

Exploration of Low-Carbon Transformation Paths for Enterprise Supply Chains from the Perspective of Green Logistics

Fei Hou^{1*}

¹ China Logistics Group Co., Ltd., Beijing, China

Email Address

hoad@foxmail.com (Fei Hou)

*Correspondence: hoad@foxmail.com

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Abstract:

The growing urgency of global climate change has made low-carbon transformation a critical priority for enterprises. As supply chains account for a large share of carbon emissions, achieving sustainable operations requires integrating emission reduction strategies into logistics processes. From the perspective of green logistics, this study examines the theoretical foundations of low-carbon supply chains, analyzes the current challenges under policy pressures, market demands, technological conditions, and internal barriers, and explores transformation paths in transportation, warehousing, packaging, procurement, and digital empowerment. The findings highlight that green logistics offers both practical tools and strategic direction for reducing supply chain emissions while enhancing efficiency and competitiveness. This exploration provides enterprises with actionable pathways to align economic performance with environmental sustainability in the era of carbon neutrality.

Keywords:

Low-carbon Supply Chain, Green Logistics, Transportation Decarbonization, Digital Empowerment

1. Introduction

In the context of global climate change, the pursuit of carbon neutrality has become a strategic goal for both governments and enterprises. Supply chains, as the backbone of modern production and distribution, are significant contributors to greenhouse gas emissions due to their complex networks of transportation, warehousing, procurement, and packaging activities. With increasing regulatory pressures and rising consumer awareness of environmental sustainability, enterprises are facing unprecedented challenges and opportunities in transitioning toward low-carbon operations.

Green logistics, which emphasizes energy efficiency, emission reduction, and resource optimization across logistics processes, offers an effective perspective for achieving low-carbon supply chain transformation. By integrating environmentally

friendly practices into transportation, warehousing, packaging, and procurement, green logistics not only reduces the carbon footprint of enterprises but also enhances competitiveness, brand reputation, and long-term resilience. At the same time, the rapid advancement of digital technologies such as big data, the Internet of Things, and blockchain provides enterprises with new tools for carbon monitoring and optimization.

This study aims to explore the transformation paths of enterprise supply chains from the perspective of green logistics. It analyzes the theoretical foundations of low-carbon supply chains, identifies current challenges and barriers in their transition, and proposes practical transformation strategies with logistics as the core entry point.

2. Theoretical Foundations of Low-Carbon Transformation in Supply Chains

The push to transform enterprise supply chains for low-carbon development is anchored in the broader concept of a low-carbon economy. This paradigm advocates decoupling economic growth from carbon emissions, aiming to reduce greenhouse gas output while still fostering sustainable development. Within this framework, supply chains are re-envisioned not just through the lens of efficiency and cost, but also in terms of their capacity to minimize environmental harm. The theoretical foundation draws from an integration of ecological economics and supply chain management, emphasizing that true performance must account for both economic gains and ecological stewardship. This perspective echoes the triple bottom line approach—balancing profit with environmental and social responsibility—and aligns with calls from ecological economics to reconcile growth with planetary limits.

Green logistics emerges as a crucial bridge between low-carbon theory and practical supply chain management. It entails embedding environmentally conscious practices into logistics operations such as transportation, warehousing, and packaging. By emphasizing energy efficiency, adoption of renewables, and waste reduction, green logistics directly translates abstract low-carbon goals into concrete actions on the ground. For example, optimizing vehicle routes and loads, switching to electric or fuel-efficient vehicles, improving warehouse energy use, and designing eco-friendly packaging are all core green logistics measures that shrink a supply chain's carbon footprint. Such initiatives align with circular economy principles of reuse and resource efficiency and broader sustainable development imperatives. In this way, logistics functions are reframed from being mere operational tasks into strategic levers for carbon reduction and sustainable value creation.

The synergy between green logistics and low-carbon supply chain transformation can be understood as a coupling mechanism focused on continuous resource optimization and emission reduction. Decisions at the logistics level have cascading effects on the supply chain's overall carbon profile. For instance, key choices in logistics include:

Optimization of Transportation Routes and Modes: Utilize big data and intelligent algorithms to plan globally optimal transportation routes, while prioritizing multimodal transport methods such as “shift from road to rail” and “shift from road to water” to reduce carbon emissions from transportation.

Technological Upgrades of Transportation Vehicles: On one hand, increase the adoption of zero-emission vehicles, such as pure electric and hydrogen fuel cell

vehicles, in urban distribution and short-distance transportation. On the other hand, reduce the carbon emissions per unit distance of traditional fuel-powered vehicles through measures like engine energy-saving modifications and upgrades to exhaust gas aftertreatment technologies.

Energy Efficiency Management of Logistics Facilities: With the goal of building “low-carbon parks” and “green warehouses,” optimize warehouse network layouts, integrate photovoltaic power supply systems, and apply technologies such as intelligent temperature control and LED energy-efficient lighting to transition storage facilities from “passive energy saving” to “active carbon reduction.”

Development of a Green Packaging System: On one hand, replace non-degradable plastics with biodegradable and recyclable biomass materials (e.g., corn starch-based packaging and recycled paper boxes). On the other hand, reduce excessive packaging through modular design and precise size matching, while establishing a packaging recycling and reuse system to form a closed-loop process of “production-use-recycling-reuse.”

Each of these decisions directly influences the supply chain’s greenhouse gas emissions and resource consumption. Moreover, the integration of advanced information technologies amplifies this coupling mechanism. Tools like big data analytics, Internet of Things (IoT) sensors, and AI-driven management systems enable real-time monitoring and adaptive optimization of logistics activities. This creates feedback loops for continuous improvement, where data on fuel usage, routing efficiency, or inventory levels can prompt swift adjustments to further cut emissions. Theoretically, such integration fosters a virtuous cycle: efficiency gains, cost savings, and carbon reductions reinforce one another over time. This forms a strong foundation for supply chains that are not only low-carbon and environmentally sustainable, but also more resilient and competitive in the long run.

3. Current Situation and Challenges of Supply Chain Low-Carbon Transition

3.1. Policy and regulatory pressures under carbon neutrality goals

Governments worldwide have adopted carbon peak and carbon neutrality strategies, embedding emission reduction targets into national development agendas. These policies translate into strict environmental regulations, mandatory carbon reporting, and compliance standards for enterprises. For supply chains, this means greater scrutiny of logistics operations, procurement processes, and energy use. Companies are compelled to adopt green logistics practices not only to avoid penalties but also to access policy incentives such as subsidies, tax reductions, and carbon credits. The increasing institutionalization of carbon governance places regulatory compliance at the core of supply chain decision-making, thereby driving enterprises toward low-carbon transformation.

3.2. Market and consumer demand for greener products

Beyond policy pressures, market forces are reshaping the landscape of supply chain management. With growing awareness of climate change, consumers are demanding environmentally friendly products and services, and many are willing to pay a premium for sustainable alternatives. This trend pushes enterprises to green their supply chains as a means of maintaining competitiveness and enhancing brand

reputation. For example, multinational corporations increasingly require suppliers to disclose carbon footprints and adopt sustainability standards. Failure to respond to these demands risks market exclusion, while proactive adaptation may open new market opportunities and strengthen customer loyalty. Thus, consumer-driven sustainability expectations act as a catalyst for supply chain decarbonization.

3.3. Technological opportunities and constraints

Technological innovation presents powerful tools for advancing low-carbon supply chains. Digital technologies such as big data analytics, blockchain, and the Internet of Things enable real-time monitoring of logistics operations and transparent tracking of carbon emissions. At the same time, clean energy vehicles, automated warehouses, and eco-friendly packaging materials provide concrete solutions for emission reduction. However, the diffusion of such technologies is uneven across industries and regions. High capital investment, technical expertise requirements, and compatibility issues with existing systems often constrain their large-scale adoption. Consequently, while technology provides opportunities for radical improvements in logistics efficiency and carbon reduction, its accessibility and cost remain critical challenges.

3.4. Internal barriers such as costs and organizational resistance

Within enterprises, internal barriers often slow the pace of low-carbon supply chain transformation. Implementing green logistics measures usually requires significant upfront investments in infrastructure, technology, and training, which may be perceived as financial burdens in the short term. Additionally, organizational inertia and resistance to change hinder the adoption of innovative practices. Employees and managers may prioritize traditional performance indicators such as cost reduction and delivery speed over environmental objectives, creating conflicts between economic and ecological goals. Without strong leadership commitment and a cultural shift toward sustainability, enterprises may struggle to align internal processes with low-carbon strategies.

4. Transformation Paths from the Perspective of Green Logistics

4.1. Transportation decarbonization

Transportation is one of the most carbon-intensive activities in supply chains, mainly due to fossil fuel-powered vehicles and inefficient routing. Decarbonization in this sector is therefore a key entry point for building low-carbon supply chains under the framework of green logistics.

A primary measure is the adoption of clean energy vehicles, including electric trucks, hybrids, and hydrogen-powered fleets. These alternatives reduce direct emissions and, with the support of renewable charging infrastructure, can ensure a more sustainable energy supply. At the same time, route optimization through digital tools such as big data and AI enables enterprises to cut fuel consumption by minimizing distances, avoiding congestion, and consolidating deliveries.

Multimodal transport further strengthens decarbonization by shifting freight from high-emission modes, such as road and air, to lower-emission rail or water transport. For the last mile, which often accounts for a large share of emissions, enterprises are experimenting with electric bicycles, automated delivery robots, and micro-distribution centers in urban areas.

Through a combination of clean energy vehicles, intelligent routing, multimodal systems, and greener last-mile delivery, enterprises can significantly reduce logistics emissions while improving supply chain efficiency and resilience.

4.2. Warehousing decarbonization

Warehousing is another critical link in supply chains where large amounts of energy are consumed for lighting, refrigeration, heating, and automated operations. Decarbonization in this stage requires both technological upgrades and management improvements.

A key pathway is the construction and retrofitting of energy-efficient facilities. The use of LED lighting, smart temperature control, and natural ventilation reduces electricity consumption. In parallel, the installation of renewable energy systems, such as rooftop solar panels, helps warehouses shift toward cleaner power sources.

Digitalization also plays a role by enabling smart inventory management. Advanced warehouse management systems (WMS) can optimize storage layouts, reduce unnecessary handling, and shorten equipment operation time, thereby lowering indirect emissions. Moreover, practices such as cross-docking and just-in-time storage reduce the need for long-term warehousing, cutting both energy demand and carbon output.

Together, energy-efficient infrastructure and intelligent management form the foundation of low-carbon warehousing, helping enterprises lower operating costs while meeting sustainability goals.

4.3. Packaging decarbonization

Packaging is a significant source of carbon emissions in supply chains, stemming from both the carbon-intensive production of materials and the impacts of packaging waste. For example, packaging materials make up around 40% of municipal solid waste in Western Europe, illustrating how disposal contributes to emissions in addition to manufacturing. Decarbonizing this area therefore centers on material substitution, innovative design, and robust recycling/reuse systems to tackle emissions across the packaging lifecycle.

A key strategy is to switch to low-carbon, biodegradable or recyclable materials in place of conventional plastics. Using paper-based, recycled, or plant-based biomaterials reduces reliance on fossil-fuel plastics and can lower the lifecycle carbon footprint of packaging. In parallel, lightweight packaging design techniques minimize raw material usage and reduce the weight of shipments, cutting fuel consumption during transport. In fact, studies show that using lighter packaging can cut associated CO₂ emissions on the order of 10%, while substituting materials yields a similar ~10% reduction. Enterprises are also deploying modular and reusable packaging systems – standardized crates, pallets, or containers that can be circulated multiple times – to avoid single-use waste. Replacing disposable packages with durable, returnable ones has been shown to achieve even greater emission reductions (roughly 16% or more in CO₂ savings) by amortizing the material over many uses. This kind of design innovation not only cuts manufacturing emissions but also significantly shrinks the waste stream.

4.4. Green procurement

Procurement decisions shape the entire supply chain's carbon footprint, as they determine which suppliers and materials a company relies on. In many industries, upstream (Scope 3) emissions from the supply chain far exceed a firm's direct emissions – for instance, one global analysis found supply chain emissions to average 11.4 times higher than operational emissions. Green procurement addresses this leverage point by embedding sustainability criteria into purchasing choices, ensuring that environmental performance is considered alongside traditional metrics. In practice, this means selecting suppliers and inputs that meet high environmental standards, thereby pushing low-carbon principles into the upstream stages of production.

Enterprises now increasingly require suppliers to measure and disclose their carbon emissions, as well as to adopt eco-friendly practices such as using renewable energy, low-carbon manufacturing processes, and responsible sourcing of raw materials. For example, major buyers might ask key suppliers to report their greenhouse gas emissions and set reduction targets, or mandate that certain components be made with recycled or certified-sustainable materials. Green criteria are being integrated into supplier evaluation and RFQ/RFP processes – carbon performance is emerging as a critical procurement metric on par with cost, quality, and delivery considerations. Procurement departments are developing supplier scorecards that include CO₂ intensity, requiring bids to document emissions data, and giving preference to vendors with verified climate credentials (such as ISO 14001 certification or science-based targets). By making emissions transparency and reduction a condition of doing business, companies create competitive pressure for suppliers to improve their sustainability.

4.5. Digital empowerment

Digital technologies are a powerful enabler of low-carbon supply chain transformation, providing the tools for precise monitoring, transparent reporting, and data-driven optimization. Through big data analytics and artificial intelligence (AI), companies can gain real-time visibility into their logistics operations and make smarter decisions to cut emissions. For example, AI-powered route optimization systems can dynamically adjust delivery routes to minimize distance and avoid delays, directly reducing fuel burn and transportation emissions. Similarly, machine learning models for demand forecasting allow firms to predict sales more accurately and fine-tune inventory levels – ensuring production and distribution are closely aligned with actual demand. This reduces overproduction and idle inventory (which wastes energy in storage and often ends up as scrap), thereby cutting unnecessary supply chain emissions. By leveraging vast datasets (from weather and traffic patterns to sales trends), digital analytics help eliminate inefficiencies and trim the “fat” from logistics and warehousing, leading to leaner operations with a smaller carbon footprint.

The Internet of Things (IoT) further strengthens supply chain sustainability by connecting vehicles, equipment, and facilities to a continuous data stream. IoT sensors embedded in trucks, containers, and warehouse systems enable granular tracking of energy use and emissions at each step. For instance, telematics devices in fleet vehicles can monitor fuel consumption, driver behavior, and engine health in real time, allowing proactive maintenance and route adjustments to improve mileage. In warehouses, IoT meters and smart controls track electricity usage for lighting, heating/cooling, and material handling, helping identify inefficiencies and peak usage times for energy savings. This high-resolution data collection builds a foundation for

accurate carbon accounting across the network. Meanwhile, blockchain technology adds a layer of transparency and trust to the process of managing and sharing this emission data. By recording transactions and carbon metrics on an immutable distributed ledger, blockchain ensures that any emissions reductions claimed by different parties are verifiable and traceable. For example, a blockchain-based system can log each supplier's input of carbon data or renewable energy credits, creating an audit trail that all stakeholders can trust. Such a framework was shown to enable precise tracking and automated verification of supply chain carbon emissions, greatly improving data reliability for ESG reporting. In short, IoT provides the eyes and ears for monitoring carbon performance, while blockchain provides a secure record-keeping backbone – together bolstering transparency across the entire chain.

5. Conclusions

The transformation of enterprise supply chains toward low-carbon development is both a pressing necessity and a strategic opportunity in the era of carbon neutrality. From the perspective of green logistics, enterprises can achieve emission reduction by rethinking and redesigning transportation, warehousing, packaging, and procurement, while leveraging digital technologies to enhance transparency and efficiency. These pathways demonstrate that economic performance and environmental sustainability are not mutually exclusive but can be pursued in parallel through integrated supply chain strategies.

At the same time, enterprises must recognize that low-carbon transformation is not free of challenges. Policy and regulatory pressures, evolving consumer expectations, technological constraints, and internal organizational barriers require coordinated responses. Successful transformation depends on leadership commitment, cross-sector collaboration, and supportive policy frameworks that encourage innovation and investment in green logistics solutions.

Looking ahead, the future of low-carbon supply chains will likely be shaped by the deep integration of digital technologies, greater international cooperation in carbon governance, and the expansion of circular economy models. By embedding green logistics into the core of supply chain management, enterprises can not only reduce their carbon footprint but also enhance resilience, competitiveness, and social responsibility in a rapidly evolving global landscape.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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