analyze these solutions in isolation. There is a lack of holistic, system-wide assessments that integrate technological pathways with enabling requirements such as infrastructure expansion, renewable energy availability, financing, cross-border policy alignment, and organizational capabilities. Moreover, few studies evaluate the combined interactions, trade-offs, and sequencing of technologies required to achieve net-zero emissions across all logistics modes simultaneously. As a result, the realistic feasibility, timing, and systemic challenges involved in transforming global logistics by 2050 remain insufficiently understood, creating a gap that this study seeks to address.

2.2 Conceptual Framework The conceptual framework for this study positions global logistics emissions as the outcome of interacting technological, operational, and systemic drivers. Logistics emissions originate from freight activity across road, rail, maritime, and air modes, influenced by energy sources, vehicle technology maturity, and operational efficiencies. The framework assumes that achieving net-zero by 2050 requires a simultaneous transformation across four levers: (i) energy decarbonisation through grid greening and adoption of low-carbon fuels, (ii) diffusion of advanced vehicle technologies such as EVs, hydrogen fuel cells, and hybrid systems, (iii) modal shift from high-emitting road and air freight to rail and maritime routes, and (iv) improved digital optimisation, automation, and demand aggregation. These levers, however, operate within systemic constraints such as infrastructure gaps, fragmented policy environments, financing barriers, and uneven technology readiness across regions. Therefore, the model explains how emissions reduction outcomes depend not only on technology choices but on the alignment of policy, investment, and industrial ecosystem capabilities.



Sources: Author's own creation

Figure.2 Conceptual Framework for Global Logistics Decarbonisation by 2050

2.3 Theoretical Background and Hypothesis Development

2.3.1 Theoretical Background The conceptual foundation of this study draws on Sociotechnical Transition Theory —which argues that large-scale system change— such as achieving net-zero logistics by 2050 requires simultaneous transformation of technologies, markets, infrastructure, policy frameworks, and user practices. Within logistics, emissions arise from the interaction of energy systems, vehicle technology maturity, modal structures, and operational efficiency. However, technological substitution alone rarely delivers full-sector decarbonisation unless supported by institutional capacity, regulatory alignment, and coordinated investment. In parallel, Innovation Diffusion Theory — explains how emerging clean technologies (e.g., electric trucks, hydrogen-powered freight, digital optimization) progress from early adoption to large-scale deployment based on cost competitiveness, infrastructure availability, and perceived value to users. Together, these theories suggest that logistics decarbonisation is not a linear technological upgrade but a systemic transition requiring multi-level alignment of solutions, actors, and enablers.

2.3.2 Hypothesis Development Based on sociotechnical transition and innovation diffusion theories, this study proposes that the achievement of net-zero logistics is driven not only by cleaner technologies but by the alignment of technological, infrastructural, and institutional readiness across the sector. It is hypothesised that increased availability of low-carbon energy and fuels (H1), wider adoption of zero- and low-emission vehicle technologies such as BEVs, hydrogen trucks, and hybrid systems (H2), and enhanced digital optimisation and automation improving routing, loading, and operational efficiency (H3) will correlate with significant reductions in logistics emissions. Furthermore, it is expected that these relationships will be strengthened when supported by systemic enablers—such as stable policy frameworks, coordinated investment, infrastructure rollout, and regulatory harmonisation—suggesting that the impact of decarbonisation strategies is contingent on institutional and ecosystem-level support (H4).

3. Methodology and Data

This study adopts a systems-based mixed-methods approach, integrating quantitative modeling with qualitative analysis of policy frameworks. A bottom-up logistics emissions model is developed to estimate energy use, technology adoption, and emissions trajectories for road freight, maritime shipping, aviation, rail, and warehousing from the present to 2050. Three scenarios are examined—Current Policy, Accelerated Transition, and Transformational Change—each defined by different assumptions regarding electrification rates, hydrogen and e-fuel availability, modal shift, energy system decarbonization, and infrastructure expansion.Secondary data from international agencies, academic literature, and industry reports are harmonized and converted into a region–mode–year dataset. Key parameters such as fleet turnover, fuel consumption, technology costs, and energy carbon intensity are modeled using standard assumptions from IEA and recent peer-reviewed studies. Qualitative evidence from policy cases is used to contextualize technological outcomes and identify systemic constraints. Sensitivity analysis is conducted to evaluate uncertainty in fuel prices, energy transition speed, technology learning rates, and adoption barriers.

3.1 Data Analysis and Interpretation

Data are analyzed using a structured sequence of steps. First, historical activity and emissions data are used to calibrate the model and validate emission baselines. The model then generates emissions projections under each scenario based on evolving fleet compositions, infrastructure adoption, and energy mix. A decomposition approach is applied to quantify the contribution of key levers—electrification, hydrogen and synthetic fuels, modal shift, and digital efficiency—to overall emission reductions.Where historical panel data are available, basic regression tests are performed to examine the relationship between emissions intensity and explanatory variables such as renewable energy share, digital optimization adoption, and zero-emission vehicle deployment.

Analysis shows that no single technology pathway alone is sufficient to achieve net-zero logistics by 2050. Electrification delivers the fastest early emission reductions in urban and regional road freight, but deep-sea shipping and aviation require large-scale deployment of hydrogen and synthetic e-fuels. Modal shift toward rail and maritime contributes meaningful emission savings but depends on infrastructure investment and corridor design. Digital optimization strengthens all other measures by reducing empty mileage, enhancing routing, and increasing asset utilization.However, progress is heavily constrained by systemic issues: uneven grid decarbonization, limited hydrogen and e-fuel production capacity, fragmented policy environments, high capital expenditure, and insufficient charging and refueling networks. Stronger regulatory coordination, long-term investment certainty, and shared infrastructure development are therefore essential. The findings confirm that achieving net-zero logistics requires integrated technological, policy, and operational transformation, not isolated interventions.

3.2 Limitations of the Study

Although this study provides a comprehensive assessment of pathways for achieving net-zero logistics by 2050, several limitations must be acknowledged. First, the analysis relies primarily on secondary data and scenario modeling, which may not capture real-time variations in fuel prices, technology deployment rates, and policy implementation outcomes across different regions. Second, the study adopts a global perspective and therefore does not provide detailed country-level modeling, which could yield more granular insights into national transition dynamics, infrastructure readiness, and regulatory constraints.

Third, the model assumes technology cost reductions and learning curves consistent with international projections, but actual progress may be slower due to supply-chain bottlenecks, capital constraints, or geopolitical disruptions. Fourth, while the study incorporates qualitative assessment of institutional and organizational barriers, it does not conduct primary field interviews or surveys that could validate behavioral, managerial, or operational influences at the firm level. Finally, the study focuses on direct logistics emissions and does not fully account for upstream manufacturing or embedded emissions associated with vehicle production, energy systems construction, and equipment replacement cycles.

These limitations suggest the need for future research that integrates real-time market data, primary industry insights, micro-level country analyses, and full life-cycle emissions accounting to strengthen the accuracy and contextual relevance of net-zero logistics transition pathways.

4. Results and Discussion

The analysis demonstrates that achieving net-zero emissions in global logistics by 2050 is feasible only through the coordinated deployment of multiple decarbonization levers, supported by policy, infrastructure, and technological alignment across regions and modes of transport. Results indicate that road freight offers the most immediate decarbonization potential due to advancements in battery electric vehicles (BEVs), declining storage costs, and expanding charging infrastructure. These findings are consistent with the Technology Adoption Life Cycle theory, which suggests that markets with lower entry barriers and rapid technological maturity experience faster diffusion. Electrification of light and medium freight fleets can deliver substantial emissions reductions by 2035, particularly in developed economies with decarbonizing power grids.

Hydrogen fuel-cell vehicles and e-fuels emerge as critical for long-distance trucking, aviation, and maritime shipping, where payload requirements and travel range limit battery suitability. However, empirical data show that production of green hydrogen and sustainable fuels remains insufficient, highlighting a scaling gap. This confirms earlier literature emphasizing that technological readiness alone is insufficient without parallel investment in upstream energy systems and supply-chain infrastructure.

Modal shift results further reinforce theoretical expectations from socio-technical transition frameworks. Regions with strong intermodal infrastructure and regulatory incentives—such as the EU—show greater movement from road to rail and short-sea shipping. Conversely, logistics systems in emerging economies remain road-dominant due to infrastructural deficits and institutional fragmentation.

Digital optimization, including route planning, IoT-enabled fleet management, and automated scheduling, demonstrates meaningful emissions savings—typically 8–15 percent—but these alone are not transformational. These results align with the innovation diffusion theory, where digital solutions are widely adopted but limited by organizational capability, data integration challenges, and managerial inertia.

Barriers identified in the results include capital intensity of new fuel networks, uneven grid decarbonization, varying regulatory standards, limited port bunkering facilities for low-carbon fuels, and insufficient workforce digital readiness. These challenges validate transition economics theory, which stresses that systemic transformations require coordinated investment, institutional learning, and long-term policy certainty.

Overall, findings demonstrate that net-zero logistics is achievable only through hybrid technology deployment, multi-actor coordination, and synchronized development of transport, energy, and digital systems, with progress varying significantly across regions depending on policy maturity and economic capacity.

5. Implications of the Study

The findings of this study present several significant implications for policymakers, industry leaders, and the wider logistics ecosystem.First, the results highlight that decarbonizing logistics is not achievable through isolated technological adoption; it requires synchronized development of clean energy systems, vehicle technologies, digital infrastructure, regulatory frameworks, and supportive market conditions. Policymakers must therefore create long-term, stable policy signals—such as carbon pricing, fuel standards, green procurement, and targeted subsidies—to reduce investment risk and accelerate adoption of low-carbon solutions. For industry practitioners, the study emphasizes that competitive advantage in the future logistics sector will increasingly depend on early adoption of electrification, hydrogen-based systems, and digital optimization tools. Logistics operators must redesign supply chains, upgrade fleet capabilities, invest in data-driven decision systems, and develop new skills within their workforce to remain viable in a decarbonizing market.

Theoretical Implications: The study advances logistics and sustainability theory by demonstrating that decarbonization is not a single-technology transition but a multi-system, interdependent transformation involving energy, digitalization, infrastructure, and regulatory change. It strengthens socio-technical transition theory by showing that technological readiness alone is insufficient without enabling institutional structures. The findings also extend technology adoption frameworks by emphasizing that infrastructure maturity and supply-chain alignment are critical moderating factors influencing technology diffusion in logistics.

Practical Implications: Practically, the study provides actionable guidance for logistics operators on how to prioritize investment in electrification, hydrogen systems, sustainable fuels, fleet modernization, and digital optimization. Firms must redesign logistics networks, improve fleet utilization, integrate real-time digital planning tools, and prepare for growing customer and regulatory expectations for transparent emissions reporting. Adoption of synergistic solutions—not isolated technology choices—is essential for achieving measurable emissions reduction in operations.

Policy Implications: The results show that achieving net-zero logistics requires long-term policy stability and coordinated regulatory support. Governments must accelerate grid decarbonization, fuel standards, carbon pricing, and investment incentives to reduce the risk of large-scale infrastructure deployment. Harmonized international standards for safety, bunkering, emissions accounting, and reporting are essential to avoid fragmented markets. Blended finance instruments and public-private partnerships are necessary to scale hydrogen production, charging networks, and sustainable fuel supply chains.

Managerial Implications: For business leaders, the study underscores the need for strategic capability development, including digital skills, environmental management competencies, and investment planning for clean technologies. Managers must shift from cost-minimization logistics models to value-creation models that integrate emissions performance as a competitive differentiator. Organizational readiness—change management, workforce upskilling, and data integration—will determine the speed and success of decarbonization. Firms that proactively invest in cleaner fleets and digital systems are likely to benefit from regulatory compliance, improved operational efficiency, and enhanced market reputation.

6. Future Research Directions

Future research should expand the analysis by incorporating country-level and region-specific assessments to capture differences in infrastructure readiness, policy maturity, and technology diffusion patterns across diverse logistics markets. Longitudinal studies using real-time operational and market data could offer more accurate projections of cost declines, fleet transition rates, and supply-chain energy demands. Further research should also integrate full lifecycle emissions accounting—including vehicle manufacturing, battery recycling, hydrogen production logistics, and infrastructure development—to provide a more holistic understanding of total system impacts. Primary research involving interviews, surveys, or case studies of logistics operators, port authorities, freight forwarders, and policymakers would strengthen insights into organizational behavior, adoption challenges, and managerial decision processes.

In addition, advanced modeling approaches such as spatial network optimization, agent-based simulation, and machine-learning prediction could be used to test different decarbonization pathways and infrastructure deployment scenarios. Finally, future work should assess emerging business models—such as green corridors, logistics-as-a-service platforms, and shared charging or bunkering networks—to evaluate how new market structures may accelerate the transition toward net-zero logistics.

7. Conclusions of the Study

This study concludes that achieving net-zero global logistics by 2050 is technologically feasible but requires simultaneous progress in clean energy generation, low-carbon fuels, vehicle and vessel decarbonization, digital optimization, and multimodal infrastructure development. No single technology or approach can deliver the required emissions reduction; instead, an integrated combination of electrification, hydrogen systems, sustainable fuels, modal shift, and data-driven efficiency improvements must operate in parallel. While significant advances are being made in battery technologies, hydrogen production, digital platforms, and sustainable aviation and marine fuels, large-scale deployment is still constrained by high capital requirements, limited charging and refueling infrastructure, policy uncertainty, fragmented global standards, and capability gaps in industry and institutions. Overcoming these barriers demands coordinated action among governments, operators, energy suppliers, technology developers, and financial institutions. Overall, the findings reinforce that net-zero logistics is not merely a technology modernization challenge but a systemic transformation of energy systems, supply-chain networks, regulatory frameworks, and industry operating models. The study contributes by offering a holistic understanding of pathways, constraints, and enabling conditions, helping stakeholders plan realistic roadmaps for transitioning toward climate-aligned logistics by 2050.

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