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Optimization Pathways for the Thermal Coal Trade Supply Chain from an Energy Security Perspective

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Abstract: Thermal coal has long dominated China's primary energy structure and is a key support for the stable operation of the power system and economic and social development. In the context of the "dual carbon" goal and energy transformation, the supply chain of thermal coal trade faces challenges such as international market fluctuations, geopolitical risks, and domestic supply-demand imbalances. This article focuses on supply security, price security, and strategic security from the perspective of energy security. It systematically analyzes the structural characteristics of upstream production, midstream transportation, and downstream consumption in the supply chain, as well as their coupling mechanism with energy security. Using literature review and case analysis, combined with energy data and practice, identify issues such as regional supply-demand imbalance, transportation bottlenecks, concentrated import sources, fluctuations in freight and exchange rates, and imperfect reserve systems. Propose optimization path: expand import sources and diversify trade layout, reduce external dependence; Building a multimodal transport and regional reserve network to enhance supply resilience; Applying big data, artificial intelligence, and blockchain to promote digital governance; Improve tariff and reserve mechanisms, enhance institutional safeguards; Deepen international cooperation and risk prevention and control, and enhance resilience to shocks. Research has shown that diversification, resilience, and digitization are the core directions for optimization, which have important theoretical and practical significance for improving energy security, ensuring stable supply, and promoting high-quality development.

Keywords: Energy Security; Thermal Coal; Supply Chain Optimization; Trade Supply Chain

1. Introduction

Thermal coal has long played a pivotal role in China's primary energy structure, serving as a critical foundational resource for ensuring the stable operation of the power system and supporting industrial and residential energy consumption. In recent years, despite the reality that coal-fired power remains the primary source of power generation, China's total primary energy production and consumption have continued to grow, with key indicators such as coal production and electricity generation showing steady increases, providing a solid foundation for the stable operation of the economy and society. Statistics show that in 2023, the output of China's major energy products continued to grow, with both coal and electricity production achieving positive growth, providing a solid foundation for ensuring supply and stabilizing prices [1]. At the same time, from a global perspective, China is not only the largest coal consumer and trade influencer but also a key pillar for the flexibility and security of the coal-fired power system. The importance of coal in China's energy consumption and power supply is unlikely to be replaced in the medium to short term [2,3].

However, energy security centered on thermal coal is facing multiple challenges: first, increased volatility in the international energy market. In 2024, China's coal imports reached a record high. The combination of cyclical fluctuations in prices and freight costs, coupled with exchange rate changes, has led to a temporary shift in the substitution and supply functions of imported coal, creating uncertainty for the trade chain and pricing management. Meanwhile, the structure of supply sources is being reshaped by geopolitical rivalry and policy disruptions, with adjustments in the share of major supplier countries increasing the complexity of trade management. [4] Second, domestic supply and demand are highly mismatched spatially, and the “north-to-south coal transportation” and “west-to-east coal

redistribution" patterns are unlikely to change fundamentally in the foreseeable future. The coordination of capacity and bottleneck constraints across railways, ports, and waterways persist, increasing the spatiotemporal organizational costs and systemic vulnerabilities of the supply chain [5,6]. Third, price transmission and risk hedging mechanisms are still under development. To alleviate the "price inversion" between coal and electricity and the pressure to ensure supply, the National Development and Reform Commission has successively promoted the improvement of the linkage mechanism between coal prices and grid-connected electricity prices. However, the stability under extreme market conditions, cross-sectoral cost transmission, and market behavior constraints still need optimization [7].

Under the dual priorities of achieving carbon peaking and carbon neutrality while pursuing high-quality development, the thermal coal trade supply chain must seek a dynamic balance among the three objectives of "safety, efficiency, and environmental sustainability." On one hand, as the rapid growth of renewable energy capacity and enhanced regional power interconnection capabilities highlight the need for system flexibility, the strategic role of coal-fired power as a "backstop" becomes even more critical in the short term; On the other hand, cross-regional supply systems, import channels, and port and shipping logistics networks must possess greater resilience and flexibility to cope with demand peaks and troughs and external shocks. This is not only a reformation of the traditional production, supply, storage, and sales system but also a process of evolving from a traditional supply chain to a data-driven modern supply chain characterized by "visibility, predictability, and dispatchability" [3].

From a supply chain perspective, the thermal coal trade chain comprises three key segments: upstream production and mining, midstream transportation and port operations, and downstream distribution and consumption. Each segment plays a distinct yet highly interdependent role in supporting energy security: an efficient transportation and handling system directly determines the timeliness and stability of supply; diversified import and domestic transportation networks help mitigate systemic risks associated with reliance on single sources or routes; and demand forecasting, inventory optimization, and emergency scheduling based on data and algorithms are key levers for enhancing system resilience and reducing overall costs. In recent years, pilot projects and research on digital technologies (including blockchain applications in contract fulfillment and logistics tracking) within the coal supply chain have been steadily advancing, demonstrating their potential to enhance transparency, traceability, and collaborative efficiency [8].

Based on the aforementioned realities and challenges, this paper analyzes the optimization path of the thermal coal trade supply chain from the perspective of energy security. It aims to provide theoretical support and policy recommendations for China to build a more resilient and adaptive thermal coal trade supply chain under the overall objectives of "ensuring supply and stabilizing prices, improving quality and efficiency, and reducing costs and increasing resilience."

2. Analysis of the Relationship between Energy Security and the Supply Chain of Thermal Coal Trade

2.1 Connotation of Energy Security

Energy security is an integral part of the national security system and a key condition for ensuring the sustained and stable development of the economy and society. Against the backdrop of profound changes in the global energy landscape and accelerated domestic energy transition, its scope has continued to expand, primarily encompassing three aspects: supply security, price security, and strategic security.

2.1.1 Supply security

Supply security emphasizes the stability of energy sources and the reliability of supply, ensuring that energy needs for national economic and social operations are met even under complex conditions. In China's energy structure, coal remains dominant, and the stability of thermal coal supply directly impacts the operation of power systems and industrial production. Currently, China faces an expanding energy supply-demand gap and slow progress in optimizing consumption structure. It is urgently necessary to enhance supply security by coordinating domestic and international resources, deepening cooperation along the Belt and Road Initiative, and establishing a diversified supply system [9,10].

2.1.2 Price security

Price security reflects the controllability of energy costs and the affordability of the economy. As a commodity, coal price fluctuations can be transmitted through the supply chain, affecting the cost structure of downstream industries. When thermal coal prices rise significantly, coal-fired power companies may face “price inversion,” where procurement costs exceed electricity sales revenue, leading to reduced profitability or even losses. This not only weakens the stability of power supply but also impacts the overall economy. Therefore, maintaining price security relies not only on market mechanisms but also on the coordinated efforts of policy guidance, reserve mechanisms, and price formation mechanisms to mitigate the risks of severe fluctuations.

2.1.3 Strategic security

Strategic security emphasizes the country's independent controllability and emergency regulation capabilities in the field of energy supply. At the level of thermal coal trade, this includes two aspects: first, building a stable domestic integrated system of production, transportation, and sales, and consolidating the foundation of energy supply; The second is to enhance the ability to resist international market fluctuations and geopolitical risks through diversified import channels and medium - to long-term contract arrangements. The core is to establish a "bottom line security" guarantee mechanism, which relies on independent control, flexible scheduling, and emergency reserves to maintain national energy supply from fundamental threats in extreme situations.

2.2 Structure of the Thermal Coal Trade Supply Chain

The thermal coal trade supply chain is a complex system encompassing production, transportation, distribution, and consumption, characterized by a tightly integrated structure spanning upstream, midstream, and downstream segments.

2.2.1 Upstream: Production and mining

The upstream segment is the source of the supply chain. China's thermal coal resources are highly unevenly distributed. Northern regions such as Shanxi, Shaanxi, and Inner Mongolia account for over 70% of the nation's total reserves, while economically developed coastal and central regions in the east and south, which have strong demand, lack such resources. This “north supplies, south demands” pattern results in a “long supply chain” structure, with coal needing to be transported thousands of kilometers to consumption areas. This not only increases costs but also imposes higher demands on logistics efficiency and stability.

2.2.2 Midstream: Transportation and ports

The midstream segment centers on transportation and ports, serving as the critical link between production and consumption areas. “North-to-South coal transportation” and “West-to-East coal redistribution” form the main lines of China's coal logistics network. Major ports such as Qinhuangdao, Caofeidian, and Huanghua leverage their geographical and infrastructure advantages to function as key transshipment hubs, seamlessly integrating with rail and maritime transport systems. In recent years, upgrades to the Yangtze River waterway have promoted the development of intermodal transport involving railways, ports, and waterways, enhancing transportation efficiency and economic viability.

However, the midstream segment still faces bottlenecks: first, transportation costs are uncertain due to fluctuations in oil prices and freight policies; second, during peak demand periods, railway capacity is strained and port handling capacity is insufficient; third, policy and infrastructure disparities between regions hinder transportation coordination.

2.2.3 Downstream: Distribution and consumption

The downstream segment includes distribution and consumption, marking the endpoint of supply chain value realization. Thermal coal is primarily used for thermal power generation, accounting for over 60% of total consumption, serving as the “stabilizing force” of the power system with stability and regulatory flexibility; some coal is also used in industries such as construction materials and metallurgy. Downstream demand is highly volatile, with significant increases in electricity demand during summer and winter peak periods. Coal inventory and transportation scheduling become critical during these periods. If supply is insufficient or transportation is disrupted, it may lead to fuel shortages at power plants, posing risks to electricity supply. Therefore, the downstream sector imposes higher demands on the supply chain's peak-shaving capabilities, necessitating coal inventory management and transportation optimization to ensure the stable

operation of the power system.

2.3 Coupling Mechanism Between Energy Security and Thermal Coal Trade Supply Chain

There is a close coupling relationship between the thermal coal trade supply chain and energy security, with the two interacting to jointly shape the stability of the energy market, primarily manifested in the following three aspects:

(1) Efficient supply chains enhance supply stability

Supply chain efficiency determines the stability of energy supply. By optimizing railway scheduling, applying capacity allocation algorithms, and utilizing real-time monitoring technology, transportation punctuality and reliability can be improved; modernized port handling equipment and intelligent management can accelerate turnover; and a multimodal transport system combining rail, water, and road transport can shorten transportation cycles. Taking the "North-South Coal Transport" initiative as an example, these optimization measures help alleviate transportation pressure, reduce delays and losses, and lower the risk of energy disruptions, thereby ensuring supply stability.

(2) Diversifying trade channels to mitigate risks

In recent years, China's coal imports have continued to grow, but they are concentrated in a few countries such as Indonesia, Russia, Mongolia, and Australia, posing risks of over-reliance. In the event of political, natural, or policy-related emergencies, this could lead to supply disruptions and price fluctuations, threatening energy security. Therefore, promoting import diversification, expanding new channels, and establishing long-term cooperative relationships are of critical importance. By locking in prices and supply volumes through medium- to long-term contracts, the predictability and stability of coal supply can be enhanced.

(3) Digital management enhances scheduling and emergency response capabilities

In the context of increasingly complex energy systems, emerging technologies such as big data, artificial intelligence, and blockchain provide new tools for supply chain management. Big data can predict supply and demand changes and optimize transportation and inventory; artificial intelligence can achieve real-time optimization of transportation routes and schedules through intelligent scheduling systems and provide risk warnings; blockchain ensures the transparency and traceability of contract and logistics information, enhancing trust and emergency reconstruction capabilities. When transportation is disrupted, blockchain can quickly trace the source and adjust plans to ensure timely coal supply, thereby enhancing the resilience of the energy system.

3. Major Issues in the Current Thermal Coal Trade Supply Chain

China's thermal coal trade supply chain faces multiple challenges both domestically and in international trade. These challenges are not only reflected in structural contradictions in resource distribution and transportation, but also involve insufficient information technology, concentrated import dependence, international market volatility, and imperfect policies and management mechanisms.

3.1 Domestic Issues

(1) Regional imbalance in supply and demand

China's coal resources are highly unevenly distributed. Northern energy bases such as Shanxi, Shaanxi, and Inner Mongolia have abundant reserves, while the densely populated and economically active regions in the eastern, central, and southern parts of the country face high demand but lack resources. This "north rich, south poor" pattern has shaped the transportation landscape of "coal from the north to the south" and "coal from the west to the east." Coal relies on major rail lines such as the Daqin Line and the Shen-Shao-Huang Line to be transported to coastal ports, from where it is shipped by sea to southern consumption markets. Long-distance, large-scale transportation increases dependence on railways and ports, making the transportation segment a potential weak link in the supply chain.

(2) Insufficient coordination between transportation and logistics.

Despite ongoing improvements in railway and port infrastructure and increased transport capacity, transportation bottlenecks remain prominent. During peak coal consumption seasons, railway transport capacity is strained, and port loading and unloading capacity is insufficient, leading to congestion and "bottleneck" issues. The multimodal transport system remains incomplete, with poor coordination between railways, highways, and

waterways, and insufficient information sharing, resulting in high costs and low efficiency in the transport chain. Delays or disruptions caused by coordination issues during multiple transshipments increase costs and risks.

(3) Insufficient level of informatization.

The coal supply chain has limited informatization in areas such as forecasting, scheduling, and emergency management, with issues such as reliance on experience-based decision-making and information asymmetry still existing. Insufficient real-time data sharing and lagging supply-demand forecasts make it difficult for enterprises to promptly adjust production and transportation plans, resulting in low scheduling efficiency. Especially during critical periods such as the summer and winter peak seasons, the lack of prediction and scheduling tools based on big data and intelligence can lead to regional supply shortages or even power shortages, impacting energy security.

3.2 International Issues

(1) Concentration of import sources

In recent years, China's coal imports have continued to increase, reaching a record high in 2024. However, imports are heavily reliant on a few countries such as Indonesia, Russia, Mongolia, and Australia. While centralized procurement helps reduce costs, any restrictions on exports by major source countries due to policy adjustments, market fluctuations, or geopolitical factors could directly impact domestic supply. For example, coal trade between China and Australia was temporarily disrupted due to political friction, leading to domestic supply shortages, significant price hikes, and immense pressure on relevant enterprises.

(2) Fluctuations in international logistics costs

Cross-border transportation involves maritime shipping, port operations, and settlement processes, and is influenced by multiple factors such as freight rates, oil prices, and exchange rates. In recent years, the international shipping market has experienced frequent fluctuations, with significant fluctuations in freight rates; the US dollar interest rate hike cycle has exacerbated exchange rate instability, further increasing the uncertainty of import costs. Such fluctuations have heightened business operational risks and amplified the vulnerability of supply chains in terms of price stability, making it challenging for coal enterprises to mitigate risks when formulating procurement and sales strategies.

(3) Trade frictions and geopolitical risks

Energy trade is closely linked to geopolitics and is susceptible to trade frictions and international relations. The disruption of China-Australia coal trade is a typical example, leading to imbalances in import structures and price fluctuations. As the global geopolitical landscape becomes increasingly complex, some countries may implement trade protectionism for political or economic interests, restricting exports or raising tariffs, further increasing the uncertainty and disruption risks in China's coal supply chain.

3.3 Management and Policy Issues

(1) Lack of interdepartmental coordination mechanisms

The thermal coal supply chain involves multiple sectors such as energy, transportation, ports, and foreign trade, but currently lacks an effective interdepartmental coordination mechanism. Different policy objectives across departments lead to fragmented governance. The energy sector emphasizes supply security, the transportation sector focuses on transport efficiency, and the port sector prioritizes operational management. The absence of a unified information-sharing and coordination platform results in policy implementation gaps and redundant efforts, undermining overall efficiency and resilience.

(2) Lagging emergency reserve system

Although the state has made some arrangements for strategic reserves, the scale of thermal coal reserves is limited and unable to cope with market volatility or supply chain disruptions. The current reserve structure is dominated by government reserves, with insufficient participation from commercial reserves and no established market-based mechanisms. Compared to other energy sources such as oil, the institutionalization and normalization of coal reserves are relatively low, and emergency response mechanisms are inadequate, limiting their regulatory role in sudden situations.

(3) Inadequate price linkage and market mechanisms

The contradiction between coal and electricity prices has persisted for a long time. Coal prices are largely market-driven and are significantly influenced by supply and demand changes, while electricity prices remain subject to policy

restrictions and cannot fully reflect market costs. This mismatch in mechanisms may result in losses for coal-fired power companies when coal prices rise, affecting production incentives and supply stability. Although the state has promoted coal-electricity price linkage, it remains unable to fully cover cost fluctuations under extreme market conditions, and the lack of smooth price transmission weakens the market's regulatory role.

Table 1. Comparison of the Coupling Mechanism of the Thermal Coal Trade Supply Chain and Actual Issues

Supply Chain Component / Coupling Mechanism	Theoretical Mechanism	Practical Issues	Impact on Energy Security
Supply-Demand Structure	Regional supply-demand coupling: Northern production areas and eastern/southern consumption areas achieve complementarity through cross-regional flows, enabling efficient resource allocation.	Regional supply-demand imbalance, forming a "resource-rich north, resource-poor south" pattern; long-distance transport heavily reliant on railways and ports, exacerbating spatial-temporal mismatches.	Disruptions in transport can lead to coal shortages in southern regions, causing power supply instability and affecting socioeconomic operation.
Transportation System	Transportation network coupling: Railways, ports, waterways, and highways form an integrated transport chain, ensuring efficient connectivity and flexible scheduling	Prominent transport bottlenecks; poor coordination in multimodal transport; severe port congestion during peak seasons and insufficient information sharing.	Fragile transport chain increases risks of supply disruptions and logistics costs, weakening supply chain resilience and emergency response capacity
Information Flow	Information-sharing coupling: Data-driven scheduling and forecasting enhance chain coordination, enabling visualized management and real-time optimization.	Low informatization level; insufficient data sharing; scheduling reliant on empirical decisions, leading to delayed forecasting.	Inaccurate supply-demand predictions and slow emergency responses increase regional shortages and resource waste, threatening supply security.
International Trade	International supply coupling: Imports supplement domestic shortages, optimizing supply structure and achieving diversification and risk dispersion.	Over-reliance on a few countries for imports; frequent fluctuations in transport costs and exchange rates; heightened uncertainty from geopolitical frictions.	High external risks to the supply chain, threatening price and supply stability, and increasing vulnerability to import disruptions and domestic market fluctuations.
Policy and Governance	Policy mechanism coupling: Cross-departmental coordination, market-based regulation, and reserve systems provide institutionalized support.	Insufficient cross-departmental coordination; lagging emergency reserve systems; incomplete coal-power price linkage mechanisms, leading to fragmented governance.	Fragmented policy implementation, prominent price conflicts, and limited reserve effectiveness weaken strategic security and price controllability.

As shown in Table 1, the thermal coal trade supply chain can effectively support the core elements of energy security—including supply stability, price controllability, and strategic security capabilities—through an efficient transportation network, diversified trade channels, information-based management, and policy coordination mechanisms. However, multiple constraints remain in practice: domestically, regional supply-demand mismatches, transportation bottlenecks, and insufficient information technology lead to low resource allocation efficiency; internationally, concentrated import sources, fluctuating logistics costs, and geopolitical risks amplify external uncertainties; and at the policy and management level, insufficient interdepartmental coordination, lagging reserve systems, and incomplete price linkage mechanisms further weaken overall resilience. These issues not only reduce the operational efficiency and peak-shaving capacity of the supply chain but also increase vulnerability across three dimensions—supply security, price security, and strategic security—potentially amplifying the risk of energy disruptions and impacting the stability of power systems and socio-economic development.

Therefore, it is necessary to start from the actual operation of each link in the supply chain, coordinate domestic and international resource allocation, optimize transportation and logistics networks, enhance information management levels, and improve cross-departmental

coordination, reserve, and price adjustment mechanisms to achieve effective alignment between theoretical mechanisms and practical operations.

4. Optimizing Pathway Design

Within the framework of energy security strategy, the optimization of the thermal coal trade supply chain is not only crucial for the operational efficiency of the coal market but also a core component in ensuring national energy security. The design of its optimization pathway must comprehensively consider the dynamic evolution of domestic and international supply-demand dynamics, the capacity thresholds of transportation and storage systems, the potential for enhancing information technology levels, as well as the constraints and opportunities posed by policy directions and the international cooperation environment. This section will systematically explore five dimensions: trade layout, logistics and storage, digital transformation, policy and institutional safeguards, and international cooperation.

4.1 Diversified Trade Layout

The security of thermal coal supply heavily relies on the diversity and stability of import sources. China has long been dependent on a few countries such as Indonesia, Australia, and Russia, resulting in high import concentration and vulnerability to supply disruptions and price fluctuations. Therefore, the following optimization paths are proposed:

(1) Expand import sources to reduce reliance on a single source

Deepen cooperation with resource rich countries such as Mongolia, South Africa, and Colombia, and build a diversified import system. Adopting a procurement strategy that combines long-term contracts with spot trading, long-term contracts lock in stable low-priced sources, while spot trading flexibly responds to market fluctuations. For example, Mongolia has abundant coal resources and is geographically close, which can reduce its dependence on sea transportation and diversify risks through land transportation.

(2) Optimize the integration of coastal and inland waterway transportation

Fully leverage the throughput capacity of southeastern coastal ports to efficiently transport imported coal to central regions and the Yangtze River Economic Belt via sea-river intermodal transport or direct sea-river routes, thereby reducing transportation costs and enhancing supply chain resilience. This model promotes complementary allocation between imported and domestic coal, enhancing flexibility.

(3) Advance the construction of international energy corridors

Relying on the Belt and Road Initiative, build land transportation corridors such as the China-Mongolia-Russia and China-Pakistan Economic Corridors to enrich cross-border transportation routes, reduce dependence on a single port or shipping route, and alleviate the impact of geopolitical and natural disaster risks on the supply chain.

4.2 Enhancing Logistics and Reserve Capacity

The stable operation of the supply chain relies on efficient logistics and a sound reserve system. Currently, the “north-to-south coal transport” and “west-to-east coal transport” channels are under significant pressure, and regional reserve capacity is insufficient. In response to this, the following measures are proposed:

(1) Optimizing the multimodal transport system

Promote in-depth coordination between railways, ports, highways, and waterways, build dedicated coal transport channels, and develop smart dispatch platforms. Utilize big data and intelligent algorithms to optimize transportation routes and scheduling plans, reduce time and costs, and enhance transportation efficiency and reliability.

(2) Establish a strategic and commercial reserve system

Set up strategic reserve centers in coal-intensive regions such as East China and South China, combining them with corporate commercial reserves to form a multi-tiered system characterized by “national safety net, corporate participation, and market regulation.” Strategic reserves address fluctuations in the international market, while commercial reserves flexibly adjust supply and demand to stabilize market prices.

(3) Strengthen emergency transportation capabilities

Establish an emergency transportation capacity dispatch mechanism, form standby transportation fleets and shipping fleets, and pre-set emergency routes to ensure rapid allocation of reserve coal or imported coal to key regions in cases of extreme weather, geopolitical conflicts, etc., thereby enhancing

emergency response efficiency.

4.3 Digitalization and Information Technology Development

Information asymmetry, delayed forecasting, and inefficient scheduling are the primary constraints on supply chain security. Digitalization and intelligent technologies offer new pathways for optimization:

(1) Applying big data and artificial intelligence to predict supply and demand

By integrating power load data, industrial production indices, international coal prices, and meteorological data, precise predictive models can be constructed to dynamically analyze demand trends, optimize procurement and transportation decisions, and mitigate the risk of supply-demand imbalances.

(2) Promoting the application of blockchain technology

Leveraging blockchain's immutable and fully traceable characteristics to enhance trade contract transparency and logistics tracking efficiency, thereby reducing credit risks. For example, using blockchain to record coal origin, transportation routes, and other information ensures data authenticity and regulatory convenience.

(3) Establish a national-level supply chain information platform

Build a coal supply chain platform that enables data interoperability, eliminating "information silos," and integrate price monitoring, risk warning, and emergency command functions to provide decision-making support for governments and enterprises, enabling timely identification and response to market risks.

4.4 Policy and Institutional Support

Supply chain optimization requires sound institutional and policy support. Specific measures include the following:

(1) Optimizing import tariffs and reserve policies

Adjust import tariffs dynamically in response to international market conditions to balance domestic supply and demand. Lower tariffs when international coal prices are low to expand imports, and raise tariffs when prices are high to protect domestic industries. Improve strategic reserve policies by clarifying reserve scales, rotation mechanisms, and activation procedures to ensure reserve effectiveness.

(2) Establish a cross-departmental coordination mechanism

Establish an energy supply chain coordination body to oversee departments such as energy, transportation, and customs, and unify planning for production, transportation, and reserves. Regular coordination meetings should promote information sharing and collaborative operations to enhance governance efficiency.

(3) Integrate environmental and safety constraints

Incorporate the "dual carbon" goals into institutional design, promote green transportation methods such as electric trucks and railway electrification to reduce carbon emissions. Improve transportation safety management systems to ensure the safety and sustainability of supply chain operations.

4.5 International Cooperation and Risk Prevention and Control

Thermal coal trade is significantly affected by international markets and geopolitics. Cooperation and risk management are needed to enhance supply chain security:

(1) Participate in international energy governance

Actively participate in the formulation of global energy market rules to enhance China's voice, advocate a fair and transparent trade order, and contribute Chinese solutions to international energy forums.

(2) Promote long-term contracts and regional cooperation

Sign long-term contracts with major exporting countries to lock in supply volumes and price ranges, thereby reducing market volatility risks. Promote the development of an East Asian energy cooperation platform, establish a regional risk-sharing mechanism, and enhance emergency response capabilities.

(3) Develop Differentiated Risk Contingency Plans

Develop early warning and adjustment plans in response to geopolitical risks such as climate disasters in Southeast Asia and the Russia-Ukraine conflict. Expand new supply channels in Central Asia, the Middle East, and other regions to ensure supply chain stability under extreme conditions.

5. Conclusions and Recommendations

5.1 Research Conclusions

This study adopts an energy security perspective

to conduct a comprehensive and systematic investigation into the structural characteristics, operational issues, and optimization pathways of the thermal coal trade supply chain. Thermal coal has long held a dominant position in China's primary energy structure, and the stability of its supply chain is closely tied to national energy security and the smooth operation of the economy and society. It is a critical factor in ensuring the stable supply of national energy and the development of the economy and society. Currently, China's thermal coal supply chain faces challenges both domestically and internationally. Domestically, regional supply-demand imbalances are prominent, with significant disparities in demand and supply capacity across different regions, leading to supply shortages in some areas and overcapacity in others; transportation channels are constrained, resulting in low coal circulation efficiency and increased transportation costs and time; the reserve system is incomplete, with unreasonable scale and layout, making it difficult to respond to emergencies, and overall resilience is insufficient. Internationally, imports are overly concentrated in a few countries, making them susceptible to political, economic, and natural factors in those countries. External market fluctuations and geopolitical risks have exacerbated supply chain uncertainty. Additionally, the supply chain's level of informatization is low, information transmission is often untimely and inaccurate, management mechanisms are outdated, and there is a lack of effective coordination and emergency response measures, all of which weaken overall operational and emergency response capabilities. Based on this, the optimization of the thermal coal trade supply chain requires multi-dimensional coordination and advancement. To enhance external stability, it is necessary to establish a diversified import layout, expand import sources, and reduce reliance on a single country; strengthen the construction of a multimodal transport system, integrate transport modes, and improve transport efficiency and flexibility. To enhance internal resilience, it is necessary to improve the reserve system and establish a multi-tiered reserve network; improve cross-departmental coordination mechanisms, and strengthen information sharing and collaborative cooperation. To improve operational efficiency, the key is to promote digitalization and informatization, utilizing information technology to achieve intelligent management and enhance predictive, scheduling, and emergency response capabilities. Diversification, resilience, and digitalization are the core elements of future thermal coal supply chain optimization and also represent important strategic directions for ensuring China's energy security.

5.2 Policy Recommendations

Based on the above research findings, this paper proposes the following targeted policy recommendations to further promote the optimization of the thermal coal trade supply chain and enhance energy security:

(1) Establish a diversified import structure.

The government should support enterprises in exploring diversified import sources and promote coal cooperation with regions such as Mongolia, Russia, Central Asia, and Africa to reduce dependence on a single country. At the same time, the stability of the supply chain should be enhanced through a combination of long-term contracts and spot transactions.

(2) Improve the reserve and transportation system.

Strategic reserves and regional reserve centers should be established in major consumption areas, combined with commercial reserves to form a multi-tiered supply network. In terms of transportation, efforts should be made to expand railway capacity and enhance port logistics capabilities, establishing an efficient multimodal transportation network integrating railways, ports, waterways, and highways.

(3) Promote the digitalization of the energy supply chain.

At the national level, a unified information-sharing platform should be established to integrate data on coal production, transportation, trading, and consumption, enabling cross-departmental dynamic monitoring and risk warning. Technologies such as blockchain, big data, and artificial intelligence should be supported for application in contract management, transportation tracking, and demand forecasting.

(4) Improve cross-departmental coordination and emergency response mechanisms.

A national-level energy supply chain coordination body should be established to centrally coordinate coal production, imports, and transportation resources. In the event of

emergencies, a rapid response mechanism should be activated to mobilize reserve coal and coordinate transportation capacity to ensure energy supply for key industries.

(5) Strengthen international cooperation and risk management.

At the international level, actively participate in energy governance and rule-making to enhance influence in international markets. Simultaneously, develop differentiated risk management contingency plans for different supplier countries, covering geopolitical conflicts, natural disasters, and transportation disruptions, to ensure the long-term security of the supply chain.

5.3 Future Research Directions

Under the "dual carbon" strategy and the trend of energy transition, the development of thermal coal faces challenges, and there are numerous directions for future research. First, as the proportion of renewable energy generation increases, thermal coal demand will slow down. It is necessary to study the complementary and synergistic mechanisms between thermal coal and clean energy sources such as wind power, solar power, and natural gas to achieve optimal energy allocation, efficient utilization, and enhanced system stability. Second, the coal supply chain must balance safety and resilience with carbon reduction and environmental constraints. Key research areas include green transportation initiatives, such as the use of clean energy transport vehicles, while strengthening environmental regulation in production and processing to promote industrial green transformation. Third, given the frequent fluctuations in global energy prices, exploring the use of financial derivatives such as futures, forward contracts, and insurance to build a risk management system and enhance supply chain risk hedging capabilities is a worthwhile direction. Fourth, under regional cooperation frameworks such as the Belt and Road Initiative, strengthening energy cooperation within the region, establishing a unified market and coordination mechanisms, improving cross-border supply chain infrastructure, achieving coordinated development of cross-border coal and new energy supply chains, and building a regional energy security community are essential to promoting sustainable regional economic development.

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