

Research on Improving Supply Chain Risk Management and Resilience of Energy Production Enterprises

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Abstract: The accelerating reshaping of the global energy system and intensifying geopolitical competition have exposed the supply chains of energy production companies to complex risks. Traditional management paradigms urgently need to shift to a balance of efficiency and resilience. This paper focuses on energy production companies to systematically analyze their supply chain risk identification and resilience improvement paths. At the theoretical level, it clarifies the evolutionary logic of the concept of resilience and defines four core dimensions of supply chain resilience: redundancy, flexibility, visibility, and adaptability. In practical terms, it reveals the triple structural difficulties faced by energy supply chains: supply concentration risk caused by resource dependence, flexibility rigid constraints caused by infrastructure specificity, and institutional regulatory pressures. It also identifies external disturbances such as geopolitical conflicts, market fluctuations, and tightening environmental regulations, as well as intrinsic bottlenecks such as lagging digital transformation and information islands. Accordingly, it proposes collaborative strategies such as building diversified supply networks, providing theoretical support and practical guidance for energy companies to optimize resilience management decisions and cope with uncertain environments, and providing reference value for safeguarding national energy security.

Keywords: Energy-producing enterprises; Supply chain resilience; Risk identification; Digital transformation; Green transition.

1. Introduction

The global energy industry is undergoing profound transformation and structural reshaping. As the traditional fossil energy system accelerates its transition to renewable energy, the complexity and vulnerability of the energy supply chain increase simultaneously. As core participants in the industrial chain, the ability of energy producers to manage supply chain risk directly affects national energy security, stable economic operations, and the achievement of sustainable development goals. However, the combined impact of multiple global crises in recent years has made the supply chain of energy companies face unprecedented challenges. On one hand, geopolitical conflicts and international trade frictions continue to unsettle the global energy market. The Russia-Ukraine conflict and the Sino-US trade game and other international situation changes restrict access to key raw materials. Policies such as Russia's reduction of natural gas exports to Europe and China's export controls on lithium ore have directly affected the global energy supply chain. On the other hand, the mismatch between supply and demand of key mineral resources has become increasingly prominent. According to the 'Energy Industry Outlook 2024', the acceleration of clean energy transformation has driven an explosive growth in demand for strategic resources such as lithium, cobalt, rare earth elements, and photovoltaic silicon materials. However, the three to four-year lead time required for expansion of mining and smelting capacity has led to a lack of supply and demand flexibility and dramatic price fluctuations. The procurement difficulties and cost increases of core equipment such as photovoltaic modules and wind turbine blades have followed. Meanwhile, aging physical infrastructure and supply chain bottlenecks have become hard constraints that constrain energy transformation. The industry assessment in the 'Reliability Performance and Regional Risk Assessment 2024' report

indicates that the lead time for high-voltage electrical equipment such as transformers, circuit breakers, and transmission cables has extended to two to four years, compared to pre-pandemic levels. Wind power installation ships and grid connection construction capacity are critically short. A large number of new power generation and transmission projects have failed to come online due to supply chain delays. In addition, climate risk, represented by frequent extreme weather events, poses a direct threat to the energy supply chain. Research shows that about 28% of global energy companies reported more than ten supply chain disruptions in 2020. A small risk in a single link may trigger a chain reaction of production stagnation, delivery delays, and sharp cost increases, causing significant damage to corporate financial performance and brand reputation. In this context, supply chain resilience construction has evolved from a strategic choice for enterprises to a must-have capability for survival and development.

As the pulse of the global economy, the energy supply chain ensures efficient flows from energy sources to end consumers. A safe and stable energy supply chain is crucial to a country's economic and social development, directly shaping its strategic layout and social stability. The 20th Party Congress report clearly stated the need to 'ensure the security of food, energy resources, and important industrial chains and supply chains.' Moreover, a stable energy supply chain is an essential part of the national security system. Its resilience and security directly determine the continuous availability of energy, price stability, and supply reliability. In recent years, global 'black swan' events, such as the coronavirus pandemic, the conflict between Russia and Ukraine, and the conflict between Israel and Palestine, have severely impacted the international energy market, highlighting the inherent vulnerabilities in traditional energy supply chains. Therefore, improving supply chain resilience and security has become a top priority in global energy governance. With the

acceleration of global energy transformation, the renewable energy supply chain is more reliant on key minerals and foreign suppliers, further amplifying the risk of disruption. Building a fault-tolerant, flexible, and resilient energy supply chain system has become an essential requirement for ensuring national energy security and coping with complex international situations. The supply of key minerals, such as lithium, cobalt, nickel, and rare earth elements, is highly concentrated, and their geopolitical risks and supply uncertainties directly affect the energy transformation process. Countries around the world have prioritized supply chain resilience in their national security strategies. Therefore, enhancing energy system resilience has become an important prerequisite for ensuring energy security. It is necessary to establish a safe, stable, and self-controlled industrial chain supply chain to address the 'decoupling' risk brought by the accelerated restructuring of global industrial chains and supply chains.

Accordingly, this paper selects energy production enterprises as the research object, focusing on supply chain risk identification, assessment, and resilience improvement pathways, aiming to provide theoretical foundations and practical solutions for building a new, safe, reliable, green, and intelligent supply chain management system, and provide decision-making reference for addressing energy supply security challenges under uncertain future conditions.

2. Literature Review

(1) Resilience

The concept of resilience originates from materials science and ecology. In engineering contexts, resilience refers to the speed with which a system returns to equilibrium after being disturbed—its ability to rebound. This perspective was introduced into the supply chain arena in the late 1990s and early 2000s, with the core assumption being that there is a 'normal' operating state, a disruption is a temporary deviation, and the goal of management is to return to normalcy as quickly as possible. However, this view has limitations: it assumes that the system faces a 'known-known' uncertainty, where the disruption's pattern and consequences are predictable. Wieland & Durach (2021) distinguishes two resilience perspectives. Traditional engineering resilience presupposes a single equilibrium point, triggered by a clear disruption event, with the goal of rapidly restoring the system to its previous stable state after an impact. In contrast, more advanced socio-ecological resilience is based on a multi-stable state cognition, arguing that a system may shift to a new state under persistent stress or sudden shocks, revealing fundamentally different assumptions of system dynamics. Ivanov (2023) further suggests that the stability perspective views resilience as an indicator of performance recovery after a disruption, while the adaptive perspective views resilience as an intrinsic property that enables the system to maintain viability in the face of continuous environmental changes. The two perspectives are complementary rather than antithetical: the former addresses short-term shocks, while the latter responds to long-term structural shifts. As research advances, more and more scholars view resilience as a dynamic process rather than a static attribute. Namdar et al. (2020) proposed a four-dimensional framework to illustrate the way resilience works along a timeline: resilience is a process encompassing 'anticipation-preparation-stable operation-recovery-learning and transformation'.

(2) Supply chain resilience

Supply chain resilience is strategically vital to energy security. In existing research, most scholars define supply chain resilience as the ability of a system to return to its original or better state after experiencing disruptions, shocks, or changes. Zhao et al. (2023) note that it refers not only to the ability to absorb disruptions but also to the ability of the supply chain to quickly respond and recover to original or even better performance after a disruption. Hosseini Shekarabi et al. (2025) argue that supply chain resilience encompasses forecasting, adapting, responding, recovering, and learning capabilities. In terms of resilience assessment and core dimensions, Leng et al. (2025) highlight three basic assessment capabilities: absorption, adaptation, and recoverability. Durability, flexibility, and transformation are three interrelated but distinct dimensions of supply chain resilience identified by Taghikhah et al. (2025). Each dimension affects the scope and degree of performance over short and long periods in different ways. The achievement of supply chain resilience relies on multiple interconnected and functionally distinct dimensions, which can be grouped into four categories. First, redundancy: storing spare resources (inventory, capacity, suppliers) within the system. When the primary path fails, alternatives can take over, thus maintaining function in the midst of a disruption. Second, flexibility: the ability to adjust the structure and processes within the supply chain network, including vendor switching, production line conversion, and logistics path re-planning. Flexibility enables the system to quickly reconfigure rather than passively wait for recovery. Third, visibility: end-to-end information transparency enables decision makers to detect and respond to disruption signals in a timely manner, mitigating the bullwhip effect caused by asymmetric information. Visibility is the information basis for anticipation. Fourth, adaptability: beyond passive response, it represents the ability of an organization to learn, adjust strategies, and reconstruct networks from disruptions. Kähkönen et al. (2023) found that companies with dynamic capabilities (rapid decision-making, resource reallocation) can turn crises into opportunities for capacity upgrades. In action research on supply chain resilience, Hart Nibbrig et al. (2025) argue that supply chain resilience strategies reduce vulnerability and maintain continuity during disruptions by addressing resilience in three key dimensions: organisational resilience, operational resilience, and structural resilience. Organisational resilience focuses on relationship factors that support adaptability and coordination; operational resilience emphasizes immediate response decisions; and structural resilience involves long-term strategies to strengthen the supply chain network. Bruckler et al. (2024) describe resilience actions as proactive preventive and anticipatory measures. Decision makers can enhance resilience indicators by adopting such measures to enhance absorption (e.g. physical protection of facilities), adaptability (e.g. route switching), and recoverability (e.g. provision of maintenance teams).

3. Present Situation and Characteristics of Supply Chains of Energy Enterprises

(1) Analysis of the structure of the supply chain of energy companies

The supply chain of energy companies has a complex,

multi-level structure, typically encompassing four core components: supply, manufacturing, distribution, and demand. The upstream sector includes raw material suppliers and equipment manufacturers, such as well operators, mining companies, and suppliers of steel pipes, chemical products, and mechanical materials, responsible for energy resource extraction and equipment provision. The traditional energy sector focuses on the exploration and exploitation of coal, oil, and natural gas. The new energy sector relies on the controlled access of lithium, cobalt, silicon materials, and wind and solar resources. This segment directly supports the supply chain's foundation and cost security. The midstream sector involves energy production and transportation, including power generation, efficiency improvement, and energy storage projects. It relies on pipelines, dedicated fleets, warehouses, and digital dispatching systems to enable large-scale, cross-regional energy transmission and storage. The downstream sector covers distribution, delivery, and end-user services, including power grid operators, power sales companies, distributors, and end-users such as industrial customers, commercial institutions, and residents. Through gas stations, charging networks, power sales platforms, and industrial direct supply channels, energy products are accurately delivered to users such as transportation, industry, and residents, and further extended to value-added services such as energy efficiency management and carbon asset management.

(2) Core characteristics of the energy supply chain

Energy companies are highly dependent on natural resource endowments. The development of oil, gas, coal, and renewable energy requires significant upfront capital investment. The entire life cycle, from exploration and production to construction and operation, is characterized by long capital commitment periods and slow returns, requiring strong financing and risk resistance. This capital-intensive nature leads to a relatively concentrated supply chain structure, with large energy companies dominating and small and medium-sized enterprises having difficulty accessing key segments.

The energy supply chain relies on highly specialized infrastructure, such as pipelines, power grids, gas storage facilities, and terminals. Once these assets are built, they are difficult to repurpose and exhibit high asset specificity. Moreover, as the infrastructure becomes networked, the service coverage expands with the increase of nodes, generating significant network effects and strengthening the competitive advantage of established companies. New entrants not only face high barriers due to high construction costs but also face competition from existing networks.

Policy sensitivity and environmental constraints are the external driving forces for the development of the energy supply chain. The energy industry is heavily influenced by policies, including price regulation, subsidy schemes, environmental standards, and carbon emission requirements. Policy changes directly alter the cost and structure of the supply chain. Particularly under the 'dual carbon' goals, environmental constraints have become a core driver for supply chain optimization, prompting companies to accelerate their green transformation, explore low-carbon paths, and strike a balance between compliance and efficiency.

(3) Current supply chain management models

The traditional linear supply chain model, which was the initial management approach adopted by energy companies, features a one-way linear process of 'supply-manufacturing-

distribution-end user'. Under this model, each stage operates independently, with slow and asymmetric information flow. Upstream suppliers, midstream manufacturers, and downstream distributors lack deep collaboration. Companies typically plan and schedule based on forecasts, resulting in inefficient inventory turnover and poor responsiveness to market changes. While this model is suitable for environments with stable demand, it exhibits significant vulnerabilities and poor responsiveness when faced with market fluctuations and emergencies.

Driven by advances in information technology, the supply chain collaboration model has become increasingly popular. This model emphasizes information sharing and business collaboration among various components of the supply chain. By establishing supplier partnerships, implementing collaborative planning and forecasting (CPFR), and applying just-in-time (JIT) management, upstream and downstream participants can achieve transparent demand information, optimal inventory levels, and significantly improved response speed. Through contract arrangements and long-term cooperation mechanisms, the collaboration model reduces transaction costs and improves the overall efficiency of the supply chain, marking an important transition from traditional models to a higher level.

The digital supply chain model represents the cutting-edge development of supply chain management. Supported by the Internet of Things, big data, artificial intelligence, and blockchain technologies, it digitally and intelligently automates the entire supply chain process. By building a supply chain control tower, companies can achieve real-time visual management of key links such as inventory, logistics, and production. AI algorithms support demand forecasting and intelligent scheduling, enabling dynamic optimization and automatic decision-making. The digital supply chain not only improves operational efficiency, but also enhances supply chain resilience and flexibility, enabling energy companies to respond quickly and continuously innovate in complex and changeable environments. It is the core support for energy companies to achieve their 'dual carbon' goals and digital transformation.

4. The Core Challenges Faced by Energy Companies' Supply Chains

(1) Triple Rigid Constraints

Due to a heavy reliance on natural resource endowments, the uneven geographical distribution of energy and resources naturally leads to a high concentration on the supply side. Currently, more than half of the world's energy-related minerals are subject to various forms of export controls. These controls are increasing in number and scope, covering raw materials, refined materials, and even refining technologies for lithium and rare earth elements. This high concentration significantly amplifies supply chain vulnerabilities. The supplier concentration risk also manifests in excessive reliance on specific regions or categories of suppliers. Natural disasters, pandemics, or policy changes in these regions can cause large-scale supply disruptions. The dual pressures of resource dependence and supply concentration make energy companies lack sufficient buffers and alternatives in the face of geopolitical risks, trade frictions, and emergencies, which are key bottlenecks restricting supply chain resilience.

The energy industry's infrastructure, including pipelines,

power grids, gas storage facilities, terminals, and refining and chemical facilities, is highly asset-specific. Once these assets are built, it is difficult to change their uses or adjust them. For example, a natural gas pipeline can only transport natural gas and cannot be used for other energy products. UHV power transmission lines have fixed voltage levels and capacities, making them difficult to adjust dynamically according to changing demands. This rigid constraint characterizes infrastructure planning and construction, significantly limiting companies' ability to adjust in response to changing demands, technological iterations, or geopolitical shocks. However, in practice, energy infrastructure development typically prioritizes maximum capacity utilisation, leaving insufficient margin for future uncertainties, resulting in costly later modifications. The network effect of energy infrastructure further reinforces this rigidity: an improved existing network raises the barriers for new entrants, and vested interests tend to maintain the status quo rather than promote flexible reforms.

The energy industry is subject to multiple layers of institutional regulation from government regulators, industry associations, and international organizations, exerting influence through policies, rules, technical standards, and compliance requirements. Under the guidance of the 'dual carbon' goals, environmental laws such as carbon emission quotas, environmental standards, and green certification requirements have become core constraints in supply chain management. Companies must ensure compliance in energy production, trace and manage the carbon footprint across the supply chain, significantly increasing management complexity and costs. Meanwhile, frequent adjustments to policy tools such as energy price regulation, resource development permits, and safety requirements undermine the expected stability of long-term supply chain planning. Companies are forced to build inventory redundancy and diversify supply channels to hedge against policy volatility. More importantly, regulatory standards vary across countries and regions. Global energy trade faces increasing trade barriers and compliance reviews. Multinational energy companies must navigate complex compliance systems such as the EU's carbon border adjustment mechanism and the US's supply chain transparency requirements. These multifaceted institutional constraints drive up operating costs and create a dilemma between compliance costs and efficiency losses, making it difficult for energy companies to balance economic benefits with regulatory obligations.

(2) External risk factors

The geopolitical risks to the energy supply chain have significantly increased, becoming a central uncertainty in reshaping global energy flows. Conflicts in the Middle East and spreading trade sanctions continue to unsettle the energy market. For example, the Strait of Hormuz handles about 30% of global seaborne oil trade and 20% of liquefied natural gas trade, directly impacting global energy supplies. Sanctions have expanded from traditional energy sectors to strategic minerals and refining technologies. Rising resource nationalism complicates cross-border energy collaboration through compliance reviews and market access restrictions. Trade is taking a detour-reshaping trend: companies are diversifying supply chains and rerouting shipments to avoid risks, but this drives up costs, takes liquidity, and creates additional friction risks.

The market volatility risks in the energy supply chain continue to deepen. Price fluctuations and demand

uncertainties are major operational pressures for companies. Driven by geopolitical conflicts, logistical disruptions, and regional supply changes, international oil commodity prices fluctuate frequently and are transmitted throughout the supply chain. Rising global tensions in defense and trade security have driven up shipping costs, lengthening the delivery cycles for energy products, and increasing overall costs. Uneven demand recovery complicates supply chain planning. Raw material chain prices are struggling to stabilize, reshuffling profit distribution among companies.

Environmental regulatory risks are external constraints in the energy supply chain that cannot be ignored. The global 'dual carbon' goals have led to continuous tightening of environmental protection legislation. The International Maritime Organization (IMO) has set medium- to long-term carbon reduction targets for the shipping industry. Starting in 2026, the EU's Carbon Border Adjustment Mechanism (CBAM) will require real-time monitoring data for imports, or carbon-related costs could increase by 30-50%. In China, the three major stock exchanges have issued guidelines for sustainable development reports of listed companies, and the Ministry of Finance has issued basic standards for sustainable disclosure of enterprises, strengthening ESG disclosure requirements. Downstream multinational customers are increasingly demanding detailed tracking of the entire supply chain's carbon footprint. Green and low-carbon capabilities have become a key prerequisite for obtaining customer resources.

(3) Internal management challenges

The digital transformation of most energy companies' supply chains is progressing slowly, with many still in the initial stage of informationization. Traditional energy companies' decision-making processes are complex, and system update cycles are long. Their digital technology applications lag behind market demand changes. Although some companies have deployed basic systems like ERP and WMS, they lack full-chain integration and intelligent analysis capabilities, unable to achieve dynamic supply chain optimization and intelligent decision-making. The long return on investment cycle and high technical barriers place additional burdens on small and medium-sized enterprises undergoing transformation. With the acceleration of energy transformation, the digital transformation gap limits response speed and operational efficiency, becoming a key bottleneck in enhancing supply chain competitiveness.

There is a significant information island problem within the energy supply chain, with suppliers, manufacturers, and distributors lacking data sharing mechanisms. First, due to concerns over trade secret protection and competitive barriers, companies are reluctant to disclose key operational data, resulting in limited visibility within the supply chain. Second, internal systems are developed by different vendors, resulting in inconsistent data interfaces and incompatible formats, creating 'technical islands.' Third, the lack of unified data standards and sharing protocols raises the cost of information collaboration across companies and systems. Fourth, asymmetric information amplifies the bullwhip effect, leading to both overstocking and shortages, thereby impairing the overall efficiency of the supply chain.

The green supply chain construction of energy companies is still in its infancy, with a general lack of carbon management awareness and implementation capabilities. Most companies focus solely on their own operational carbon emissions, lacking systematic assessment and restraint

mechanisms for the environmental performance of upstream and downstream suppliers. Green procurement standards are inconsistent, making it difficult to quantitatively evaluate suppliers' green performance and effectively transmit environmental protection requirements to the entire chain. Facing the 'dual carbon' goals, energy companies urgently need to establish a life-cycle carbon management system to promote the green transformation of suppliers. At the same time, insufficient investment in green technology research and development and an imperfect low-carbon product certification system limit the further development of the green supply chain.

The lack of transparency and traceability in the supply chain is a significant internal management challenge. Data records for each stage of the supply chain, from raw material procurement to product delivery, are incomplete and discontinuous, making full chain traceability impossible. Energy products have complex sources and numerous intermediate links. Cross-border supply chains pose additional challenges for compliance review and traceability certification. The lack of unified traceability standards and digital platforms hinders management functions such as product quality traceability, liability determination, and risk early warning. In a context of increasingly stringent ESG disclosure requirements, this lack of supply chain transparency exposes companies to compliance and reputational risks.

5. Strategies to Enhance the Resilience of the Energy Supply Chain

(1) Build a Diverse Resilience Network

To enhance supply chain resilience, energy companies should build diversified supply networks to mitigate the risks posed by excessive dependence. First, adopt a multi-supplier strategy: for key raw materials and equipment, cultivate multiple qualified suppliers to avoid excessive reliance on a single source and diversify the risk of supply disruptions. Second, develop alternative supply routes: expand intermodal transport options such as land, sea, and pipeline to increase the flexibility of logistics routes and enable rapid switching if main routes are blocked. Third, expand the recycling of key materials: build a recycling system for strategic resources such as rare metals and energy storage materials to reduce reliance on primary resources while reducing carbon footprints and promoting sustainable development.

(2) Digital transformation pathways

With the dual constraints of carbon neutral goals and energy security, how to achieve a sustainable development path through digital transformation, technological innovation, and ecosystem collaboration has become a core issue for energy companies. With the increasing popularity of digital technologies, Internet of Things sensors collect supply chain data in real time, supporting real-time operational monitoring and anomaly detection. Cloud computing provides data storage and computing resources. Blockchain ensures the traceability and transparency of supply chain data, enhancing trust across multiple entities. Generative adversarial networks can address the 'data gap' and 'insufficient sample size' issues in constructing supply chain carbon finance indices. Generative AI dynamically adjusts logistics routes, predicts carbon emissions, and monitors regional environmental regulations updates in real time to alert compliance risks. GAI accelerates supply chain data processing and scenario

simulation, generating real-time adjustment plans. For example, when there is a sudden demand surge, it can quickly match alternate suppliers, improving coordination flexibility, including dynamic procurement cycle adjustments.

(3) Green sustainable development transformation

Green and sustainable development transformation is the core path for energy companies to respond to the 'dual carbon' goals. First, actively integrate renewable energy into the supply chain: increase the deployment of photovoltaics and wind power in raw material acquisition, manufacturing, and logistics transportation to reduce carbon emissions from the source. Second, implement green procurement and life cycle assessment: establish supplier environmental access standards and systematically evaluate product environmental performance. Simultaneously, build a carbon management system and deploy digital tools to trace the entire chain's carbon footprint, achieving accurate carbon reduction management. Finally, promote circular economy solutions: promote the recycling of discarded equipment and materials, reduce resource consumption and environmental pressure, and form a closed-loop green system.

(4) Logistics and infrastructure upgrading

Logistics and infrastructure upgrades are key to enhancing the efficiency and resilience of the energy supply chain. By building an integrated multimodal transport system of rail, road, waterway, and pipeline, we can optimise the mix of transport routes, reducing logistics costs and carbon emissions. Promote the development of smart grids: deploy digital technologies to optimise energy distribution, achieve dynamic supply-demand balance, and improve the efficiency and stability of the grid. Deploy energy storage solutions: store power during low-load periods and release it during peak periods, alleviating the contradiction between supply and demand and providing a buffer for renewable energy consumption. Additionally, upgrade key node infrastructure, enhance emergency supply assurance capabilities, and maintain supply chain continuity in emergencies, thus providing a solid guarantee for energy security.

6. Conclusion

This research system examines the supply chain risk management and resilience improvement of energy production companies. It identifies three rigid constraints faced by the energy supply chain: supply concentration risk caused by resource dependency, flexibility limitations caused by infrastructure specificity, and institutional and regulatory pressures. External risk factors include three dimensions: geopolitical risk, market volatility risk, and environmental regulatory risk. Internal management challenges include lagging digital transformation, poor information islands and data sharing, inadequate green supply chain development, and lack of transparency. Based on this, this paper proposes strategies such as building diversified resilience networks, promoting green sustainable development, and upgrading logistics infrastructure, providing a theoretical framework and practical path for energy companies to enhance supply chain resilience.

Future research can be furthered in three directions. First, develop a supply chain resilience evaluation system, including quantifiable indicators and early warning models. Second, explore the deep integration of digital technologies, including the application of blockchain and artificial intelligence in supply chain visualization and intelligent decision making. Third, study the supply chain reconstruction

in the context of global energy transformation, analyzing the long-term impact of the 'dual carbon' goals on supply chain layout. In practical terms, energy companies are advised to establish an inter-departmental risk collaboration mechanism, increase digital investment, promote green and low-carbon transformation, and continuously improve the resilience and competitiveness of the supply chain.

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