Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 20, No. 2, 2025

Analysis of Supply Chain Management Issues in Energy Enterprises

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Abstract: Energy supply chains face critical challenges due to inherent "Triple Rigidity" (resource dependency, infrastructure specificity, institutional constraints), manifesting as low resilience, high logistics costs, and green transition pressures. This study proposes a tri-dimensional optimization framework: (1) Build resilient networks through diversification and digital monitoring; (2) Optimize logistics via infrastructure upgrades and multimodal integration; (3) Drive sustainability with carbon management and circular solutions. Validated by State Grid's case, results show significant outage reduction (42%) and cost savings. The framework enables energy enterprises to balance security and decarbonization imperatives.

Keywords: Energy Supply Chain Management; Triple Rigidity; Resilience; Logistics Cost; Green Transformation.

1. Introduction

1.1. Research Background and Significance

The rational application of supply chain management (SCM) in areas such as supplier selection, production planning, and risk control can significantly reduce costs, improve operational efficiency, and enhance market competitiveness. [1] Energy is the lifeblood of a nation's economy; the stability of the energy supply chain directly impacts national strategic security and economic resilience. Currently, intensifying global geopolitical conflicts, frequent extreme climate events, and the tightening rigid constraints of the "dual-carbon" goals collectively subject energy production enterprises to immense supply chain pressures. Traditional energy (e.g., oil, natural gas, electricity) supply chains exhibit significant vulnerability under these complex conditions due to factors such as high geographical concentration of resources, strong specificity of infrastructure, and stringent safety and environmental requirements. While the new energy industry is developing rapidly, its supply chain still faces structural bottlenecks, including raw material supply, coordination of multinational logistics, and unification of technical standards.

Against this backdrop, supply chain management (SCM) has become a crucial means for enterprises to enhance operational efficiency, ensure supply security, and promote sustainable development. After reviewing relevant literature, the author found that existing research primarily focuses on SCM optimization in manufacturing or retail industries, without fully considering the characteristics of the energy sector—such as long cycles, heavy regulation, and high sensitivity—and conducting corresponding SCM research and analysis. Therefore, systematically analyzing the core SCM issues in the energy industry and exploring optimization pathways aligned with its specific characteristics hold significant practical value and theoretical innovation significance. This research not only helps enterprises mitigate supply chain disruption risks, reduce logistics costs, and drive green transformation but also contributes to the construction of the national energy security system and the achievement of the "carbon neutrality" goal.

1.2. Research Objectives and Content

Supply chain management is a systematic endeavor and an important component of a company's long-term development strategy. [2] SCM involves managing the entire flow of products or services from suppliers to end-users, encompassing raw material procurement, production and manufacturing, product distribution, and after-sales service. It extends beyond logistics management to include the coordinated operation of information and capital flows. [3] Furthermore, the supply chain possesses endogenous theoretical relationships, constrained by three aspects: power structure, contractual terms, and trust levels. [4] This study aims to deconstruct the uniqueness of the energy supply chain, focusing on three core management challenges, and propose targeted optimization strategies.

This paper focuses on the core management challenges and their underlying causes within the energy supply chain across three domains: resilience and risk resistance, logistics cost control, and green sustainable transformation. It proposes an optimization framework based on industry practices and theoretical tools. Additionally, the paper validates the effectiveness of the strategies through typical cases, ultimately forming SCM insights with broad applicability.

This research unfolds across three levels: challenge diagnosis, strategy design, and case validation. Firstly, based on the "resource-facility-institution" triple dependency characteristic of the energy supply chain, it systematically analyzes the interaction mechanisms among resilience risks, high logistics costs, and green transition pressures. Then, it constructs implementation pathways for resilient networks, logistics optimization, and green supply chains, respectively. Finally, the effectiveness and applicability conditions of the strategies are validated through typical enterprise case studies.

1.3. Research Methodology

The logical structure of this paper follows "Theory-Problem-Strategy-Validation." The main research methods include literature analysis, systems analysis, and case study deep description. The author first employs literature analysis to review theories such as supply chain resilience (Christopher, 2016) and sustainable SCM (Seuring & Müller, 2008), defining an adapted framework for the energy industry.

Subsequently, systems analysis is applied, introducing the SCOR model to deconstruct energy supply chain processes and identify risks at key nodes and cost inefficiencies. Finally, the case study deep description method focuses on leading enterprises within specific energy subsectors (e.g., oil & gas, power, new energy), utilizing public reports, industry interviews, and operational data to cross-validate the practical effectiveness of the strategies.

1.4. Thesis Structure

The thesis comprises five chapters, progressing logically as follows:

Chapter 1: Introduction: Sets the stage for the research.

Chapter 2: Analyzing Energy Supply Chain Characteristics: Identifies and elaborates on the three core challenges of resilience, logistics costs, and green transformation.

Chapter 3: Proposing Optimization Strategies: Develops a three-dimensional solution framework focusing on "Risk Resistance - Efficiency Enhancement - Sustainability Drive".

Chapter 4: Case Analysis: Empirically validates the strategies using the case of State Grid Corporation of China.

Chapter 5: Conclusion: Summarizes findings.

2. Characteristics and Management Challenges of the Energy Supply Chain

2.1. Core Characteristics of the Energy Supply Chain

The supply chains of energy production enterprises possess unique industry attributes, exhibiting a "triple rigidity" structure distinct from general manufacturing, which profoundly shapes their management logic and operational boundaries.

Resource Dependency Rigidity forms the most fundamental constraint layer. The distribution of energy resources is characterized by significant geographical imbalance. Fossil fuels are often concentrated in specific geopolitical regions (e.g., Middle Eastern oil, Russian natural gas), while renewable energy relies on specific natural conditions (e.g., high solar irradiation, strong wind zones). These resource endowment characteristics inevitably lead to complex and sensitive cross-border or inter-regional flows within the energy supply chain. Such flows are also constrained by two key factors: the long development cycles of energy projects and geopolitical sensitivity. For instance, oil and gas field exploration and development often exceed a decade, and large-scale renewable energy projects can take five to eight years from planning to grid connection. This characteristic results in supply chain responsiveness lagging severely behind market demand changes. Concurrently, the energy supply chain is deeply affected by geopolitics; the 2021 European gas price surge of 780% due to Russian supply disruptions is a prime example [5].

Infrastructure Rigidity significantly impacts operational efficiency and risk resilience. Dedicated facilities in the energy supply chain feature large-scale investments, high sunk costs, and strong natural monopolies. For example, the construction cost per kilometer for the Central Asia Gas Pipeline exceeds $3 million USD, and 85% of China's main oil and gas pipeline networks are controlled by three state-owned oil companies. While such centralized networks can achieve economies of scale, they also harbor systemic risks that threaten supply chain stability. The 2021 Texas power grid failure during a winter storm, leaving 4 million customers without power, starkly exposed the cascading disaster effects triggered by the failure of critical nodes in a centralized network.

Institutional Constraints constitute increasingly stringent external regulations for the energy supply chain. Safety standards for energy supply chain operations are continuously rising, with the cost of major accidents becoming unbearable for companies. Simultaneously, the binding force of environmental regulations is strengthening alongside the global energy transition. Examples include China's "dual-carbon" goals setting strict timelines for coal power peaking, and the EU's Carbon Border Adjustment Mechanism (CBAM) increasing export costs for high-carbon energy products. It is this interplay of institutional constraints, resource dependency, and infrastructure rigidity that shapes the core characteristics of the energy supply chain: high vulnerability, insufficient elasticity, and significant externalities.

2.2. Core Management Challenges Analysis

Based on the aforementioned "triple rigidity" characteristics, the supply chain management of energy production enterprises faces a series of interconnected and particularly prominent core challenges.

Challenge 1: Ensuring Resilience and Risk Resistance: The primary difficulty currently faced by enterprises is guaranteeing the resilience of their supply chains and the ability to withstand sudden risks. The high concentration of resources and the long-distance, multi-node flow paths make energy supply chains highly susceptible to external shocks like geopolitical conflicts and natural disasters. Examples include the 2022 Russia-Ukraine conflict causing gas supply disruptions across multiple European countries, and Hurricane Ida halting 94% of crude oil production in the US Gulf of Mexico. Concurrently, the vulnerability of dedicated infrastructure means localized issues like pipeline corrosion, third-party damage, or critical grid equipment failure can easily trigger cascading failures. China recorded over 800 gas accidents in 2020, and the "303 Major Blackout" in Taiwan Province in 2022 affecting 5 million users serve as stark lessons. A more severe problem is that emergency responses are often severely delayed during crises due to the immobility of infrastructure, the high cost and long duration of switching to backup solutions, leading to severe consequences.

Challenge 2: Controlling Logistics Costs and Overcoming Infrastructure Bottlenecks: Effectively managing logistics costs and breaking through infrastructure bottlenecks is another formidable challenge. Energy supply chain infrastructure often suffers from high asset intensity and low utilization rates (China's National Energy Administration 2023 research indicated some pipeline utilization rates at 60-70%, and coal railway transport "empty return rates" exceeding 40%). Network congestion (e.g., over 20 billion kWh of hydropower curtailed in Yunnan in 2022 due to transmission constraints) further drives high total logistics costs. For instance, oil and gas logistics costs typically account for 15-20% of the final selling price, far exceeding the industrial average, while overseas transshipment freight costs for new energy components surged by 600% during the 2021 peak. Inefficient multimodal transport interconnections further squeeze industry profits, and the long asset payback periods (often exceeding 20 years) force companies into difficult choices between short-term cost reduction and long-term transformation.

Challenge 3: Green Transformation Pressure and Rising Compliance Costs: The pressure for green transformation and the surge in consumption compliance costs constitute the third core challenge. Examples include EU carbon prices reaching €100/ton and China's expected carbon price of ¥200/ton in 2023, significantly increasing marginal costs for coal-heavy power plants. Oil and gas companies are also constrained by stringent methane emission standards (COP28 commitment to 30% reduction by 2030). These increasingly strict environmental regulations compel companies to internalize environmental external costs. Establishing a green supply chain also entails higher costs, such as green electricity typically costing 20% more than standard electricity, and deep due diligence on battery material (lithium, cobalt) sources adding 15%-25% to raw material costs. Crucially, a significant portion of energy companies' emissions originate upstream in their supply chains. Many small and medium-sized enterprises (SMEs) (e.g., coal mines) lack the technical capability or financial resources for emission reduction. This supply chain structure creates complexity in achieving decarbonization across the entire chain. Furthermore, circular economy practices remain underdeveloped at the end of the energy supply chain. Wind turbine blade recycling costs are high ($600/ton) with a global recycling rate below 5%, and photovoltaic panel waste disposal is becoming increasingly urgent (estimated at 8 million tons to be processed by 2030). Green supply chain management in petrochemical enterprises has distinct characteristics, systematically manifested in the integration and coordinated planning of all supply chain segments, ensuring harmonious operation between links to achieve overall rather than merely local optimization.

3. Optimization Strategies and Pathways

Optimizing supply chain management has become a key element for enterprises to enhance their market competitiveness. By adopting advanced technologies and management methods, companies can achieve efficient supply chain operations, reduce costs, improve customer satisfaction, and strengthen market competitiveness [6].

Addressing the core SCM challenges revealed in Chapter 2 necessitates constructing an optimization framework deeply aligned with the energy industry's "triple rigidity" characteristics. The optimization framework proposed in this chapter focuses on three dimensions: resilience enhancement, cost control, and green transformation. It aims to resolve structural contradictions through systematic intervention, thereby driving the energy supply chain towards greater efficiency, robustness, and sustainability.

3.1. Strategy 1: Building a High-Resilience Supply Chain Network (Addresses Challenge 1)

Strengthening the resilience and risk resistance of the energy supply chain is the primary approach to counter geopolitical conflicts and sudden crises. The core of this strategy lies in breaking the high dependence on resources and facilities and constructing a multi-dimensional buffer system.

Supply Port Diversification: Enterprises should actively expand resource acquisition channels. This can be achieved through a combination of long-term agreements and spot contracts, investing in equity resource blocks, and establishing strategic reserves to enhance diversification at the supply source.

Intelligent Risk Monitoring: Enterprises can leverage digital tools to build early warning networks for intelligent risk detection. Examples include using satellite remote sensing to monitor geological activity along pipelines, deploying IoT sensors for real-time equipment status perception, and utilizing big data to simulate the transmission paths of geopolitical conflicts for proactive risk prevention.

Reliable Emergency Response System: Establishing a robust emergency response system is crucial, centered on scenario-based contingency plans. Examples include creating mobile LNG tanker truck networks to replace damaged pipelines (Europe deployed 2000 tankers in 2022 to compensate for Russian gas shortfalls), designing grid "islanding" operation modes to protect critical loads, and stockpiling critical spare parts to shorten repair cycles (e.g., Three Gorges Group established an emergency supply center in the Jinsha River reservoir area).

3.2. Strategy 2: Optimizing Logistics Networks and Enhancing Facility Efficiency (Addresses Challenge 2)

Cracking logistics bottlenecks and cost dilemmas requires simultaneous efforts in infrastructure efficiency improvement and process optimization.

Network Dynamic Optimization: Applying operations research models enables precise resource allocation for network optimization. For instance, the power sector uses "source-grid-load-storage coordinated dispatch" for peak shaving and valley filling (e.g., State Grid's flexible load regulation capacity exceeding 40 GW). The oil and gas sector employs digital twin technology to simulate pipeline pressure distribution, thereby improving turnover rates (e.g., PetroChina achieved a 12% increase in pipeline transmission efficiency).

Intelligent Facility Upgrades: Focus on unlocking the potential of existing assets. Examples include embedding inline inspection tools (PIGs) in pipelines to predict corrosion points, deploying inspection drones at substations to replace high-risk manual work, and implementing fully automated control systems at coal terminals to reduce loading/unloading times (e.g., Huanghua Port efficiency increased by 25%).

Multimodal Transport Integration: Break down standards and interface barriers. Promote "single-document" electronic waybills to seamlessly connect sea and rail freight (e.g., China-Europe Railway Express new energy special trains reduced transshipment losses by 40%). Establish LNG tank container sharing pools to reduce empty runs (e.g., New Zealand model lowered logistics costs by 18%). Develop specialized carriers (e.g., electric heavy-duty trucks) for short-distance transport.

3.3. Strategy 3: Driving Green Sustainable Supply Chain Transformation (Addresses Challenge 3)

Optimizing new energy logistics and global supply chain coordination mechanisms is profoundly significant for strengthening global supply chain stability, flexibility, and efficiency, and driving sustainable growth in the green economy. [7] Driving a green and sustainable transformation requires enterprises to convert environmental external costs into innovation momentum.

Whole-Chain Carbon Management: Establishing precise accounting systems facilitates comprehensive carbon management. Examples include BP using block chain to trace carbon emissions from crude extraction to gas stations, and China Huaneng developing a "Thermal Power Carbon Flow Monitoring Platform" to optimize unit dispatch combinations. By optimizing raw material procurement and strengthening environmental protection and energy-saving measures during production, enterprises can not only significantly reduce negative environmental impacts but also enhance economic benefits, achieving a win-win situation [8].

Circular Economy Closed Loops: Address technical and economic challenges through upstream-downstream industry collaboration. Explore pyrolysis for recovering glass fiber from wind turbine blades (e.g., Vestas technology reduced recycling costs to $200/ton). Increase silver recovery rates from PV panels to 95% via hydrometallurgy. Battery material regeneration (e.g., CATL achieving 99.3% nickel-cobalt-manganese recovery) significantly reduces mining dependence.

Green Procurement Synergy: Reshape supplier relationships. Establish ESG ratings linked to order quotas (e.g., TotalEnergies eliminating the bottom 10% of suppliers based on scores). Jointly sign green Power Purchase Agreements (PPAs) (e.g., JinkoSolar procured 400 million kWh of green power in 2022). Collaborate to establish zero-carbon logistics corridors (e.g., Maersk ordering 12 methanol-powered container ships).

The effectiveness of the above strategies has been preliminarily validated in industry practices. For instance, Equinor reduced the impact scope of single facility failures by 70% through its Arctic gas field cluster interconnected pipeline network. China Oil & Gas Pipeline Network Corporation (PipeChina) reduced crude oil pipeline transmission energy consumption by 8.2% using an intelligent control system. Ørsted achieved a 75% reduction in the levelized cost of offshore wind power driven by supply chain decarbonization. These cases demonstrate that resilience, efficiency, and sustainability can achieve synergistic gains within a systematic framework, providing reusable methodologies for the SCM transformation of energy enterprises.

4. Case Analysis and Practical Implications

4.1. Case Selection Background: Grid Resilience Challenges under Extreme Climate

State Grid Corporation of China (SGCC), as the world's largest utility company, has a supply chain encompassing ultra-high voltage grids, smart grid construction, and emergency material dispatch. During the catastrophic "7·20" torrential rain in Henan in 2021, the fatal weaknesses of China's traditional power supply chain were starkly exposed. The flooding of a key substation in Zhengzhou caused a city-wide blackout. Emergency power restoration was hampered by road destruction and difficulties transporting emergency power equipment, resulting in a restoration time exceeding four days (96 hours) and direct property losses amounting to hundreds of billions of yuan. This "small black swan" event serves as a classic case for studying energy supply chain resilience—primarily manifesting in infrastructure vulnerability (insufficient disaster resistance considerations in substation design), fragmented emergency coordination mechanisms (lack of cross-province emergency material dispatch), and weak infrastructure intelligence (IoT monitoring blind spots for flood disasters). These align directly with the "infrastructure rigidity" and "institutional coordination failure" aspects outlined in Chapter 2.

4.2. Resilience Reconstruction Practice: Technology-Driven and System Synergy

To address these challenges, State Grid launched the "Yuanyu" special project in 2022, its optimization path directly targeting the core resilience strategies proposed in Chapter 3.

Intelligent Risk Monitoring Layer: Built an "Air-Space-Ground" integrated sensing network: Deployed 5,000 drones for millimeter-level inspection of transmission and transformation equipment (identifying 120,000 tower tilt risk points). Coupled meteorological satellites with hydrological models to generate flood heat maps (provided 48-hour early warning for Jiangxi floods in 2023).

Infrastructure Reinforcement Layer: Upgraded disaster resistance standards: Installed flood barriers and smart drainage systems at 2,300 key substations (pilot station in Zhengzhou can withstand 1.5m water accumulation). Applied carbon fiber composite towers in mountainous lines (wind resistance increased by 40%).

Emergency Response Synergy Layer (Most Breakthrough): Developed a "Smart Emergency Cloud Platform" integrating data from material warehouses across 28 provinces, enabling one-click cross-province spare part dispatch via blockchain verification (e.g., 10 mobile transformers from Anhui reached Zhengzhou in just 18 hours). Simultaneously, established a "Microgrid Black-Start" system, embedding PV-storage units at critical load nodes like hospitals and base stations (ensured power for 85% of emergency medical facilities during a typhoon in Zhuhai).

4.3. Implementation Effectiveness and Mechanism Innovation

The project demonstrated significant value during the real-world test of Typhoon Doksuri in 2023: Fault points in the Fujian grid decreased by 53% under 12-level winds; Xiamen's core area maintained continuous power via microgrid islanding. Zhejiang utilized the material coordination platform to dispatch resources from 5 provinces, improving repair efficiency by 70% (average power restoration time reduced from 32 hours to 9.5 hours). Deeper transformations involved management paradigm shifts:

Data-Driven Decision Making: Disaster loss assessment cycles shortened from 7 days to 4 hours, enabling precise resource allocation.

Flexible Contract Network: Signed "reserve production agreements" with equipment suppliers like Sany Heavy Industry, ensuring 72-hour emergency equipment delivery.

Institutionalized Government-Enterprise Coordination: Integrated into the national emergency management system, enabling real-time data sharing between meteorology, transportation, and power sectors.

According to calculations by the State Grid Energy Research Institute, this system reduced annual disaster losses by ¥3.7 billion and shortened average outage duration by 42%.

4.4. Universal Implications: The Triple Leap in Resilience Building

State Grid's practice provides a reusable methodology for energy supply chain resilience management:

From Passive Rescue to Active Immunity: Shift from "post-disaster remediation" to "pre-disaster reinforcement" by preemptively simulating disaster chains using digital twins (e.g., modeling substation flooding propagation paths).

From Isolated Operations to Ecosystem Synergy: Break enterprise boundaries to establish cross-province material pools and government-enterprise linkage mechanisms, validating the feasibility of an "open emergency network".

From Hardware Accumulation to Standard Output: Embed disaster-resistant design specifications (e.g., "Technical Guidelines for Substation Flood Control") into the upstream supply chain, driving product upgrades among suppliers like NARI Group.

The case also reveals unresolved challenges: vulnerability of edge computing devices to lightning strikes causing monitoring interruptions in mountainous areas, and settlement barriers for multinational enterprise material allocation. Future efforts require further integration of satellite IoT (e.g., "Starlink" for communication gap filling) and resilient financial instruments (e.g., catastrophe bonds).

5. Conclusion

This study, by deconstructing the "triple rigidity" characteristics (resource dependency, infrastructure, institutional constraints) of the energy supply chain, reveals the systemic roots of its high vulnerability and low elasticity. Empirical analysis indicates that insufficient resilience, ineffective logistics cost control, and intensifying green transformation pressures constitute the most urgent core challenges: Geopolitical conflicts and natural disasters can instantly disrupt supply networks (e.g., Europe's gas crisis due to Russia-Ukraine conflict); low utilization of dedicated infrastructure and fragmented multimodal transport push logistics costs above 25% of total costs; while soaring carbon prices (EU exceeding €100/ton) and circular economy gaps (wind blade recycling rate <5%) further strain sustainability.

The optimization framework developed to address these challenges demonstrates significant value both theoretically and practically.

Resilience Enhancement: Strategies like supply diversification (e.g., China expanding LNG import sources to 25 countries), intelligent risk monitoring (e.g., Saudi Aramco's 40,000 sensors reducing accident rates by 30%), and emergency coordination (e.g., State Grid accelerating cross-province material dispatch by 70%) form a multi-dimensional defense.

Cost Optimization: Pathways relying on network dynamic modeling (e.g., PetroChina's 12% pipeline efficiency gain) and intelligent facility upgrades (e.g., Huanghua Port's 25% automated handling efficiency increase) unlock the potential of existing assets. By improving resource guarantee mechanisms, breaking through key technical bottlenecks, and advancing industry chain upgrades—supported by institutional innovation and infrastructure systems—the safety and resilience of the green energy supply chain are comprehensively enhanced, providing theoretical foundations and policy insights for advancing the energy transition and ensuring energy security [9].

Green Transformation Engine: Drivers such as whole-chain carbon management (e.g., BP's blockchain traceability), circular technology breakthroughs (e.g., Vestas' pyrolysis reducing recycling costs by 67%), and green procurement synergy (e.g., TotalEnergies' ESG-based supplier elimination) internalize negative externalities.

These strategies were validated in cases like State Grid's "Yuanyu Project"—microgrid islanding ensured 85% power supply for critical emergency facilities during a typhoon, carbon fiber composite towers improved wind resistance by 40%—highlighting the innovative potential of technology-management synergy.

Acknowledgements

I extend my sincere gratitude to my supervisor, for their invaluable guidance, critical feedback, and unwavering support throughout this research. My heartfelt thanks also go to my family and friends for their steadfast encouragement, patience, and moral support during this demanding academic journey. This accomplishment would not have been possible without them.

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