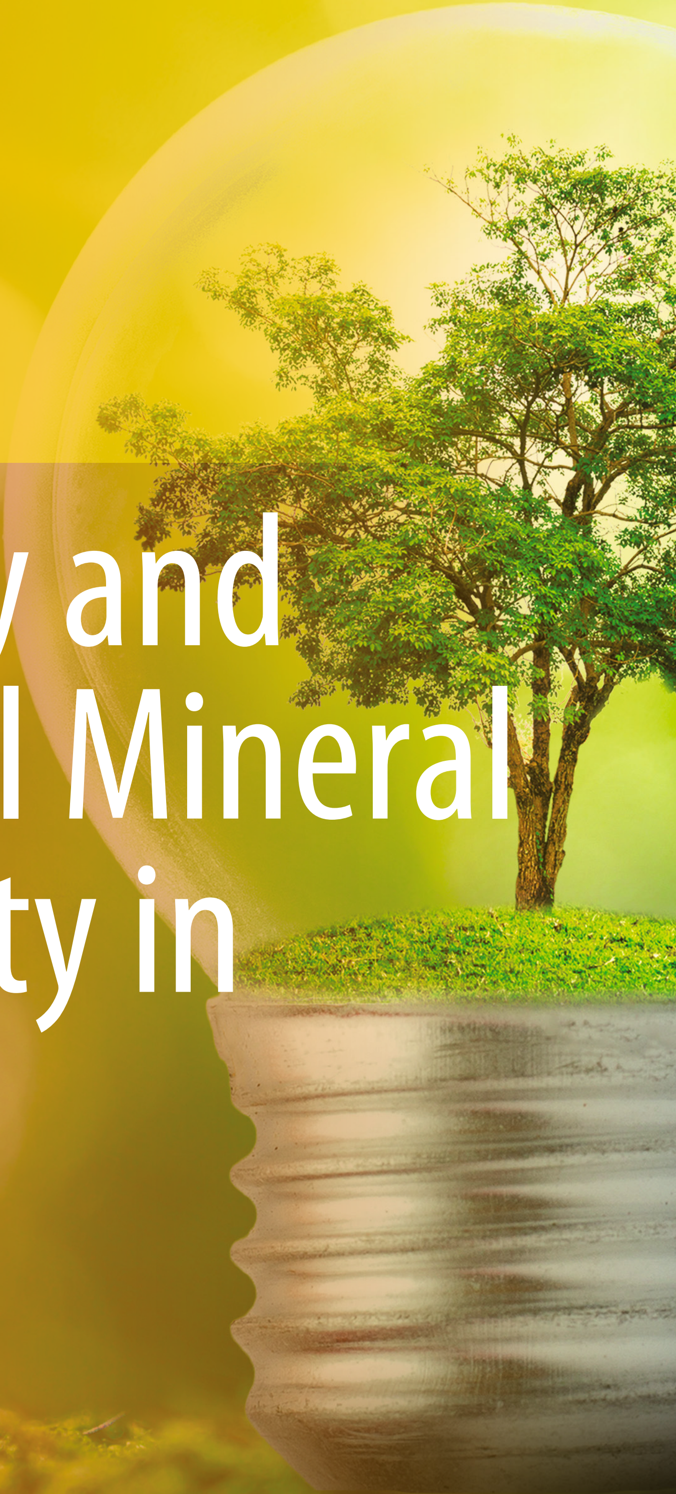
Climate Change and Energy Transition

Xiaolei Sun
Qiang Ji *Editors*

Energy and Critical Mineral Security in China



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Preface

This book focuses on the hotspots and frontier issues of China's energy resource security strategy, aiming to develop a general framework for understanding the new security landscape of constructing a modern energy system and accelerating the low-carbon transition. It attempts to sketch out the core issues of energy and critical mineral resource security in China's current and future low-carbon transition process and brings forward a combination of theoretical and empirical analyses on the critical issues.

With the development of globalization, energy and critical mineral security have become crucial components of the development strategies of various countries. Energy is the foundation for the survival and development of modern society, and the driving force for the operation of the world economy. Critical mineral resources, as an indispensable material cornerstone for strategic emerging industrial processes, such as green and low-carbon energy transformation and high-end equipment manufacturing, have become increasingly prominent in the strategic position of countries around the world in seizing the high ground of a new round of technological revolution and industrial transformation. Especially with the surge in global demand for renewable energy, clean energy sources, such as electricity, wind energy, and solar energy, are widely used. The importance of critical mineral resources, such as lithium, cobalt, and nickel, that support the production, manufacturing, and technological innovation of these industries is becoming increasingly prominent. Following the International Energy Agency's view of "whether critical metal minerals can support the low-carbon transformation of future energy" as a major global challenge, the United Nations' "2024 World Economic Situation and Prospects" report once again emphasizes the cornerstone role of mineral resources in industrial manufacturing, energy supply, and infrastructure construction.

Energy and critical mineral security are complex systems that are interrelated and interdependent. On the one hand, the supply security of critical mineral resources directly affects the production and consumption security of energy, such as solar panels requiring silicon, lithium batteries for electric vehicles requiring lithium, and wind turbines requiring rare earths. On the other hand, the security of the energy supply will also affect the development and utilization of critical mineral resources, such as fluctuations in energy prices affecting the mining costs and market prices of critical mineral resources, and interruptions in energy supply affecting the processing and transportation of critical mineral resources. Thus, in the future era of renewable energy, the relationship between energy and critical minerals has become very close. With the explosive growth of clean energy technology applications, the demand for critical minerals, represented by lithium, nickel, cobalt, and copper, has surged. Critical minerals have become an important cornerstone for the green and low-carbon transformation of energy. Therefore, to achieve energy and critical mineral security, the resource security concept based solely on its own supply security has limitations, and a safe, stable, and sustainable cross-category resource security concept needs to be urgently established.

The 20th National Congress of the Communist Party of China (CPC) emphasizes the need to deepen the energy revolution, accelerate the planning and construction of a new type of energy system, promote energy low-carbon clean transformation, and implement carbon peak actions in a planned and phased manner. China initially formed a diversified energy production system driven by coal, oil, natural gas, electricity, nuclear energy, new energy, and renewable energy. However, future energy mineral resource comprehensive system stability with new energy as the main body is more complex.

Against the background of green development of "carbon peak and carbon neutrality," the accelerated pace of energy transformation and energy system evolution will continuously endow the connotation of resource security with new characteristics of the times, gradually extending from the initial supply security to strategic mineral resource security covering environmental protection and climate change issues, involving a wider range of connotations and extensions. With the acceleration of global efforts to address climate change and low-carbon transformation, there is still a risk of structural energy and critical mineral resource shortages in China. In the future, the global geopolitical game around new energy and critical minerals will become increasingly intense.

Aiming to satisfy the broad interests of both academia and policymakers, the contents of this book range from general discussions of current critical issues in China's energy and mineral resource security to quantitative analyses of key themes. We hope to bring forward a general picture of resource security in China's low-carbon transition, facilitating demands for both academic research and policy-making. The book should also provide good guidance for graduate students interested in this subject.

The main content of this book is based on solid research outcomes but with clear policy relevance. The book combines the strategy and planning of resource sectors with the practical experience of the energy and mining industry, reflecting the complexity and systematization of energy resource security. The materials presented can provide useful knowledge to policymakers as well as inspire new research ideas in relevant areas.

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Competing Interests The authors have no competing interests to declare that are relevant to the content of this manuscript.

Contents

Chapter 1
New Trends in Global Energy Security Geopolitics

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Abstract Oil security is the core and concentrated expression of energy security. The global oil geopolitical market pattern has gradually transitioned from a unipolar system initially dominated by the United States and OPEC to a bipolar system in which OPEC and independent oil-producing countries, such as Russia, confront each other. The "shale revolution" that erupted in 2009 stopped the decline and encouraged the rebound of United States oil production, opening the way for the international oil supply system to transition from a bipolar system to a "Saudi-Russia-US" tripolar system. This chapter focuses on the evolution of the energy strategies of OPEC, Russia, and the United States and presents an analysis and anticipation of the global energy landscape under the tri-polar system of oil supply. Finally, it presents a quantitative analysis conducted on the trade patterns of traditional energy sources, such as crude oil, natural gas, and coal worldwide, comprehensively reviewing the current trade patterns and development trends at both the global and national levels and providing optimized strategies for future cooperation layout.

Keywords Energy strategy evolution · Tripolar system · Energy trade network

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1.1 Energy Strategies of OPEC, Russia, and the United States

1.1.1 Evolution of the OPEC Energy Strategy

In September 1960, at a conference in Baghdad, Iraq, Iran, Iraq, Kuwait, Saudi Arabia, and Venezuela jointly initiated the establishment of the Organization of Petroleum Exporting Countries (OPEC), a permanent intergovernmental organization. Subsequently, Qatar, Indonesia, Algeria, and other countries joined, and by the end of 2023, there were a total of 13 member countries, with Saudi Arabia being the largest oil producer to date, accounting for nearly one-third of OPEC's total oil production.

OPEC is the world's earliest and most influential organization of oil-producing and exporting countries. Its mission is to "coordinate and unify the oil policies of member countries, maintain the stability of international oil market prices, and ensure that oil-producing countries obtain stable income." According to the 2023 OPEC Annual Statistical Bulletin, as of the end of 2022, the total proven oil reserves of OPEC member countries amounted to 1.243 trillion barrels, accounting for 79.5% of the global total reserves. Daily production was about 28.895 million barrels, accounting for 39.7% of the global daily production. With its absolute advantage in global oil reserves and supply, OPEC's decisions and actions have a profound impact on the global energy market (Aguiar-Conraria and Wen 2012; Brown and Huntington 2017). However, due to continuous changes in global energy supply and demand, OPEC's energy strategy has been evolving.

OPEC's influence on the international oil market is achieved through the implementation of oil production quotas, controlling the oil production of member countries, and adjusting its oil supply to the market, thereby affecting oil prices. From the mid-1970s to the mid-1980s, OPEC successively implemented "price increase to maintain value" and "production reduction to maintain value" strategies. During the price increase and production reduction stages, OPEC used a direct fixed price approach—that is, it took the Saudi light crude oil price as the benchmark oil price for OPEC and stipulated the price difference between various crude oils and the benchmark oil price. Member countries then exported crude oil at the determined price. However, due to the differences in market impacts faced by various crude oils, the strict price difference system centered on benchmark crude oil caused unfairness in the sharing of responsibilities among countries. For example, the impact of the price decline of Brent crude oil on Nigeria's oil production is much greater than that of other countries. Furthermore, OPEC does not have a compensation mechanism for countries affected by the impact. Therefore, it is difficult for OPEC member countries to give up the autonomy of production adjustments to maintain a price difference system.

From the mid-1980s to the early twenty-first century, OPEC made a significant adjustment to its market strategy, turning to the "low price to maintain volume" strategy, in an attempt to use its advantage in low oil production costs to exclude oil-producing countries with high oil production costs from the market, thus regaining the market share it had lost. During the "low price to maintain volume" stage, OPEC also set target oil prices, but in fact, it abandoned the direct fixed oil price approach, turning to a strategy of fixing production, stabilizing production on the basis of ensuring oil income, and then adjusting production according to market changes to influence prices.

Since the beginning of the twenty-first century, with the rapid development of the economies of emerging countries, such as China and India, international oil demand has grown rapidly, and the supply of non-OPEC crude oil has also increased rapidly. Facing the pressure of rising oil prices, OPEC officially announced the abandonment of the price band policy in 2005. Since then, OPEC has not formulated a clear oil price policy, stating only that it will appropriately intervene in the oil price fluctuations brought about by the fundamentals. OPEC's influence on the market has gradually weakened (Graaf 2017; Gil-Alana et al. 2020). Although OPEC's market share has not significantly decreased since 2000, according to the average production over five years, more than half of the 10 resource-rich OPEC countries with production exceeding 1 million barrels/day have seen a continuous decline in production, an unprecedented situation since OPEC's establishment. After 2008, OPEC's market share maintenance was mainly achieved by Saudi Arabia and other core OPEC members producing oil close to maximum capacity, which also brought about a decline in OPEC's production adjustment capabilities. Therefore, cooperation with oil-exporting countries outside OPEC has become a problem that OPEC must solve to continue to exert market influence.

Facing the common threat of the continuous decline in international oil prices, OPEC and non-OPEC oil-producing countries led by Russia signed the "Cooperation Declaration" at the first OPEC and non-OPEC Ministerial Conference in December 2016, proposing a joint production cut to raise oil prices. Considering that the production cut mechanism is temporary, at the sixth OPEC and non-OPEC Ministerial Conference in July 2019, the two sides signed the "Cooperation Charter," making the "OPEC+ " mechanism long-term, which also marked the official establishment of OPEC+ , a new force in the production side to respond to market oil price fluctuations. However, the establishment of "OPEC+ " did not change the trend of declining influence of oil-producing countries. Although "OPEC+ " has a high compliance rate with the production quota, under the gloss of a high compliance rate, many countries' oil production has naturally declined. In the "OPEC+ " mechanism, only Saudi Arabia, the United Arab Emirates, and Kuwait have implemented significant active production cuts, while the production adjustments of other countries are not due to compliance with the joint production cut agreement but due to passive production cuts brought about by continuous declines in oil investment.

For example, Angola's and Mexico's production decline is mainly due to equipment aging and poor management, while Iran's and Venezuela's production decline is mainly due to US sanctions. If excluding the above-mentioned involuntary production cuts, the actual role of the "OPEC+ " mechanism in regulating oil production is very limited. In the interaction with OPEC, most countries, including Russia, have adopted a "free rider" strategy, exceeding the agreed production quota in oil production. Under the impact of the COVID-19 pandemic, "OPEC+ " members agreed to cut production to reach a consensus, giving more consideration to Russia, Kazakhstan, and other countries. For example, in the first quarter of 2021, the other OPEC+ members increased the production cut from the 13.3% agreed upon in April 2020 to 17.1%; in February and March 2021, Saudi Arabia's actual production cut reached 26.2%. However, from February to March 2021, both Russia and Kazakhstan increased their monthly production by 10,000 barrels/day and 65,000 barrels/day, respectively. Giving more consideration to some member countries, especially major oil-producing countries like Russia, also signals the instability of the "OPEC+ " production cut agreement.

1.1.2 Evolution of Russia's Energy Strategy

Energy is the core of Russia's domestic and foreign affairs. Relying on the world's largest and second-largest natural gas and oil reserves, energy exports have become an important strategic means for Russia to promote domestic economic growth, participate in the world economic system, maintain geopolitical influence, and improve the political environment. Russia's energy system has gone through the extensive strategy of the Soviet era, the strategy of the transition period after the collapse of the Soviet Union, and the comprehensive development strategy implemented in recent years.

During the Soviet era, energy policy had a clear dominating feature, prioritizing the development of the oil and gas industry to meet the energy needs of heavy industries, such as the military industry; implementing low-cost strategic energy exports to Eastern European countries, with economic interests giving way to political and military goals; and by the late Soviet era, mainly relying on energy exports to exchange foreign exchange to ensure food security. This resulted in a complex relationship between energy and military–industrial systems, economic security, food security, national security, and global geopolitics. The outcome was a heavy burden on energy development and an imbalanced economic structure. The energy sector also became a target for Western strategic attacks using oil price dominance, leading to a chain reaction.

During the transition period after the collapse of the Soviet Union, Russia's energy policy had a clear open and market-oriented character. This period opened up market-oriented economic reforms, implemented privatization, stimulated private capital, and allowed foreign investment, gradually solving the problem of energy financing. Energy exports, which were initially relaxed and then strengthened, also reflected the growing dependence of the national economy on energy trade.

Since 2000, Russia's energy strategy has been more inclined toward the strategy of a strong energy country, aiming to fully utilize the advantages of being a major energy resource country to transform into economic development momentum and international influence and to build a "strong Russia." The main contents of energy policy during this period can be summarized as follows: implementing a comprehensive national energy development strategy, promoting rapid economic development, improving people's lives, and enhancing Russia's international status.

Over the past 20 years, Russia's energy policy has continued to innovate and develop, with a strong country strategy as the clear and stable main line (Zhao, 2023). In 2003, Russia issued the "2020 Energy Strategy," forming a complete system covering energy development goals, technological innovation, investment, and foreign cooperation. In 2008, it further strengthened the diversified export strategy, striving to increase the export proportion to the Asia–Pacific region from 3 to 30% while expanding the North American market. In 2009, the "2030 Energy Strategy Draft" emphasized improving energy efficiency and increasing the development and utilization of nuclear energy, solar energy, and wind energy. From 2012 to 2014, with changes in domestic and international economic situations, Russia further adjusted to take traditional industries such as energy as a breakthrough point, transitioning to innovative economic development and combining energy and innovation. In 2014, the "Russia's Energy Strategy Draft for 2035" was issued, an enhanced version of the energy power strategy, emphasizing strengthening energy reform from the aspects of regulatory systems, infrastructure construction, investment, and innovation.

After the escalation of the Ukraine crisis in 2022, the Russian environment became more severe, and the US and Western countries imposed extreme containment and sanctions on Russia, leading to a complete breakdown of relations between Russia and the West. To break the deadlock, Russia accelerated the "shift to the East" strategy and further developed bilateral and multilateral relations with Eastern countries, which became Russia's key to breaking the situation. At the 6th International Forum "Russia Energy Week" in October 2023, four main strategic directions for the transformation of the energy sector in Russia were proposed. First, ensuring a stable domestic market supply is one of Russia's primary tasks. Therefore, Russia will continue to increase investment in the oil, gas, and electricity sectors, enhance production capacity, and strengthen the construction of energy supply chains to meet domestic demand. Second, Russia plans to create higher added value by developing deep processing of oil and gas. Third, Russia will enhance the development, production, and use of domestic machinery, equipment, technologies, and application software and establish a complete sovereign technology and investment system. Fourth, Russia's energy supply will shift to other rapidly growing and promising regions of the world with robust economic growth, especially in Asia. As the main engine of global economic growth, Asia's demand for energy is increasing. With its abundant energy resources, Russia has extensive cooperation potential with Asian countries in the energy field. By strengthening energy cooperation with Asian countries, Russia can seek a larger market share and promote the international development of the energy industry.

1.1.3 Evolution of the United States' Energy Strategy

Energy independence has been the core of US' energy policy since 1973. From the global "petrodollar" system based on international oil companies after World War II and the establishment of the International Energy Agency (IEA) under US leadership after the oil crisis to continuous energy structure reforms in the twenty-first century (including the renewable energy revolution and the shale revolution), various measures have been taken to ensure US energy security and independence. Despite multiple adjustments to US energy policy due to changes in domestic and international situations, the pursuit of energy independence has remained unchanged.

The two oil crises in the 1970s had a significant impact on the US economy, leading the US government to realize the vulnerability of relying too much on imported oil. The US was once the world's largest oil importer, and its heavy dependence on oil from the Middle East became a major concern for national energy security. Therefore, the US has been working to strengthen trade relations with oil-producing countries, such as Canada, Mexico, and Venezuela, to build an energy security network in North America and Latin America. To ensure strategic control over important areas of energy resources, the US has intervened in the geopolitical situation of oil-producing regions based on its strong naval power, using sanctions, wars, and value judgments to shape an energy strategy that is beneficial to itself. In this phase, the focus of energy development was on diversifying supplies to meet the surge in energy demand, reduce dependence on potentially unstable energy suppliers, and increase investment in energy efficiency and energy technological innovation.

From 1993 to 2001, the US took measures such as releasing strategic oil stocks, and oil prices remained stable. In the twenty-first century, the US government has adopted a laissez-faire attitude toward oil prices, and international oil prices have soared nearly six times. Persistently high oil prices have exacerbated US policymakers' concerns about relying on imported energy, coupled with significant changes in the international geopolitical situation, prompting the US government to focus its energy policy on increasing domestic energy supply and reducing energy dependence on foreign countries. It has further consolidated energy supply links in the Western Hemisphere and strengthened domestic oil and gas production capacity and strategic reserves. The US signed the United States Energy Policy Act of 2005, changing its energy strategy, which relied heavily on imports, and gradually focused on a diversified domestic energy supply. The "2006 U.S. Energy Strategy Plan" further confirmed this trend, with a strong emphasis on the development of natural gas and nuclear energy as clean energy, shaping a diversified energy supply pattern. The government also advocated for energy conservation and encouraged society to actively participate through tax incentives and mandatory purchasing.

Since the 2008 financial crisis, the US has been promoting the "Clean Energy National Strategy" in a high-profile manner and has chosen the clean energy industry as a key force to respond to the economic crisis and revive the US economy. The US government hopes that emerging energy industries, such as wind, solar, and biomass, will become new drivers of economic growth and provide more jobs and has therefore adopted a series of measures in terms of taxation, industry standards, and market mechanisms. These include taxing oil companies to subsidize the rise in residential energy prices, raising fuel economy standards to drive electric vehicles, establishing a market-based cap and emissions trading system, implementing a “cap and trade permit” scheme and using the proceeds from the auction of cap and trade permits to invest in “climate-friendly” development plans, and increasing government investment in clean energy. However, clean energy projects cost a lot, their financial benefits are uncertain, private enterprises have difficulty accumulating the incentive to develop and build, and few people are willing to pay for more energy-saving and environmentally friendly but expensive clean energy products. Thus, the US government later adapted to the changes in the national energy situation and actively sought a balance between fossil energy and clean energy development.

The US government argues that the Paris Agreement restricts its right to use fossil fuels such as coal and oil, advocates strong support for the coal industry, promotes the development of the oil industry, and signs an executive order to cancel the previously launched Clean Energy Plan and replace it with a “growth plan” on the grounds of “killing jobs.” Specifically, the first is to continuously strengthen the exploitation of traditional fossil energy. Benefiting from the significant increase in shale oil production, the US government predicts that its domestic oil production will be essentially the same as that of Russia, the world’s largest country, by the end of 2019, and that its natural gas production will also show explosive growth, which may accelerate the end of the global energy “Middle East era.” Furthermore, the president of the US stood on the platform and directly came forward to promote energy exports. In April 2018, the US directly pressured Germany to drop its support for the Russia Nord Stream 2 gas pipeline and buy more US liquefied natural gas (LNG). Thus, it is not difficult to see that the traditional energy industry has become an important force in promoting the economic growth of the US.

The US government has focused its energy strategy on the clean energy revolution (Li et al. 2024). Linking energy to climate issues is an important part of the US government’s energy strategy. In November 2021, the US pushed both houses of Congress to pass the Infrastructure Investment and Jobs Act, investing about $62 billion in the energy sector. In February 2022, the U.S. Department of Energy announced the creation of two new deputy secretaries, one responsible for basic science and clean energy innovation and deployment, and the other for clean infrastructure, to more effectively implement the “Infrastructure Investment and Jobs Act” and the “2020 Energy Act.” The goal is to accelerate the construction of clean infrastructure across the country, aiming to achieve a carbon-free electricity grid by 2035 and a zero-emission economy by 2050. Unlike traditional energy, the US currently does not have a dominant position in the clean energy sector, and it heavily relies on foreign countries for key equipment, products, rare earths, and other special resources. The trade disputes with China and the disruptions caused by the COVID-19 pandemic have made the US aware of the importance of maintaining the security of critical material supply chains. Therefore, the current US energy strategy focuses on reducing dependence on foreign countries in the clean energy sector.

In February 2022, the U.S. Department of Energy released the "U.S. Strategy for Ensuring Resilient Clean Energy Supply Chain Transformation." The report states that ensuring energy supply chain security is closely related to the US government's response to climate change, national security, and economic goals. More importantly, the report emphasizes the potential of the clean energy supply chain transformation to provide opportunities to better build supply chains to support US innovation and economic growth and enhance US competitiveness. To achieve this goal, the report outlines seven key strategies: achieving the supply of critical raw materials domestically, expanding domestic production capacity, investing and supporting diversified and reliable foreign supply chains, creating markets for clean energy, improving energy utilization efficiency and waste disposal capacity, attracting and supporting skilled labor for the transformation of the clean energy supply chain, and strengthening research and decision-making on supply chains to further reduce the risks of the clean energy supply chain and enhance the US' competitive position and global leadership in the clean energy market.

1.2 Tri-Polar System Under Global Energy Geopolitics

In recent years, under the impact of the global outbreak of the COVID-19 pandemic, intensified geopolitical competition among major powers, and the promotion of low-carbon transformation, the global energy market has entered a period of intense turmoil and change. Particularly with the outbreak of the Russia–Ukraine conflict in early 2022, geopolitical tensions have escalated sharply, leading to major adjustments in the global energy landscape (Nguyen et al. 2024; Wang et al. 2023).

1.2.1 Increasing Complexity of Global Energy Geopolitical Competition

Energy weaponization has become more frequent and pronounced. Energy weaponization refers to the use of economic sanctions, such as large-scale sanctions, to inflict enormous pressure and costs on one side in terms of energy and the economy, forcing them to change their behavior or policies in key areas to achieve strategic goals that are beneficial to the other side. Although energy has long been used as a weapon, it has become increasingly frequent and widespread since the Russia–Ukraine conflict. First, both energy exporters and importers use energy as a weapon. Historically, due to the dependence of energy importers on energy, the active use of energy as a weapon has mainly been wielded by energy-exporting countries or organizations in the Middle East, which have unilaterally used their resource advantages to defend their own rights and interests. However, following the outbreak of the Russia–Ukraine conflict, both energy exporters in Russia and energy importers in

Europe have been using energy as a weapon to contain each other (Cui et al., 2023). Second, the forms, intensity, and scale of energy weaponization are unprecedented. To strangle Russia's economy, the US and European countries have imposed comprehensive energy sanctions on Russia, including restrictions on energy investment and trade, freezing energy industry assets, banning or limiting energy imports, imposing price limits on oil and gas, or even destroying the Nord Stream gas pipeline. In response, Russia retaliated by reducing or cutting off gas supplies to some European countries and implementing a "ruble payment order."

Energy competition has become all-round (Blondeel et al. 2024). With the continuous escalation of Western sanctions against Russia, Russia–Europe energy relations have deteriorated, and Russia–US–Europe energy geopolitical competition has intensified further. The US has pressured Europe to upgrade sanctions against Russia's energy sector, urging Europe to accelerate its decoupling from Russian energy. Russia has accelerated its energy strategy of "moving eastward" and "southward" to counterattack. In December 2022, the Russian president signed a presidential decree to take special economic measures against Western oil price limits. In the energy trade, the competition between Asia and Europe has intensified. Europe has actively sought new energy sources to reduce its dependence on Russian energy, further intensifying competition with Asia and other regions in the energy trade and market.

Energy cooperation has become "campaign-oriented" and "regionalized". As the international landscape accelerates its adjustments, Russia's energy exports have shifted from Europe to Asia, and the US' energy exports have shifted more toward Europe, with the Middle East, Australia, and other regions significantly increasing their energy supply to Europe. The competition between energy-consuming countries and oil-producing countries has intensified. For example, transatlantic partnerships have become closer. Under pressure from the US, the European Union (EU) has accelerated its decoupling from Russian energy, and US–European energy cooperation has intensified. The EU and the US have jointly issued several energy cooperation joint statements to strengthen strategic energy cooperation and to build an energy interest community through the transatlantic partnership and NATO. Furthermore, the partnership between OPEC+ has become increasingly close. Since the Ukraine crisis broke out, OPEC countries have maintained a neutral stance on the Russia sanctions issue, refusing to meet the requests of the US and Europe to increase production and choose sides. The agreement between OPEC+ countries has not shown any signs of cracking.

The trend of "deglobalization" and "decoupling" has also extended to the clean energy sector. The ongoing Russia–Ukraine conflict has not only intensified the politicization of the traditional energy sector intensified, but the economic nature of the clean energy supply chain has also gradually been politicized and politicized. First, the US has increased its support for the green industry through measures such as the "Inflation Reduction Act," aiming to gain a competitive edge in the global clean energy market. The EU has introduced the "Key Raw Materials Act" and the "Carbon Border Adjustment Mechanism," promoting the development of domestic clean energy supply chains and building a strategic autonomous clean energy system. Second, the US has proposed "upgrading industry standards" and issued policies such as the "New European Industrial Strategy," the "EU Solar Strategy," and the "European Green Industrial Agreement," using legislation to shape clean energy supply chain standards and rules, attempting to reshape the global clean energy supply chain with its green standards and adjust the international competition rules in the green industry. Third, ideological divisions have been used to form camps, consolidate traditional alliances, or establish new clean energy partnerships, highlighting the "de-China" and diversification of the clean energy supply chain. In 2022, the US, along with the United Kingdom (UK), Australia, France, and Germany, established the "Mineral Security Partnership," and in February 2023, it further established the "Critical Minerals Buyers Club" to try to exclude China from its critical mineral supply chain. In May 2023, the Group of Seven (G7) summit issued a clean energy initiative, emphasizing diversification in the supply chains of critical minerals and green products. Additionally, the US has collaborated with Japan, South Korea, India, and Australia in the "Indo-Pacific Economic Framework" to share energy resource supply chains and encircle China geographically.

1.2.2 Fundamental Changes in the Flow of International Energy Trade

Since the outbreak of the Russia–Ukraine conflict, the long-term global energy trade pattern, primarily driven by economic factors, has undergone significant changes. Russia has increased its exports to Asia and reduced its exports to Europe, showing a trend of "moving eastward." The US has shifted the focus of its energy exports to Europe, reducing exports to Asia and showing a trend of "rising westward and declining eastward." Europe has gradually reduced its imports of Russian energy and increased its domestic energy supply.

Following the conflict, Russia's energy export focus shifted "from the West to the East." In 2020, European countries in the Organization for Economic Co-operation and Development (OECD) accounted for 71.9% of Russia's natural gas exports. After the outbreak of the Ukraine crisis, the EU turned to US LNG, reducing Russia's European energy market. In this context, Russia's energy export focus has shifted "from the West to the East." After the conflict broke out, India significantly increased its purchase of Russian oil. In March 2022, Russia's oil exports to India reached 300,000 barrels per day, increasing to 700,000 barrels per day in April, with Russian oil accounting for about 17% of India's total crude oil imports, a significant increase from less than 1% before the conflict. Russia and China have signed long-term energy supply agreements. In early February 2022, Russia and China signed a 10-year agreement to supply 200,000 barrels of crude oil per day and a separate 100 billion cubic meters of natural gas supply agreement.

The US has expanded its global influence on fossil energy through oil and gas exports. The shale oil and gas revolution has led to a surge in domestic oil and gas production, enabling the US to break its dependence on foreign oil and gas imports and become a major global oil and gas exporter, significantly enhancing its influence on the international energy market. Since the outbreak of the Ukraine crisis, the US has increased domestic shale oil and gas production. On the one hand, the US is ramping up its domestic oil and gas production to address Europe's shortfall in energy supplies and counteract the limitations on oil and gas production capacity in the Middle East. This strategic move aims to bolster exports to Europe and sustain the nation's global dominance. On the other hand, the US has implemented a "double standard" policy for LNG exports to Europe, with prices being about 3–4 times higher than domestic prices. The sharp rise in international energy prices and US exports of LNG to Europe have brought substantial economic benefits to the US' energy industry.

The EU has diversified its natural gas supply and increased its domestic energy supply (Li and Liu 2023). To solve the European energy crisis, the EU has put forward the goal of diversifying the natural gas supply in its "Energy Independence Plan." It has increased its LNG supply and receiving capacity. The EU has established an energy joint group with the US to enhance LNG transportation capacity and ensure a short-term European energy supply. It is seeking support from Qatar and OPEC+ countries to increase production and ease the European energy crisis. It has also accelerated the increase in the domestic energy supply. The UK, and the Netherlands have relaxed restrictions on natural gas development, Norway is fully committed to ensuring natural gas supply, Germany has extended the operation cycle of coal-fired power plants, and France has restarted its nuclear energy strategy.

1.2.3 Significant Diversification of the Global Energy Transition Process

As the Ukraine crisis continues, fostering a sharp rise in fossil energy prices and sanctions against Russia, the global energy transition process will be significantly diversified. The EU will accelerate its clean energy transition, while the development of the US oil and gas industry may hinder the energy transition process. Russia's low-carbon energy transition is lacking in strength.

The EU will accelerate its clean energy transition in the short term. Europe is a global advocate and supporter of low-carbon energy transformation. Although the EU has taken measures such as diversifying imports of natural gas, expanding domestic natural gas production and reserves, building LNG receiving stations, and restarting coal-fired units to boost fossil energy industries and solve short-term energy crises, in the long term, developing green energy to achieve energy independence has become a common consensus in the region. The European Commission and EU member countries, such as Germany and France, have recently adjusted their energy strategies, significantly increased clean energy development targets, and shortened the deployment cycle of clean energy, fully reflecting that clean energy remains the long-term focus of Europe's energy strategy.

The development of the US oil and gas industry may hinder the energy transition process. The US government has released the "U.S. Long-Term Strategy: Path to Net Zero Emissions by 2050," promising to build a zero-carbon electricity grid by 2035 and achieve net zero emissions by 2050, promoting clean energy development and limiting investment in fossil energy. However, after the breakout of the Ukraine crisis, based on the US' strategy of controlling energy in Europe, the Biden administration urged an increase in domestic oil and gas exploration and development. The US drilling rig data show that the number of rigs in May 2022 increased by 58.7% compared to the same period in 2021. The sharp increase in international oil prices has greatly increased the profits of US oil companies, boosting investment in the domestic market and revitalizing the US oil and gas industry. However, this has made the high-cost problem of clean energy more prominent, which may affect commercial promotion and R&D investment in clean energy technologies to some extent.

Russia's national financial losses weaken its low-carbon energy transition. Energy exports are the lifeline of Russia's national economy, accounting for about 45% of Russia's fiscal income. As a major global energy power and carbon emitter, Russia has set a goal to achieve carbon neutrality by 2060. However, after the breakout of the Ukraine crisis, Russia has been hit hard by Western economic, military, technological, cultural, and energy sanctions, as well as restrictions on oil and gas exports. Russia's economy has suffered a severe blow. In the medium and long term, Russia's economic development will increasingly rely on the fossil energy industry. Energy transition will face constraints from national finance, economic development, and technological innovation. The probability of achieving carbon neutrality by 2060 has been greatly reduced.

1.2.4 Critical Minerals Becoming a New Focus of Major Power Competitions

With the acceleration of global carbon neutrality and the rapid development of digital and network technology, the renewable energy industry, led by photovoltaic solar, wind, and electric vehicles, has ushered in significant development opportunities. The rapid development of renewable energy has significantly increased the global demand for critical minerals such as lithium, nickel, cobalt, and copper, making critical minerals a new field of competition among major powers (Manberger and Johansson 2019; Chang et al. 2023). The recent COVID-19 pandemic and geopolitical conflicts have further intensified major powers' competition in this area, stimulating a new round of resource nationalism, and making the security of critical mineral supply chains a frontier of geopolitical competition. Major powers have taken specific measures to gain a competitive advantage in the field of critical minerals.

First, major powers have strengthened top-level design on critical mineral issues. On the one hand, Western powers led by the US have raised the importance of critical minerals at the national strategic level, focusing on using critical minerals in geopolitics to strengthen imports from countries with high resource endowments. The EU has studied the impact of supply disruptions of critical minerals on its industrial competitiveness, and Japan has paid attention to ensuring the supply of critical minerals related to its pillar industries. On the other hand, Western powers have introduced a series of laws and policy plans to enhance the institutional guarantee of their critical mineral strategy. Since 2016, major economies, such as China, the US, the EU, Japan, Canada, the UK, Australia, and India, have formulated policies based on factors such as the importance of critical minerals to national economic security, supply risks, demand levels, and scarcity, and have successively released critical minerals lists. Western countries have also paid close attention to the revision of critical mineral policies, forming a relatively complete institutional system.

Second, major powers are focusing on ensuring the security of critical mineral supply chains. This mainly manifests in three aspects. First, they are ensuring the supply of resource sources and strengthening cooperation with resource-rich countries. The US has strengthened cooperation with resource-rich countries through measures such as increasing economic investment, building resource alliances, and providing security guarantees to enhance the resilience of the supply chain. Second, Western countries are accelerating the localization of supply chains for security reasons. The US is encouraging the localization of the electric vehicle industry supply chain, and the EU has issued the "Key Raw Materials Act" and its supporting action plan to ensure the security of the supply chain through resource recycling, product innovation, and improved utilization. Third, the US is forming exclusive critical mineral supply chains with its allies. The US has established the "Mineral Security Partnership" with several developed countries, formed the "Sustainable Critical Minerals Alliance" and "Critical Mineral Buyers Club" with the Group of Seven (G7), and strengthened critical mineral supply chain cooperation through mechanisms such as the Indo-Pacific Economic Framework, the Quadrilateral Security Dialogue, and Australia, United Kingdom, and United States Security Alliance.

Third, major powers are competing for advantages in the industrial chain. Western powers are strengthening technological breakthroughs and improving the utilization efficiency of critical minerals. The EU and Japan have invested heavily in scientific research support in the areas of critical mineral recycling and utilization efficiency, trying to maintain technological advantages. The US has passed the "Inflation Reduction Act" to subsidize the new energy and battery industries, strengthening its competitiveness. Western countries have strengthened technical protection and third-party country technology reviews in high-tech fields related to critical mineral research and application through legislation, thereby achieving dominance in the industrial chain. In addition, the US is accelerating the "de-China" and "de-risk" processes in the field of critical minerals by various means.

Fourth, the US and other Western countries are trying their best to compete with each other. In view of China's significant advantages in the production, processing, and product supply of critical minerals, in the international context of the Sino–US game, the US and other Western countries have put forward so-called "de-Sinicization" and "de-risking" slogans in the field of critical minerals to accelerate decoupling from China and intensify efforts against China. One effort in this regard is to speed up the formulation and implementation of rule lock-ins. The US and European countries have launched the "Extractive Industries Transparency Initiative" and "Environmental, Social and Governance (ESG)" to monitor the availability of critical minerals, jointly establish a so-called responsible critical mineral supply chain, and restrict China's critical mineral industry. Another focus is the use of national security as an excuse to push resource countries to strengthen the review of mineral cooperation. Under pressure from the US, many countries, including Canada, Australia, and the Democratic Republic of Congo, have adopted investment restrictions, contract reviews, and additional conditions to hinder the normal operations of Chinese companies. Furthermore, the US and European countries are inciting resource nationalism in China and smearing China's image. China–Africa mineral cooperation has grown rapidly in recent years, arousing the concerns of the US and Western countries. The US and Western countries have not hesitated to stir up negative public opinion about China by cultivating the opposition and paying reporters to fabricate rumors, which has had a negative impact on Africa.

1.3 Evolution of the Global Energy Trade Networks

1.3.1 Basic Characteristic Indicators of the Trade Network

This section presents the construction of a complex network based on the global flow of crude oil, natural gas, and coal, along with the basic measurement indicators of the network, to identify the overall structure and dynamic patterns of the global traditional energy trade. The free flow of crude oil, natural gas, and coal resources between countries forms trade interactions. By depicting all trade flows, the global trade network for crude oil, natural gas, and coal can be established. According to complex network theory (Newman 2003; Cong et al. 2023), the directed trade network of crude oil, natural gas, and coal can be represented by a set $G = (V, E)$, where $V = \{v_1, v_2, \ldots, v_N\}$ represents all participating countries in the trade, and E represents all trade interactions between participating countries (Hu et al. 2023). The network structure can be represented by the adjacency matrix of the trade network (Ashfaq et al. 2023). If country v_i exports to country v_j, then $a_{ij} = 1$; otherwise, $a_{ij} = 0$. Following Ji et al. (2014), indicators such as degree and degree distribution, and clustering coefficient are used to describe the overall characteristics of the network. Degree centrality, betweenness centrality, and closeness centrality are also used to depict the trade characteristics of individual countries.

The number of connections a node has with other nodes in the network is called the degree (k) of that node. In the trade network, the degree measures the number of countries with which a trade node has trade relations. Thus, the larger a country's degree, the greater its trade influence and the more significant its role in supporting the stability of the trade network. The specific calculation formula is as follows:

$$\text{Out degree}: k_i^{out} = \sum_{j=1}^{v_N} a_{ij}, i = v_1, v_2, \cdots, v_N \tag{1.1}$$

$$\text{In degree}: k_j^{in} = \sum_{i=1}^{v_N} a_{ij}, j = v_1, v_2, \ldots, v_N \tag{1.2}$$

Degree distribution is used to describe the distribution characteristics of the number of connections across network nodes and to examine the heterogeneity of the network nodes (Chattopadhyay et al. 2020). The calculation formula is as follows:

$$P(k) = \frac{N_k}{N} \tag{1.3}$$

where N_k represents the number of nodes with k connections, and N represents the total number of nodes in the network. In the case of a random network, the degree distribution follows a Poisson distribution, where the number of connections (degrees) of nodes is roughly the same, indicating a fairly uniform network structure. A degree distribution that follows a power-law distribution $p(k) = k^{-r}$ indicates significant heterogeneity among nodes, with the presence of a few "core nodes" and many "peripheral nodes". The importance of each node varies considerably in such networks, which are referred to as scale-free networks (Ma et al. 2021).

Clustering coefficient is a statistical indicator that describes the tightness between network nodes and measures the degree of local clustering within the network (Zuo et al. 2022). It represents the probability that trade partners directly connected to a specific node v_i also have trade relations with each other. It is defined as follows:

$$C_i = \frac{E_i}{k_i \times (k_i - 1)} \tag{1.4}$$

$$C(k) = \frac{1}{N_k} \sum_{j=\{i|k_i=k\}} C_j \tag{1.5}$$

where C_i represents the clustering coefficient of node v_i, k_i represents the number of trade neighbors of node v_i; E_i represents the actual number of connections among these k_i neighbors; and $C(k)$ represents the average clustering coefficient of nodes with degree k. $C_i \in [0, 1]$, and a high clustering coefficient indicate that there are also close trade relationships among the trade neighbors of a node, reflecting a higher level of local trade connectivity.

In-degree centrality represents the import diversity of a node within a network (Shao et al. 2021). The higher the in-degree centrality of a node, the more diverse its imports are. The specific calculation formula is as follows:

$$DC_i = \frac{k_i^{in}}{N-1} \tag{1.6}$$

where k_i^{in} represents the in-degree of country v_i, and N represents the total number of nodes in the network.

Betweenness centrality represents the extent to which a node controls the relationships between other nodes (Li et al. 2021). A higher value indicates stronger intermediary control, reflecting the node's position and resource control capabilities in the trade network. It is defined as:

$$BC_i = 1 - \sum_{s \neq i \neq u} \frac{\sigma_{su}(i)}{\sigma_{su}} \tag{1.7}$$

where BC_i represents the betweenness centrality of country v_i, σ_{su} denotes the total number of shortest paths between country v_s and country v_u, and $\sigma_{su}(i)$ represents the number of shortest paths passing through country v_i connecting country v_s and country v_u.

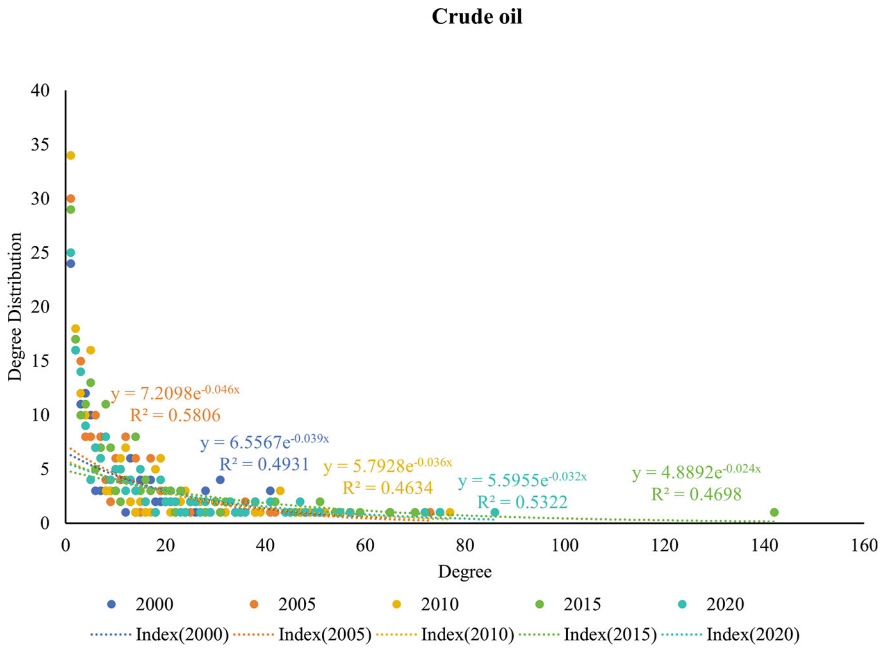
Closeness centrality measures the proximity and ease with which a country can access resources (Li et al. 2020). A higher closeness centrality value indicates that the country has stronger trade connectivity with other countries and easier access to resources. It is defined as follows:

$$CC_i = 1 - \frac{N-1}{\sum_{j \neq i} d_{ij}} \tag{1.8}$$

where CC_i represents the resource acquisition ability of country v_i.

1.3.2 Global Traditional Energy Trade Network

Figure 1.1 shows the evolution of the degree distribution in the global trade networks for crude oil, natural gas, and coal in the years 2000, 2005, 2010, 2015, and 2020, examining the heterogeneity of different trade network nodes. Comparing the degree distributions of crude oil, natural gas, and coal, the power-law characteristics of the coal and crude oil trade networks are more pronounced, exhibiting scale-free network properties. This means that most nodes have relatively few export connections, while a few nodes have many connections, highlighting significant heterogeneity among network nodes and noticeable differences in node importance (Broido and Clauset 2019). The power-law characteristics of the natural gas network are somewhat weaker, which aligns with the uneven distribution of natural gas resources, as these resources are monopolized by a few countries and regions. From 2000 to 2015,



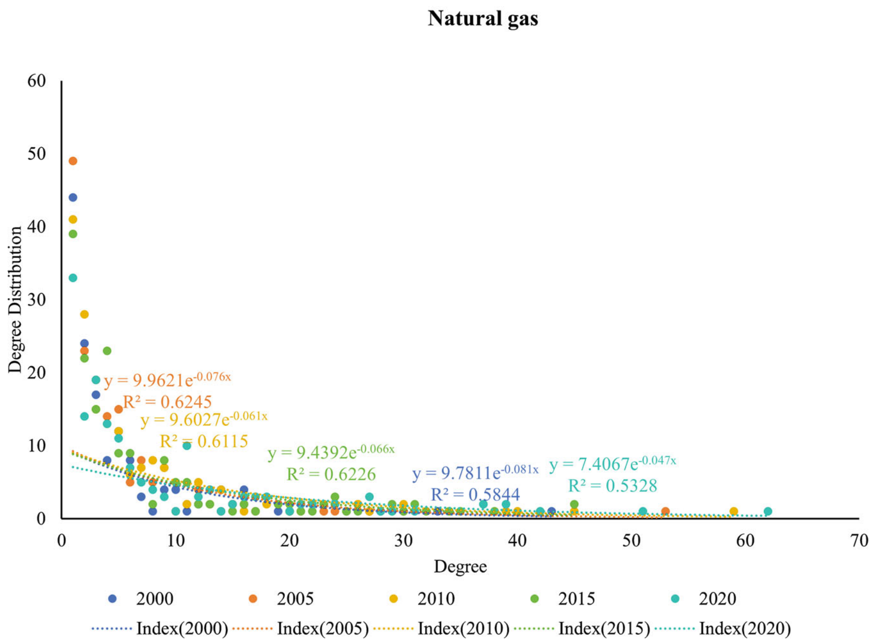


Fig. 1.1 Evolution of the degree distribution in the crude oil, natural gas, and coal trade networks

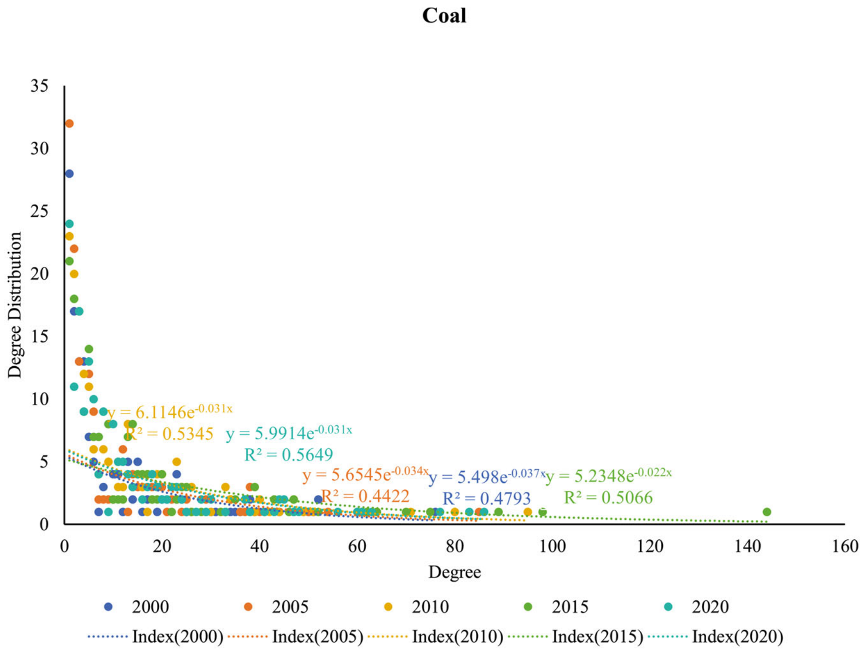


Fig. 1.1 (continued)

the scale-free characteristics of energy trade networks became increasingly evident. As non-renewable natural resources, conventional crude oil, natural gas, and coal are gradually depleting, with limited global exploration and supply growth potential, and resources are increasingly concentrated in a few countries. Environmental issues and climate change pressures related to their use have accelerated the energy transition in various countries, leading to a decrease in the scale-free characteristics of the energy trade networks by 2020.

Figure 1.2 shows the evolution of the relationship between the clustering coefficient and degree in the trade networks for crude oil, natural gas, and coal for the years 2000, 2005, 2010, 2015, and 2020. The clustering coefficient is an important indicator that describes the local tightness of network nodes and can also effectively measure whether there is a clear hierarchical structure within the network. If the $c(k)$ distribution of the network follows a power-law form ($c(k) = k^{-\beta}$), it indicates the presence of a hierarchical structure within the network (Ravasz and Barabasi 2003; Wiedmer and Griffis 2021). The power-law characteristics of the clustering coefficient are more pronounced in the crude oil and coal networks, while the power-law characteristics are slightly weaker in the natural gas network. The clustering coefficient decreases as the degree increases, with all three networks—crude oil, natural gas, and coal—exhibiting a relatively clear hierarchical structure. This indicates that in crude oil, natural gas, and coal networks, countries with smaller degrees have higher local trade tightness, forming tightly connected smaller clusters, whereas countries

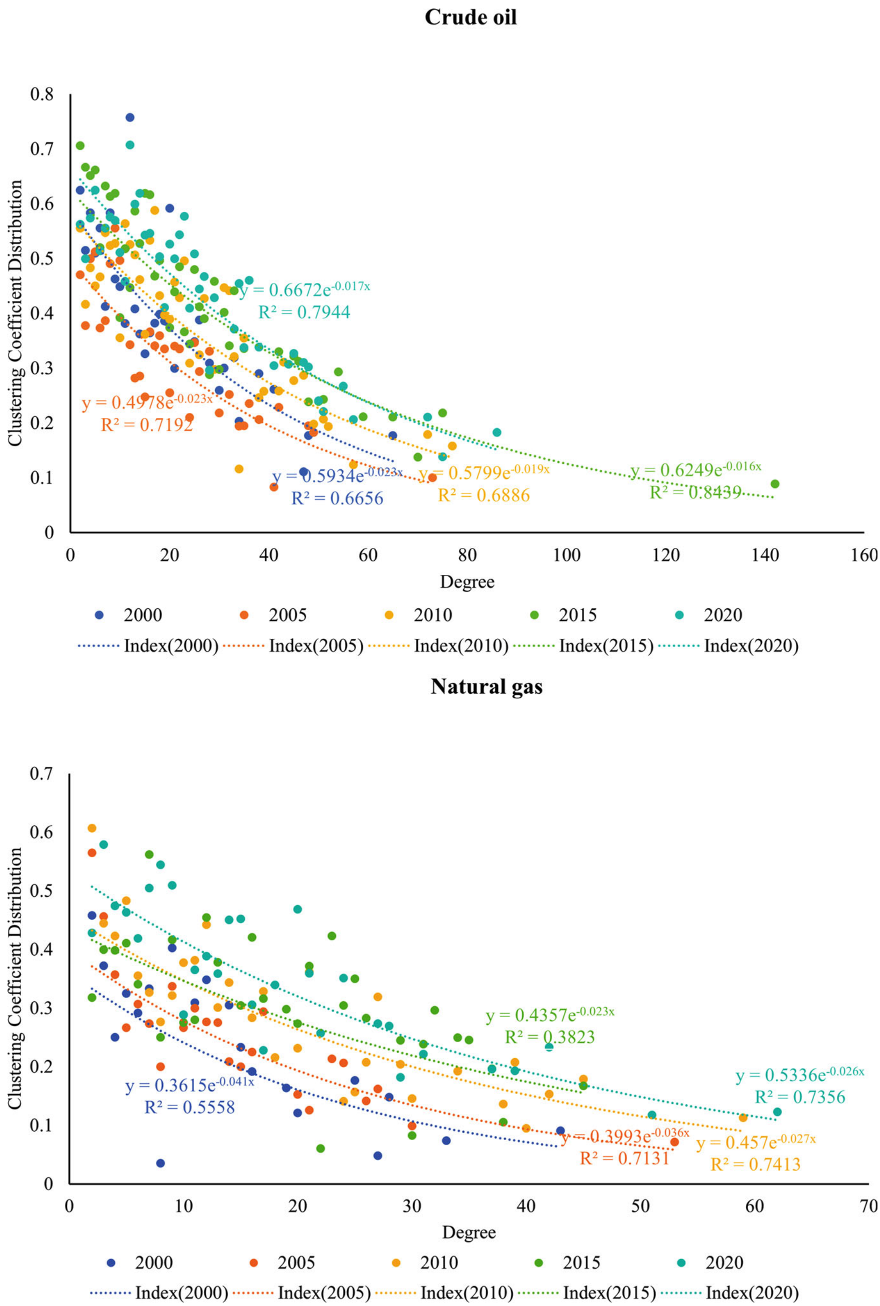


Fig. 1.2 Evolution of the clustering coefficient and degree in the crude oil, natural gas, and coal trade networks

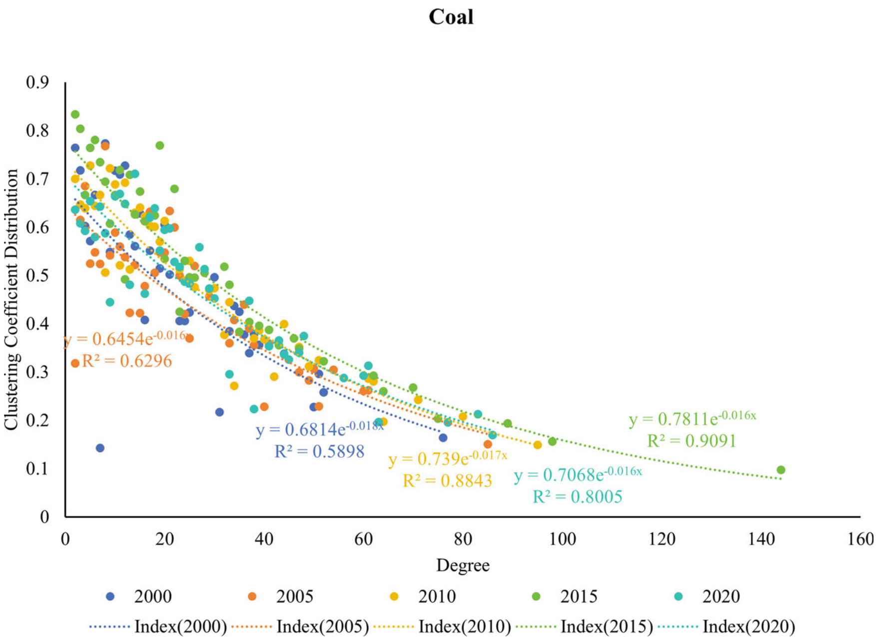


Fig. 1.2 (continued)

with larger degrees experience less frequent trade interactions with their trade partners. Nodes with larger degrees connect smaller clusters into larger, more loosely connected clusters, and then further connect these clusters through nodes with even larger degrees to form the overall network (Radicchi et al. 2004). Therefore, nodes with larger degrees play a crucial "bridge" role in the formation of trade networks. Additionally, when major trading countries meet the trade needs of their trading partners, there is relatively less trade among the trading partners of these major countries. This increases the dependency on the major trading country, enhancing its influence on the trade network, and this characteristic becomes more pronounced over time.

1.3.3 National-Level Traditional Energy Trade Network

Table 1.1 describes the major importers and exporters of crude oil, natural gas, and coal in 2022, along with their respective import and export volumes. It is evident that there are differences among the major importers and exporters for crude oil, natural gas, and coal. China is the largest importer of crude oil; the US is not only a major importer of crude oil but also a significant exporter. Saudi Arabia and Russia are the leading exporters of crude oil, dominating the global crude oil trade market. The US is the largest exporter of natural gas, with an export volume that nearly matches

Mexico's import volume. Russia is also a key exporter of natural gas, exporting more than 98.83 million tons, primarily to European and Asian countries. Mexico is the largest importer of natural gas, mainly importing from the US. India is the largest importer of coal, with an import volume exceeding 234.06 million tons, and Australia is its main coal supplier. Australia is the largest exporter of coal, with an export volume of over 335.97 million tons, primarily exporting to India, Japan, and China. Although China is a major coal producer, it still needs to import large amounts of coal, mainly from Russia and Indonesia.

Figure 1.3 illustrates the evolution of in-degree centrality for the major importers of crude oil, coal, and natural gas. Overall, crude oil has greater import diversity, with an in-degree centrality reaching 0.3. In the crude oil network, the in-degree centrality of the US shows a declining trend, while that of China, South Korea, and India is on the rise. In the natural gas network, the in-degree centrality of China and Japan shows a significant upward trend, indicating that these countries are engaging in trade cooperation with more nations, leading to increasing import diversity. In the coal network, the in-degree centrality of China, India, and South Korea fluctuates upward.

Table 1.1 Major import and export countries and import and export volumes of crude oil, natural gas, and coal (*Unit* 10,000 tons)

Importing Country	Import Volume	Exporting Country	Export Volume
Crude oil			
China	50,828	Saudi Arabia	39,312
USA	35,913	Russia	32,165
India	24,331	Canada	23,271
South Korea	13,826	USA	21,305
Japanese	13,251	Iraqi	21,284
Natural gas			
Mexico	6,003,196	USA	6,014,908
Australia	8,156	Russia	9,883
China	7,723	Qatar	7,727
Japan	7,200	Australia	7,106
Germany	5,689	Norway	6,036
Coal			
India	23,406	Australia	33,597
Japan	18,303	Indonesia	32,139
China	16,274	Russia	21,395
South Korea	12,515	USA	8,709
Germany	4,259	South Africa	7,310

Source UN Comtrade and research group calculations

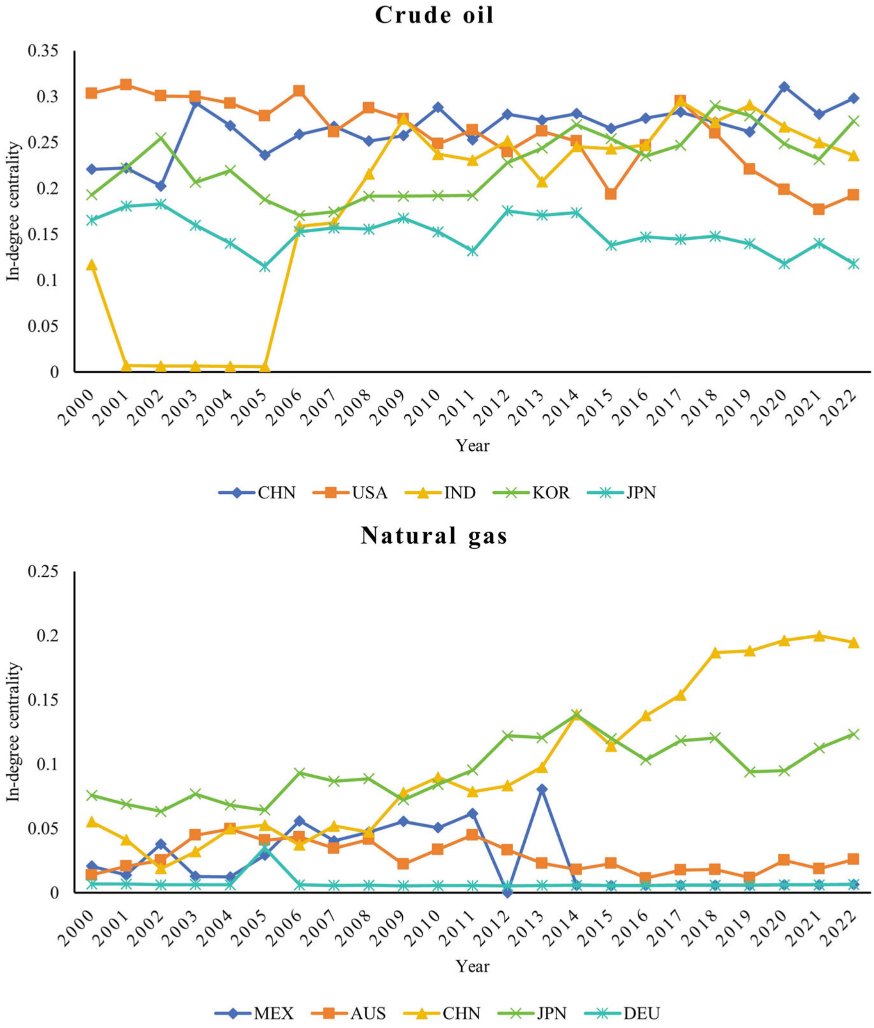


Fig. 1.3 The evolution of the in-degree centrality of major importing countries for crude oil, natural gas, and coal

Figure 1.4 illustrates the evolution of betweenness centrality for the major importing countries of crude oil, coal, and natural gas. The figure shows that the US has an extremely high betweenness centrality in the crude oil network, far surpassing other major importers, although it exhibits a fluctuating downward trend, indicating that it has a very high level of control over crude oil resources. China's betweenness centrality in the crude oil network is second only to that of the US. India's betweenness centrality fluctuates upward, indicating an increasing control over crude oil resources. In the natural gas network, China's betweenness centrality has sharply increased,

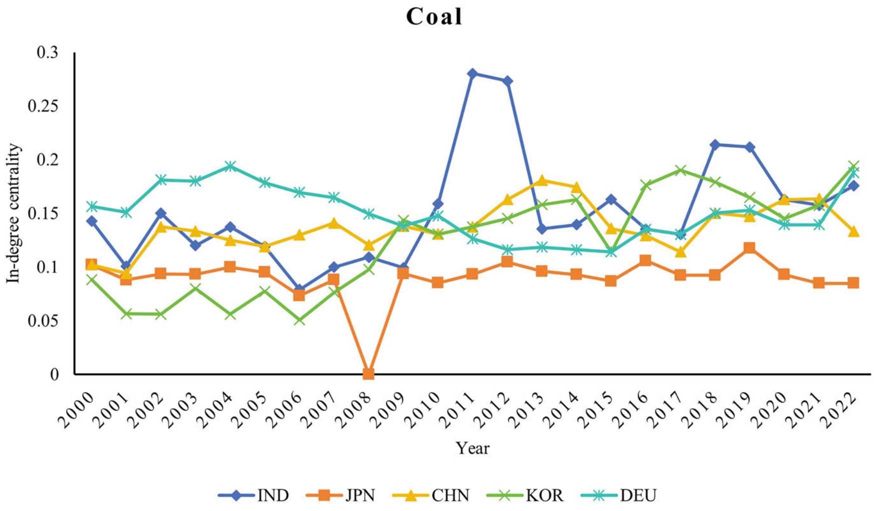


Fig. 1.3 (continued)

while Japan's and Australia's betweenness centrality has gradually declined in recent years, indicating that China's control over natural gas resources has strengthened, while Japan's and Australia's control has weakened. In the coal network, China had the highest level of control after 2013, but this control declined after 2019, likely due to the combined effects of the COVID-19 pandemic and the energy transition.

Figure 1.5 shows the evolution of closeness centrality for the major importing countries of crude oil, coal, and natural gas. In these networks, the closeness centrality of major importing countries is very similar, indicating that their ability to access resources is quite comparable. In the crude oil network, India's closeness centrality has surged, and South Korea's shows a slight increase, indicating an improvement in the ability of both countries to access crude oil. In the natural gas network, the closeness centrality of China, Japan, Mexico, and Australia follows a fluctuating trend of rises and falls. In the coal network, the closeness centrality of China, South Korea, and India increased slightly.

1.4 Conclusion

This chapter systematically analyzes the evolution of the energy strategies of OPEC, Russia, and the US and then forecasts the main trends and characteristics of the global energy landscape and the geopolitical competition under the tri-polar system of oil supply. First, global energy geopolitical competition is becoming increasingly complex. Energy weaponization has become more frequent and pronounced, with both energy exporters and importers using energy as a weapon. Energy market integration and globalization have been damaged, and energy cooperation has become

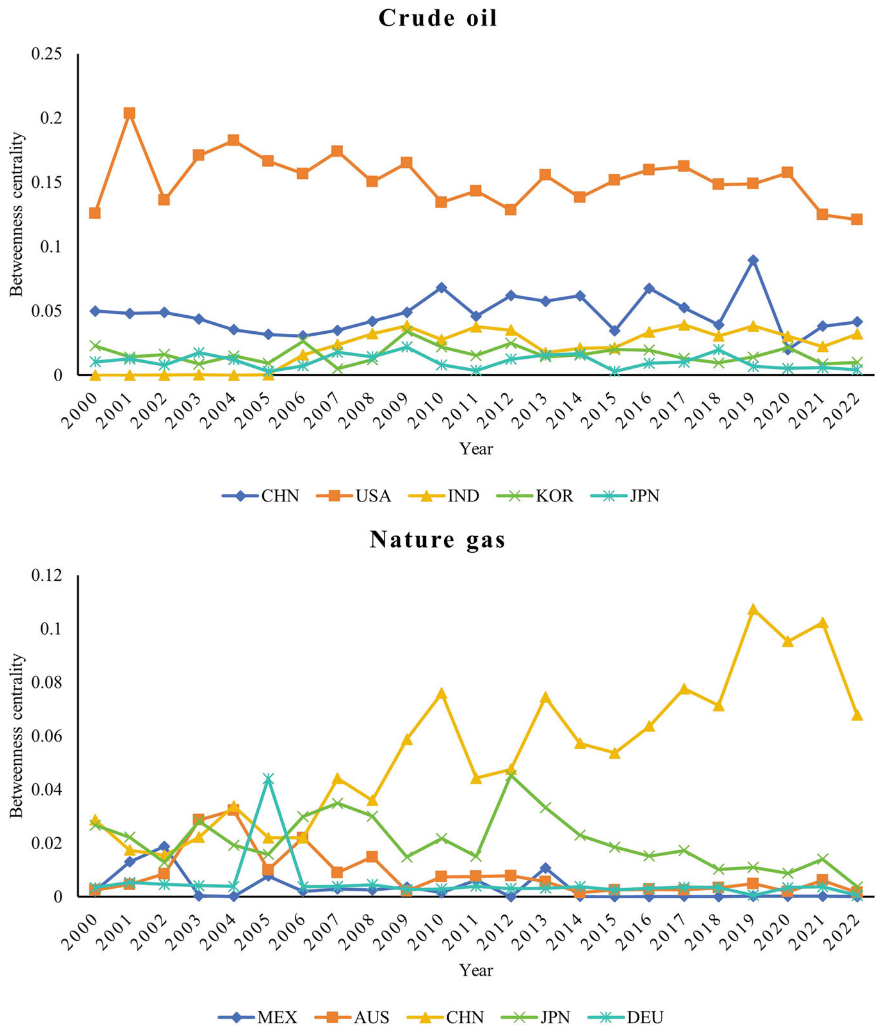


Fig. 1.4 The evolution of the betweenness centrality of major importing countries for crude oil, natural gas, and coal

more “campaign-oriented” and “regionalized.” Second, the fundamental flow of international energy trade has undergone significant changes. Russia has increased its exports to Asia and reduced its exports to Europe, while the US has shifted the focus of its energy exports to Europe and reduced its exports to Asia. Europe has gradually reduced its imports of Russian energy and increased its domestic energy supply. Third, the global energy transition process will be significantly diversified. The EU will accelerate its clean energy transition, while the development of the US oil and gas industry may hinder the energy transition process. Russia’s low-carbon

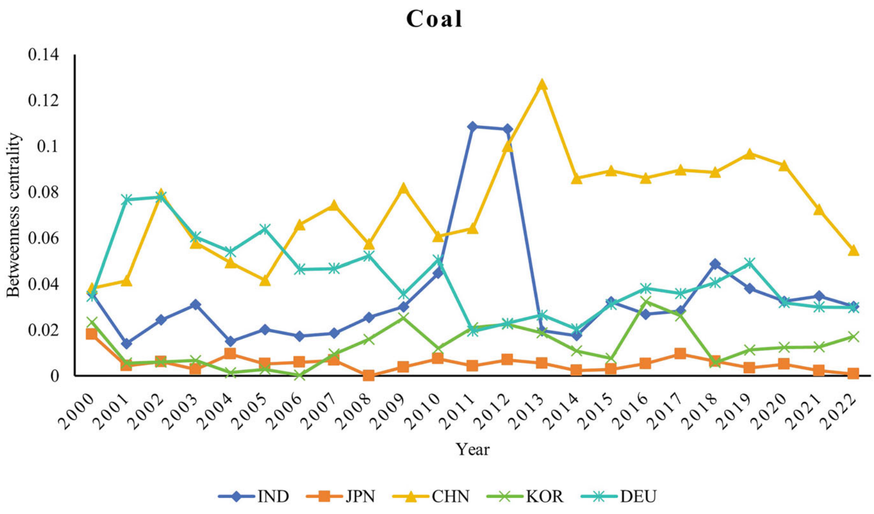


Fig. 1.4 (continued)

energy transition lacks strength. Lastly, clean energy has become a new focus of major power competition. Major powers are competing for advantages in critical minerals and core technologies, with the US and Western countries striving to exclude China from the clean energy supply chain.

In addition, this chapter also examines the trade patterns of traditional energy sources—crude oil, natural gas, and coal—using metrics such as degree distribution, clustering coefficient, in-degree centrality, betweenness centrality, and closeness centrality. Comparing the degree distributions of crude oil, natural gas, and coal, it is evident that coal and crude oil resources are more monopolistic, with natural gas being less so. From 2000 to 2015, the power-law characteristics of traditional energy became increasingly pronounced, but from 2015 to 2020, these characteristics weakened. This is consistent with the acceleration of the energy transition due to environmental problems and climate change pressures. China is a major importer of crude oil, natural gas, and coal, with an increasing trend in its in-degree centrality, indicating more diversified imports. China has strong betweenness control in both natural gas and coal trade networks, while its betweenness control in the oil trade network is second only to the US. China's closeness centrality is relatively lower than that of other major importers, indicating a relatively weaker ability to access traditional energy sources.

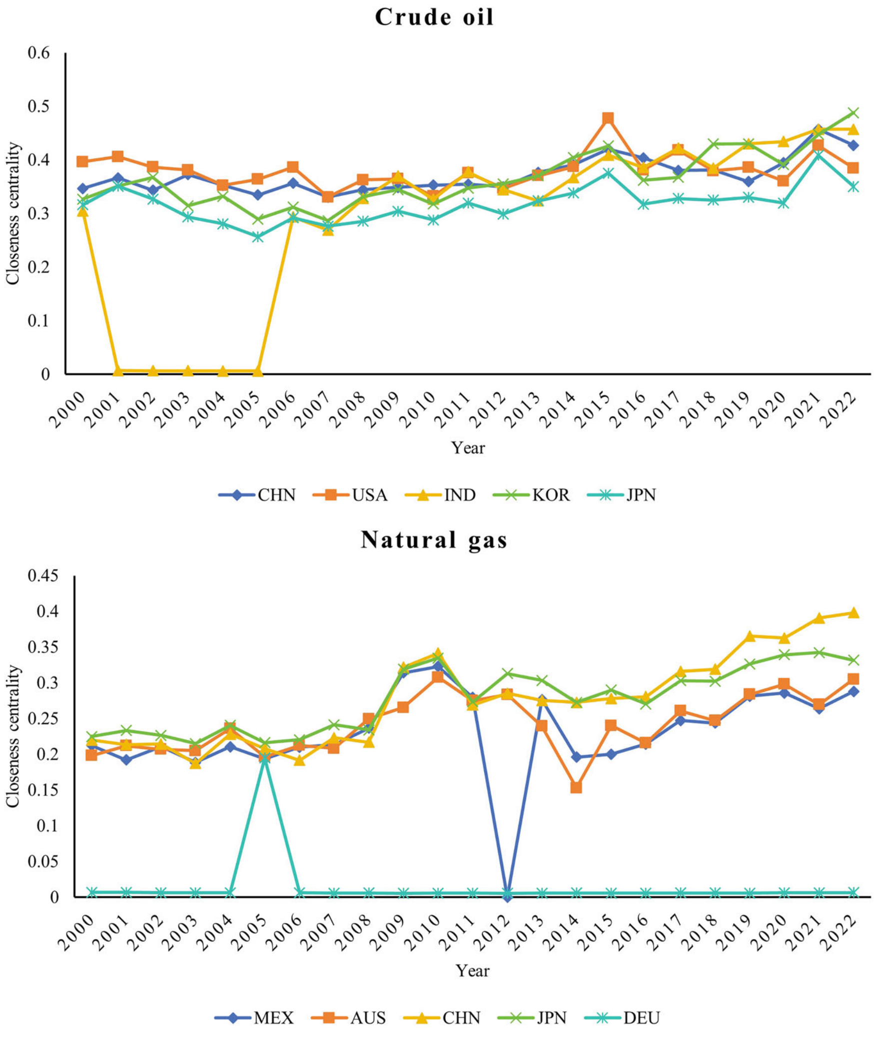


Fig. 1.5 The evolution of the closeness centrality of major importing countries for crude oil, natural gas, and coal

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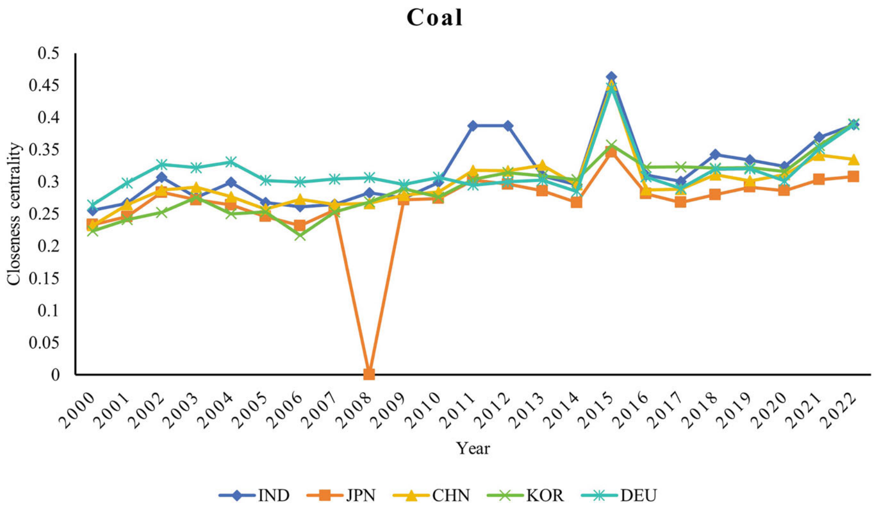

Fig. 1.5 (continued)

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Chapter 2
Challenges and Opportunities Facing China's Energy Security

Chang Liu, Yu Song, and Xiaolei Sun

Abstract As the world's largest energy importer, China's energy security is profoundly affected by the international energy system. In the face of new changes in the pattern of energy supply and demand and new trends in international energy development, the Chinese government has put forward a new energy security strategy of "four revolutions and one cooperation." China been continuously promoting structural reform of the energy supply side and enhancing its ability to guarantee energy security. It has also built a multi-wheel-driven supply system and has been accelerating the pace of its green and low-carbon energy transformation. However, under the influence of COVID-19 and geopolitical factors, the uncertainty and instability of the international energy market have increased, and structural contradictions in the domestic energy market still exist, so energy security is facing new challenges. This chapter focuses on the current situation of energy supply security in China to present a systematic review of the problems and challenges faced by the nation's energy security and a summary of the opportunities and strategies for ensuring energy security in the new era.

Keywords Energy supply security · Energy challenges · Energy opportunities

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2.1 Status of Energy Supply Security

China's energy supply has formed a multi-wheel-driven energy production system comprising coal, oil, gas, electricity, new energy, and renewable energy.

2.1.1 Increasing Capacity for Energy Production Security

Steady Growth in Energy Production, with Obvious Results in Energy Supply Preservation

China has made efforts to enhance its energy production and security capacity, focusing more on the role of coal as a "ballast stone" while continuously enhancing oil and gas exploration and development and developing a diversified and clean power supply system. These efforts have extensively safeguarded the stable development of the economy and society, as well as meeting the growing energy demand of the people's livelihood. According to the 2023 Statistical Bulletin of the National Economic and Social Development of the People's Republic of China published by the National Bureau of Statistics as shown in Fig. 2.1 and Table 2.1, China's total primary energy production in 2023 amounted to 4.83 billion tons of standard coal, a year-on-year increase of 4.2%; raw coal production was 4.71 billion tons, a year-on-year increase of 3.4%; and crude oil production was 20,902.066 million tons, a year-on-year increase of 2.1%. Its natural gas production and power generation were 945,644 million kilowatt-hours and 23,243.4 billion cubic meters, year-on-year increases of 5.6% and 6.9%.

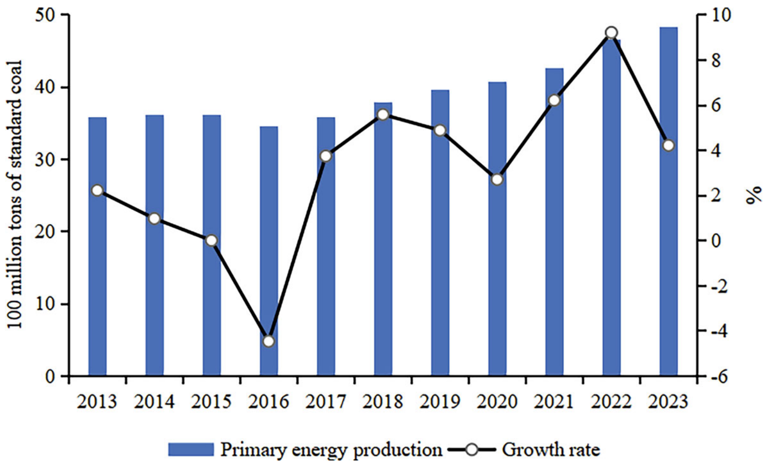

Fig. 2.1 Total energy production and growth rate, 2013–2023. (*Source* National Bureau of Statistics)

Table 2.1 Total production of major energy species, 2013–2023

Particular year	Raw coal production (billions of tons)	Crude oil production (tons)	Natural gas production (billion cubic meters)	Electrical energy (billions of kilowatt-hours)
2013	39.74	20,991.90	1208.58	54,316.35
2014	38.74	21,142.90	1301.57	57,944.57
2015	37.47	21,455.58	1346.10	58,145.73
2016	34.11	19,968.52	1368.65	61,331.60
2017	35.24	19,150.61	1480.35	66,044.47
2018	36.98	18,932.42	1601.59	71,661.33
2019	38.46	19,101.41	1753.62	75,034.28
2020	39.02	19,476.86	1924.95	77,790.60
2021	41.26	19,888.11	2075.84	85,342.50
2022	45.60	20,472.20	2201.10	88,487.10
2023	47.10	20,902.60	2324.30	94,564.40

Source National Bureau of Statistics

The layout of coal production and development has been continuously optimized. Coal production centers accelerated to concentrate in areas with good resource endowment and mining conditions. According to the National Bureau of Statistics, coal enterprises above the national scale produced 4.66 billion tons of raw coal in 2023, a year-on-year increase of 2.9%. The proportion of production in billion-ton coal-producing provinces has continued to increase. In 2023, the number of provinces with raw coal production of more than 100 million tons increased to 7 from 6 in the previous year. Among them, provinces with raw coal production exceeding one billion tons are still Shanxi Province and Inner Mongolia Autonomous Region. Five provinces have a raw coal production of 100 million tons to one billion tons: Shaanxi Province, Xinjiang Uygur Autonomous Region, Guizhou Province, Anhui Province, and Henan Province. Henan Province's output has returned to over 100 million tons since 2020. The combined output of the seven provinces was 4.131 billion tons, increasing by 3.1% year-on-year, accounting for 88.6% of the country's raw coal production above the scale, an increase of 0.1 percentage points compared to 2022. The production of the seven provinces was 4.131 billion tons, a year-on-year increase of 3.1%.

Domestic oil and gas enterprises have been increasing their exploration efforts to promote the implementation of the "seven-year action plan." The China Petroleum Institute of Economics and Technology released a "2023 domestic and foreign oil and gas industry development report" that shows China's oil and gas exploration and development investment of about 390 billion yuan, with record-high exploration and development investments. The report also shows new geological oil reserves of about 1.3 billion tons and natural gas reserves of nearly trillion cubic meters. There have

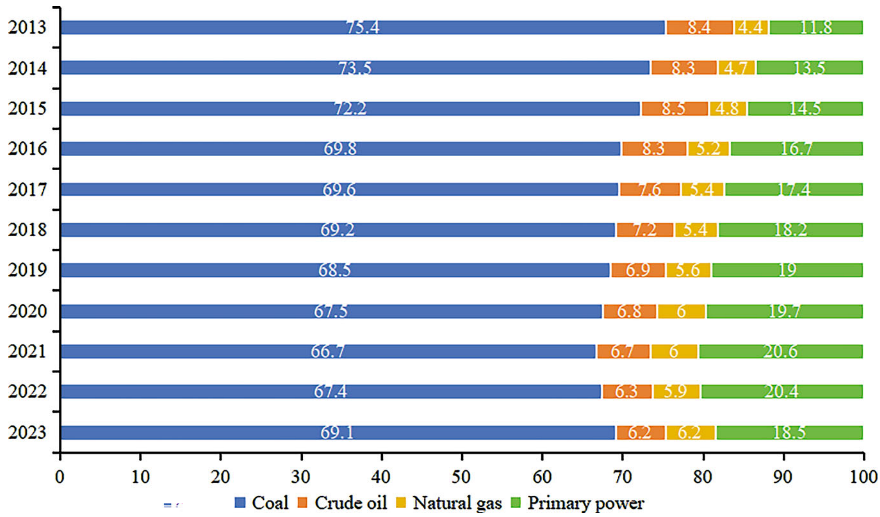

Fig. 2.2 Structure of energy production, 2013–2023. (*Source* National Bureau of Statistics)

also been significant advancements in oil and gas exploration and the development of theories, technology, equipment progress, and deep water exploration support.

New Breakthroughs in Renewable Energy Generation

In 2023, China's installed renewable energy capacity grew by more than 19.5% year-on-year, the largest increase in a decade. Its total installed power reached 2.9 billion kilowatts, an increase of 13.9% year-on-year. Renewable energy has become a new force to ensure power supply.

Figure 2.2 illustrates that the share of different varieties of energy in the past decade shows different trends. The proportion of raw coal production has fallen to below 70%, down 8.4 percentage points in 2021 compared to 2013. As the "ballast" of China's energy supply, the proportion of raw coal production rebounded in 2022 by 2.2 percentage points compared to 202. In 2023, the tense situation of coal supply and demand was effectively reversed, and its proportion rebounded by 1.7 percentage points compared to 2022.

Varying Increases in Energy Imports

In 2023, China's imports of energy products rose to varying degrees. It imported 563.99 million tons of crude oil, up by 11% year-on-year; 119.97 million tons of natural gas, up 9.9% year-on-year; and 474.42 million tons of coal, up by 61.8% year-on-year as presented in Fig. 2.3. Together, China imported 1.158 billion tons of

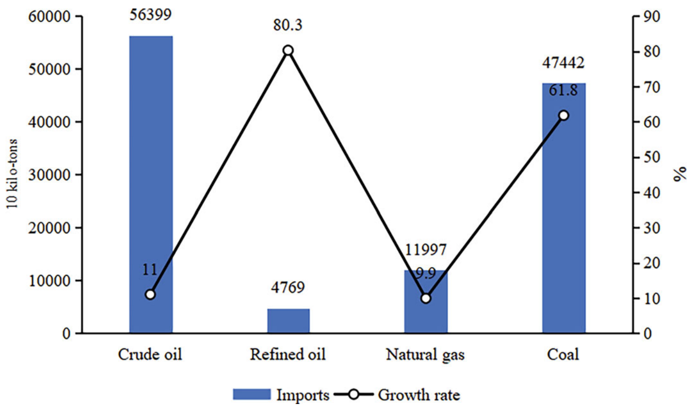

Fig. 2.3 Energy imports and growth rate, 2023. (*Source* National Bureau of Statistics)

crude oil, natural gas, coal, and other energy products, an increase of 27.2%. Table 2.2 shows that its crude oil imports hit a record high for the year, with annual imports equivalent to 11.28 million barrels per day (bpd) of imports, breaking the previous record of 10.81 million bpd of imports set in 2020. The main reason behind the strong crude oil imports is that fuel demand grew in 2023 as the economy recovered, driving the processing of oil types in refineries into normalization. The nation's natural gas imports were the second highest on record, after the 121.4 million tons imported in 2021. At the beginning of 2022, imports were greatly affected by the international energy supply and demand situation, with coal import prices much higher than domestic prices. To reduce the cost of imports and safeguard the domestic coal supply, China decided to implement zero tariffs on coal imports. This drove a significant increase in 2023 international coal imports, which had a good regulatory effect on the domestic coal market.

The sources of China's crude oil and natural gas imports remain diverse as can be seen from Fig. 2.4. In 2023, China imported a total of 563.99 million tons of crude oil from 48 countries. Presently, the sources of China's crude oil imports are relatively decentralized, and the Middle East, Southeast Asia, South America, and the North Caspian Sea are the four major source regions of China's crude oil imports. According to the statistics of the General Administration of Customs, in 2023, China's top 10 sources of crude oil imports were Russia, Saudi Arabia, Iraq, Malaysia, the United Arab Emirates, Oman, Brazil, Angola, Kuwait, and the US, whose share accounted for 87.70% of China's total crude oil imports for the year. Following the impact of the Russia–Ukraine conflict, China's imports of crude oil from Russia have increased significantly. The difference in the volume of imported crude oil between Russia and Saudi Arabia was 21.0659 million tons. Due to geopolitical conflicts and other reasons, China has shrunk its crude oil imports in the Middle East, Africa, and other regions, whereas its imports of Malaysian blended crude oil (Southeast Asia) show a year-on-year increase. Furthermore, energy trade cooperation between China and

Table 2.2 Energy imports, 2013–2023

Particular year	Coal and lignite (tons)	Crude oil (tons)	Natural gas production (billion cubic meters)	Electricity (billion kWh)
2013	32,702	28,174	525	75
2014	29,122	30,837	591	68
2015	20,406	33,548	611	62
2016	25,555	38,101	746	62
2017	27,092	41,946	946	64
2018	28,210	46,189	1246	57
2019	29,977	50,568	1332	49
2020	30,361	54,201	1397	48
2021	32,294	51,292	1675	–
2022	29,320	50,828	1508	–
2023	47,442	56,399	1656	–

Source National Bureau of Statistics, General Administration of Customs

Russia in the resource market, geographic location, etc. has increased, with obvious complementary advantages.

China's source countries of natural gas imports have also been increasing, with the main contributors being Turkmenistan, Australia, and the US as shown in Fig. 2.5.

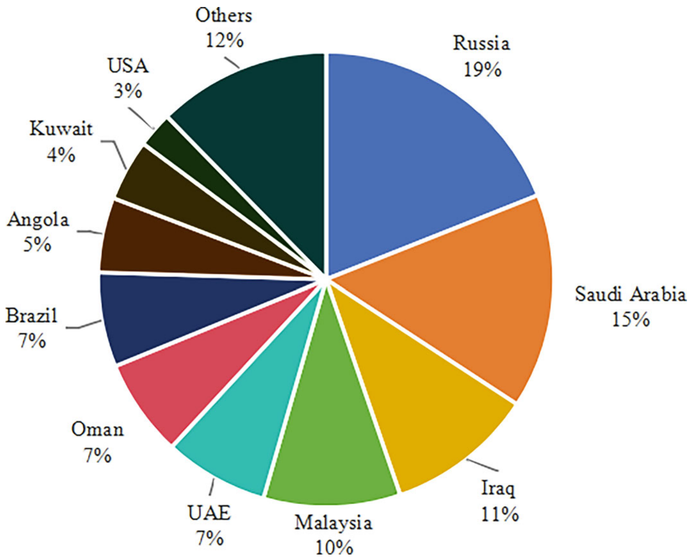

Fig. 2.4 Structure of China's crude oil import sources in 2023. (*Source* National Bureau of Statistics, General Administration of Customs)

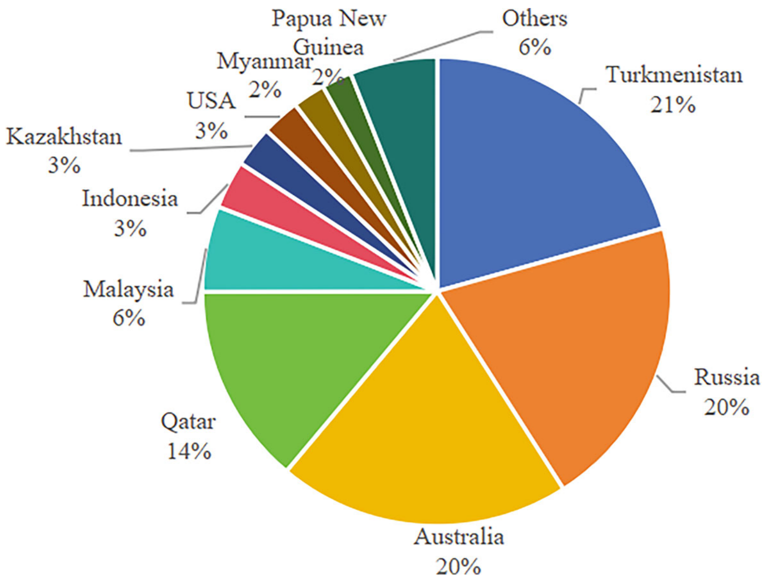

Fig. 2.5 Structure of China's natural gas import sources in 2023. (*Source* National Bureau of Statistics, General Administration of Customs)

In 2011, China had only one pipeline gas import channel in Turkmenistan, totaling about 14.25 billion cubic meters. Its liquefied natural gas (LNG) imports came from 12 countries and regions, with four major countries—Australia (29.79%), Qatar (19.07%), Indonesia (16.36%), and Malaysia (12.85%). In 2023, China's pipeline gas imports were 67.1 billion cubic meters (48.65 million tons), increasing to five pipeline import routes: Turkmenistan, Tajikistan, Russia, Uzbekistan, and Myanmar. By contrast, the source countries and regions for LNG imports expanded to 21 countries and regions, with Australia, Qatar, Russia, Malaysia, Indonesia, the US, and Papua New Guinea as the major import source countries.

2.1.2 Continuous Transformation of the Energy Consumption Structure Toward Cleaner and Lower Carbon Emissions

Low Growth in Energy Consumption

Since 2013, China's total energy consumption has been in low-speed growth mode, supporting the medium- to high-speed development of the economy with a lower growth rate of energy consumption. In 2023, the national total energy consumption was 5.72 billion tons of standard coal, an increase of 5.7% over the previous

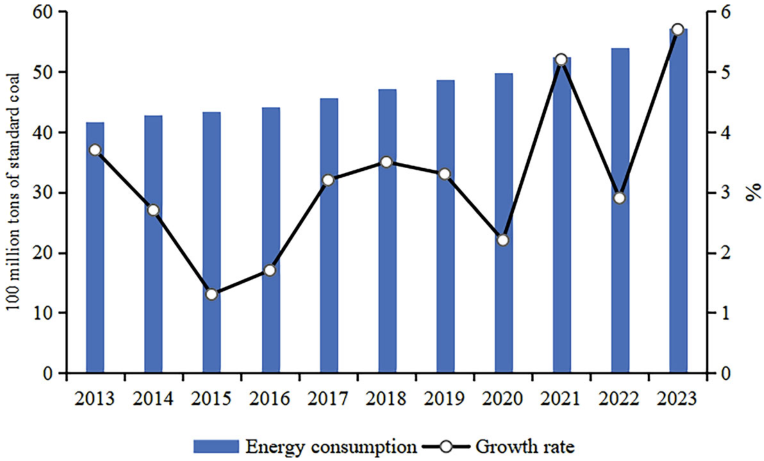

Fig. 2.6 Total energy consumption and growth rate, 2013–2023. (*Source* National Bureau of Statistics)

year as shown in Fig. 2.6. Table 2.3 presents the consumption of major species from 2013 to 2022. In 2023, coal consumption increased by 5.6%, crude oil consumption by 9.1%, natural gas consumption by 7.2%, and electricity consumption by 6.7%. Coal consumption accounted for 55.3% of total energy consumption, a decrease of 0.7 percentage points from the previous year. Clean energy consumption, such as natural gas, hydropower, nuclear power, wind power, and solar power, accounted for 26.4% of total energy consumption, an increase of 0.4 percentage points. Since 2013, China's total energy consumption has shown a year-on-year trend of increase, with a compound annual growth rate of about 3.8%. The increases in 2020 and 2022 were lower than the CAGR due to the impact of the epidemic, whereas the increases in 2021 and 2023 were higher than the CAGR due to the low base in 2020 and 2022.

Continuous Transformation of the Energy Consumption Structure Toward a Cleaner and Lower-Carbon Environment

Figure 2.7 shows that China's trend toward the low carbonization of energy consumption remains unchanged, and its share of low-carbon energy consumption is steadily increasing. Its total energy consumption showed an increase of 5.7% in 2023 compared to the previous year. The share of non-fossil energy consumption in total energy consumption in 2023 increased by 0.2 percentage points compared to the previous year, while the share of coal consumption in total energy consumption decreased by 0.7 percentage points. Oil increased by 0.4 percentage points, and natural gas increased by 0.1 percentage points.

In terms of energy varieties, the share of coal in China's energy consumption has been decreasing over the past decade, from 67.4% in 2013 to 55.3% in 2023. By

Table 2.3 Consumption of major energy species, 2013–2022 (in tons of standard coal)

Particular year	Coals	Petrochemical	Petroleum	Transmission, nuclear, wind, etc
2013	280,999.36	71,292.12	22,096.39	42,525.13
2014	279,328.74	74,090.24	24,270.94	48,116.08
2015	273,849.49	78,672.62	25,364.40	52,018.51
2016	270,207.78	80,626.52	27,020.78	57,963.93
2017	270,911.52	84,323.45	31,397.03	61,897.00
2018	273,760.00	87,696.00	36,192.00	66,352.00
2019	281,280.60	92,622.70	38,999.00	74,585.70
2020	283,540.70	93,683.00	41,858.00	79,231.00
2021	293,975.90	97,816.70	46,278.80	87,824.60
2022	304,042.00	96,839.00	45,444.00	94,675.00
2023	316,316.00	104,676.00	49,764.00	101,244.00

Source National Bureau of Statistics

contrast, the share of clean energy consumption increased from 15.5% in 2013 to 26.4% in 2023, whereas the share of oil consumption did not change significantly.

Renewable energy plays an increasingly obvious role in guaranteeing the energy supply. China's 2023 non-fossil energy generation capacity exceeded 3.3 trillion kilowatt-hours. According to the National Bureau of Statistics data in 2023, China's hydropower generation capacity was 1,285.85 billion kilowatt-hours, a decrease of 4.9 percentage points over the previous year. Its nuclear power generation capacity

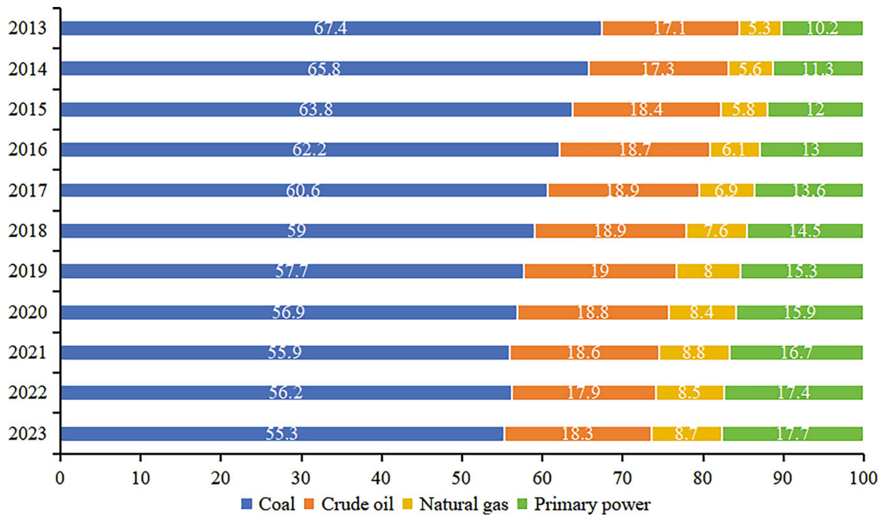

Fig. 2.7 Energy consumption structure, 2013–2023. (*Source* National Bureau of Statistics)

was 434.72 billion kilowatt-hours, an increase of 4.1 percentage points over the previous year, whereas its wind power generation capacity was 885.87 billion kilowatt-hours, an increase of 16.2 percentage points over the previous year. Its solar power generation capacity was 584.15 billion kilowatt-hours, an increase of 36.7 percentage points over the previous year. According to data from the biomass energy industry branch of the China Industry Development Promotion Association, China's biomass power generation capacity was about 198 billion kilowatt-hours in 2023, an increase of 15.6 billion kilowatt-hours compared to the previous year. The country's 2023 national renewable energy annual generation capacity was about 3 trillion kilowatt-hours, accounting for about one-third of the whole society's electricity consumption. Notably, wind power and photovoltaic power generation capacity was 1.43 trillion kilowatt-hours, accounting for about 15.8% of the total electricity consumption of the whole society, which is higher than the global average level of 13%.

2.1.3 Continuous Improvement of the Layout of Strategic Energy Import Corridors

In terms of cross-border and cross-regional energy infrastructure connectivity, China has gradually formed four major strategic oil and gas corridors in the north-west, north-east, south-west, and eastern seas and has realized power interconnections with seven neighboring countries, with a significant increase in the level of energy infrastructure interconnectivity as presented in Table 2.4. In the past decade, China's international energy cooperation has shown great progress. To safeguard national energy security, PetroChina has strengthened energy cooperation with Russia, Myanmar, and Central Asian countries. A number of landmark major projects, such as the China–Russia East Natural Gas Pipeline, China–Myanmar Crude Oil Pipeline, China-Central Asia Natural Gas Pipeline Line C, and China–Russia Crude Oil Pipeline Repeater, are now operational. The layout of transnational overland pipelines in the northeastern and southwestern directions have been completed with the pipelines passing through the Strait of Malacca. Together with the sea route through the Strait of Malacca, these regions constitute China's energy import pattern of "three seas and one land" and "four directions" (Long et al. 2023). By the end of 2022, the crude oil-receiving capacity of China's sea corridor exceeded 450 million tons/year. Its LNG-receiving capacity was 110 million tons/year. The crude oil pipeline capacity of the three major land corridors was 63 million tons/year, and the natural gas pipeline capacity was 98.2 billion cubic meters/year.

On the domestic front, after years of development, China's oil and gas "national network" preliminary formation from 2013 to 2023 included a total mileage of the long-distance oil and gas pipeline from 98,500 to 190,000 km, an increase of about 80%. According to the national "Medium- and Long-term Oil and Gas Pipeline Network Plan," the length of the national oil and gas pipeline network will reach

Table 2.4 Four major oil and gas import corridors

Conduit	Channel composition	Commissioning time	Transport capacity	Resource sites (including potential)
Northwest	China–Russia Crude Oil Pipeline and Duplicate Lines	2011	3000×10^4 t/a	Georgia
	China–Russia Gas Pipeline East (CRGP)	2019	380×10^8 m^3/a	Georgia
	China–Russia Gas Pipeline Far East	Program	100×10^8 m^3/a	Georgia
Northwestern	China–Kazakhstan crude oil pipeline	2005	2000×10^4 t/a	Central Asia, Caspian Sea, Russia
	China–Central Asia Gas Pipeline Lines A, B and C	2009	550×10^8 m^3/a	Central Asia, Caspian Sea
	China–Central Asia Gas Pipeline Line D	Program	300×10^8 m^3/a	Central Asia, Caspian Sea
	China–Russia Western Gas Pipeline	Program	300×10^8 m^3/a	Georgia
	China–Mongolia–Russia gas pipeline	Potentially	300×10^8 ~ 500×10 $m^{8\,3}$/a	Georgia
Southwestern	China–Myanmar crude oil pipeline	2017	2200×10^4 t/a	Middle East, Africa, Americas
	China–Myanmar gas pipeline	2013	120×10^8 m^3/a	Myanmar (or Burma)
At sea	Southbound corridor through the South China Sea and Southeast Asian waters, and northbound corridor toward the Russian Far East and the Arctic	Currently available	Oil: $60{,}000 \times 10^4$ t/a Natural gas: 1258×10^8 m^3/a	Asia–Pacific, Middle East, Africa, Americas, Russia
		Under construction	Natural gas: 800×10^8 m^3/a	

240,000 km in 2025, of which 163,000 km will be natural gas pipeline network mileage, and the four major strategic oil and gas import corridors of the north-west, north-east, south-west, and the sea will be further consolidated.

2.1.4 Initial Results in Building an Energy Security Reserve System

China's coal reserve capacity building has significantly improved. Unlike the US and developed countries in Europe, which mainly consume oil and gas, coal is the main source of energy in China. Coal is one of the characteristics of China's energy endowment and is its mainstay for securing the energy supply. Since the release of its 14th Five-Year Plan, China's coal reserve capacity has greatly improved, and the government's dispatchable reserve resources have continued to increase. At present, China has formed 100 million tons of government dispatchable coal reserve capacity, which plays an important role in coal supply. National Development and Reform Commission monitoring data show that in November 2023, China's northern region entered the heating season, and the national unified power plant storage of more than 200 million tons of coal—available for 33 days, the highest level in history—can effectively safeguard the needs of peak shifting.

The construction of the oil reserve project continues to advance (Long et al. 2022). In 2001, China explicitly proposed establishing strategic oil reserves. From the currently available latest oil reserve data published by the state, as of mid-2017, China has built nine national oil reserve bases, using the above reserves and some social enterprises to reserve 37.73 million tons of crude oil in their storage capacity. Overall, the construction of the country's oil reserve system has achieved positive results, but compared with developed countries, there are still certain gaps in scale, structure, system, and other aspects. Since the release of China's "14th Five-Year Plan," the construction of the oil reserve project has been continuously promoted, and the scale of the reserve is developing and expanding. In December 2022, the Hubei Coal Geological Prospecting and Surveying Team undertook two underground water sealing cave exploration projects: Jiyuan Underground Water Sealing Cave Depot of the Fourth Phase Project of the National Petroleum Reserve and Zhoushan State Reserve Plain Cave Depot of Zhejiang Province. These projects provided the basis for site selection and the next step of the construction of the cave reservoir. After the completion of the subsequent site selection, the construction of large-scale underground water oil storage caves can be used to solve the problem of a shortage of local oil storage facilities and to promote the development of the local economy at the same time.

In February 2023, China's one-time construction of the largest commercial crude oil reserve project—Dongying crude oil commercial reserve project oil—delivered success. The project officially entered the trial production and commercial operation phase, which is of great significance in enhancing the national oil supply guarantee capacity, promoting the dynamic balance of oil supply and demand, stimulating the rapid growth of the energy trade, and coping with major emergencies. Furthermore, China has strengthened the top-level design of its national reserves and improved its reserve management system, centralizing and unifying the management of the central government's reserves and integrating the National Petroleum Reserve Center into the newly established State Bureau of Grain and Material Reserves.

The construction of China's natural gas storage capacity has been significantly enhanced. Since 2014, the infrastructure has been increasingly improved, the level of interconnection has been significantly enhanced, the construction of gas storage facilities has been accelerated, and a "national network" has been formed. The mileage of natural gas pipelines in China has increased from 59,000 km to 124,000 km. The China–Russia East Line (except for the Nantong–Luji section under construction), the West–East Natural Gas Pipeline 3 (except for the Zhongwei–Zaoyang section under construction), the Shaanxi-Beijing Line ¾, and other large-scale trunk pipeline projects have been completed and are now operational. The national natural gas trunk pipelines, which initially showed the status of "should be connected as much as possible," experienced "hard bottlenecks." The "hard bottlenecks" have been eliminated, the efficiency of the regional deployment of resources has steadily improved, and the supply guarantee capacity has been further strengthened. The construction of underground gas storage tanks and coastal gas receiving terminals is increasingly improving, and the gas storage capacity has increased by more than four times. The responsibilities of each main body of the industrial chain for gas storage have been gradually clarified, and the exploration of market-oriented price models, such as peak-valley price difference and the "two-part" fee for gas storage services, has seen steady promotion. The formation of the market mechanism for gas storage and peaking auxiliary services and the enhancement of the emergency peaking capacity of natural gas are other achievements.

2.1.5 Increasing International Oil and Gas Discourse and Influence

In recent years, China has accelerated the opening and development of the futures market while focusing on improving the discourse and influence of spot trading venues in international trade. It has continuously promoted the construction of oil and gas trading and pricing, centered mainly on the Shanghai Oil and Gas Trading Center and the crude oil futures market of the Shanghai International Energy Exchange, to further enhance its discourse and influence in the international energy pricing market.

As an important force in the construction of an international oil and gas trading and pricing center, Shanghai Oil & Gas Trading Center has carried out a lot of exploration and innovation in natural gas spot trading since its trial operation in 2015. The trading center platform has formed a diversified trading mode and launched a series of innovative trading products, with the main trading modes including listing, bidding, pre-sale, and group purchase, and the main trading products including natural gas, oil products, facility capacity, and information services. In 2022, the bilateral trading volume of natural gas in the Shanghai Oil & Gas Trading Center reached 92.858 billion cubic meters, maintaining the position of Asia's largest natural gas spot trading platform in Asia (Ji et al. 2022a). The trading center has more than 3000 members, covering domestic and foreign enterprises in oil and gas, finance, and other fields.

In addition, the exchange works closely with the Global Trade Monitoring Center of the General Administration of Customs to publish three comprehensive import CIF price indices for LNG, crude oil, and LPG. It also compiles and publishes the "China Imported Spot LNG CIF Prices," reflecting the prices of LNG shipments to be delivered from mainland China's LNG receiving terminals in the next three calendar months, further enriching China's oil and gas price indices. The exchange also compiles and publishes the "China Import Spot LNG CIF Price," which reflects the price of LNG shipments to be delivered at LNG receiving stations in mainland China in the next three calendar months.

In 2018, the Shanghai International Energy Exchange listed Shanghai crude oil futures (SC) denominated in RMB, ensuring that China has a RMB-denominated system for crude oil products in terms of crude oil pricing. This move better reflects the crude oil supply–demand relationship and pricing demand in China and the Asia–Pacific market and provides the Asia–Pacific region with a pricing benchmark and a risk-avoidance tool for the crude oil trade (Ji and Zhang 2019; Sun et al. 2023a). According to the data of the "2024 Shanghai Crude Oil Futures and Options Market Development Report" released by Shanghai International Energy Exchange, in 2023, the average daily turnover of China's crude oil futures was 204,700 lots (unilateral), the average daily position was 65,100 lots, and the cumulative turnover amounted to RMB 28.78 trillion yuan. This has become the world's third largest crude oil futures contract in terms of trading scale, highlighting the rise of China in the global crude oil market (Naqvi et al. 2023; Shao and Hua 2022; Sun et al. 2023b).

Furthermore, the international pattern and international system have been profoundly adjusted, and China–Arab relations are rapidly warming up, ushering in a new strategic opportunity for "Petro RMB" (Khraief et al. 2021; Sun et al. 2022). First, the global oil supply pattern has undergone profound changes, and the conflict of economic interests between the US and Afghanistan has gradually come to the fore. China–Afghanistan relations have begun to warm up, laying the political foundation for the "Petro RMB". Second, the scale of China–Afghanistan trade has been expanding, and the economic structure of China and Afghanistan is strategically complementary, laying the economic foundation for the "Petro RMB". Finally, with the increase RMB recognition of the international of the global "de-dollarization" process, the RMB has gradually become the new choice for cross-border trade settlement and foreign exchange reserve diversification of Arab countries, which lays the credit foundation of "Petro RMB".

On December 9, 2022, President Xi's keynote speech at the China–Gulf Arab States Cooperation Committee Summit called for making "full use of the platform of Shanghai Oil and Gas Trading Center to carry out RMB settlement of oil and gas trade." On March 28, 2023, CNOOC and Total completed the first imported LNG purchase transaction settled in RMB through the platform of Shanghai Oil & Gas Trading Center, which is a beneficial attempt of Shanghai Oil & Gas Trading Center to carry out RMB settlement of the oil and gas trade. This represents an important practice to provide a new channel for international resources to participate in the Chinese market and to help build a new domestic and international double-cycle development pattern.

2.2 Problems and Challenges

2.2.1 Conventional Energy Supply and Price Risks Persist

The domestic demand for oil and gas is still in an upward stage, and the degree of external dependence continues to increase, especially following the Ukraine crisis. The international energy market has entered a period of turbulence and adjustment, and the response to the security risks of oil and gas imports has gradually become a "standby" regular arrangement. In 1996, China became a net importer of crude oil, and since then, the degree of dependence on the external oil market has been increasing annually. In 2023, China's dependence on foreign oil and natural gas reached 72.4% and 42.3%, respectively. Natural gas consumption is still in the growth stage, the domestic natural gas reserve system is relatively lagging behind, and natural gas imports and price risk have increased with the further increase in foreign dependence.

Furthermore, the diversified pattern of energy supply has been expanded, and the resilience of the oil and gas supply system has been improved, but the possibility of an extreme shortage of imports in the short term cannot be ruled out. Regarding the source of oil and gas imports, the proportion of China's crude oil imports from the Middle East and Russia further increased (Sun et al. 2015). In 2011, China's crude oil imports came from major source countries and regions—the Middle East, Russia, Africa, and Central and South America—with imports from the Middle East and Russia totaling 56.8%. In 2023, the share of China's imports of crude oil from the Middle East and Russia increased by more than 65%. Due to the sensitive geopolitical turmoil in the Middle East, crude oil imports are still subject to security risks (especially the risk of traditional corridors), and it is necessary to accelerate the formation of a diversified crude oil import pattern. The source countries of natural gas imports are increasing, and LNG imports are mainly concentrated in Australia and Qatar, with an import share of 57.2%, which should be focused on.

Another important factor affecting the safe and stable operation of China's economy in the current period is international energy price volatility, especially due to the impact of the Russia–Ukrainian conflict, with natural gas prices fluctuating sharply. Despite economic recovery to stimulate a rapid rebound in energy demand, superimposed on the frequent occurrence of extreme weather that leads to a shortage of renewable energy power supply and geopolitical impacts, global energy prices continue to rise sharply. In 2022, the international oil price was once close to 130 US dollars/barrel, with North America, Europe, Asia–Pacific, and other three major regional LNG market prices appearing to surge. Asian LNG spot prices peaked at more than $1400 per thousand cubic meters, reaching a peak in recent years. The high price of imported gas has led to serious losses for China's upstream import enterprises, and price inversion has had a serious impact on the normal operation of downstream city-fueled enterprises, which is not conducive to guaranteeing the normal operation of the natural gas market. Especially during the winter supply period, the gas price inversion phenomenon is more serious. At present, China's oil and gas reserve system lags behind in construction, with insufficient safety redundancy and a lack of effective means to resolve the impact of international oil and gas price fluctuations.

Even more serious is the insufficient discourse on international energy prices. Although China is already the world's largest importer and consumer of hydrocarbons, it has few means and insufficient capacity to influence the formation of global energy trade prices. This has led to China's lack of international energy pricing power, often passively accepting the "China premium", thus facing soaring international energy prices, resource balance tightening, and other unfavorable conditions (Liu et al. 2021; Zhang et al. 2018). At present, oil, natural gas, and other key energy pricing power are still in the hands of developed countries. One major reason for this is that energy futures market development lags behind. The energy futures price discovery function is weak, and it is difficult to effectively play the price benchmark function. In terms of the current international energy pricing system, futures prices, compared to spot prices to guide the role of stronger, have replaced the original energy spot market prices as the wind vane of international energy price changes. Taking oil as an example, at present, the important influence on international oil prices is the WTI crude oil of the New York Mercantile Exchange and the Brent crude oil of the London International Petroleum Exchange. China's energy futures market lags behind in terms of development level, which is mainly manifested in the fact that there are not many types of energy futures commodities and corresponding financial derivatives. The main participants in the futures market are still dominated by centralized enterprises, and the volume of futures products and the degree of active trading are insufficient.

Another reason for key energy pricing power remaining with developed countries is that the internationalization of the RMB is low. The US dollar, as the world currency, is closely related to international energy prices, compared to which the correlation between the RMB and energy prices, such as oil and natural gas, is relatively low, and domestic energy futures prices are still susceptible to changes in the US dollar exchange rate and changes in international energy futures prices. Despite the moderate enhancements to the bargaining power in China's energy imports with the listing of RMB crude oil futures in the Shanghai International Energy Trade Center and the continuous expansion of its trading scale, as well as some energy-exporting countries presenting prices in the RMB, the dominant position of the developed countries in terms of pricing power still cannot be shaken.

2.2.2 Inadequate Stability of Energy Supply Systems

First, the development of coal and electricity within the energy system is not coordinated. There is a transition period of conversion from the old to the new energy system. Regarding the risk of energy supply disruption caused by "breaking old establishment," the most typical is the lag in the construction of energy production, supply, storage, and marketing systems, leading to the energy upstream and downstream industries associated with poor convergence caused by regional phased supply shortages. During the "13th Five-Year Plan" period, the country withdrew a backward coal production capacity of 1 billion tons/year. According to data from the China Coal Industry Association's "Circular on Coal Economic Operation in the First Half of 2021," in the first half of 2021, the national coal consumption was about 2.1 billion tons, an increase of 10.7% year-on-year, while the national production of raw coal by enterprises above designated size amounted to 1.95 billion tons in the same period, an increase of 6.4% year-on-year. Due to the law of the coal capacity construction cycle, coal production in the short term cannot respond to market demand in a timely manner. In addition, throughout the "13th Five-Year Plan" period, the proportion of thermal power in the new installed capacity decreased from 50.65% in 2015 to 29.18% in 2020. For technical reasons, renewable energy is not yet able to provide enough stable power to fill the gap in power supply and demand left by coal power.

Second, the lack of control over parts of the energy supply chain poses a long-term external risk. Given the security and efficiency of the system of key link technologies, increasing external dependence on strategic mineral resources will become a long-term risk in the field of energy security (Wang et al. 2021). The vast majority of certain underlying core chips for the operation of the energy system rely on imports, and the development of the clean energy industry requires many critical mineral resources, such as lithium, nickel, cobalt, and manganese, for electric vehicle batteries, with an increasing degree of external dependence. Compared with traditional minerals, these strategic minerals are more geographically concentrated and inelastic in supply. With the large-scale replacement of new energy vehicles, China's demand for nickel, cobalt, lithium, and other mineral resources will continue to grow, and the resulting resource security risks may affect the entire new energy industry chain.

Third, the energy supply lacks a reasonable reserve capacity (Wei et al. 2024). Strategic oil and gas reserves are lower than the strategic reserve standards set by the International Energy Agency for member countries. As of 2023, the country's gas storage capacity will be around 39.6 billion cubic meters, accounting for about 10% of consumption, which is lower than the level of 13–27% in the US and developed countries in Europe. If calculated according to the 15% gas storage standard, the comprehensive gas storage capacity needs to reach at least 50 billion cubic meters, which exceeds the current Chinese gas storage capacity and has a large gap. In addition, China's energy reserve construction is still in its regional layout, with the need to optimize information monitoring, operation, and management. From the point of view of the distribution of China's completed oil reserve base, which is more distributed in eastern coastal areas, security needs to be strengthened to meet the convenience of use. The strategic oil reserve operation decision-making chain and operation cycle are long, and private enterprises and other market players are not sufficiently participating, resulting in energy price fluctuations that are not sensitive to changes and cannot "buy low and sell high" in a timely manner. In addition, natural gas storage requires large investment, a long construction period, and high technology content, but due to China's gas storage operation mode, charging mechanism, and other issues that have not been clarified, seasonal peak storage does not really hold an economic value, resulting in the weak enthusiasm of enterprises to build the reservoir.

Fourth, the role of market mechanisms in regulating supply and demand is limited. Under the "double-carbon" goal, the effective supply capacity of coal is constrained, and with the increasing proportion of intermittent and fluctuating power sources, the tension between energy supply and demand will become an important feature. At present, coping with this type of security problem has not yet fully considered the fundamental role of the market in regulating supply and demand. More plan-based "supply" means—that is, the energy system's production planning, inter-area scheduling, and emergency supply capacity requirements—are very high. The regular production of energy also causes a certain negative impact and will even produce counter-cyclical misalignment, leading to long-term overcapacity.

2.2.3 More Complex Impacts of Energy Transition on Energy Security

The "dual-carbon" goal has constrained the development of fossil energy to a certain extent, and the gap between supply and demand must be supplemented by other energy sources such as renewable energy. At present, the unprecedented changes are accelerating, and the international political and economic order is facing a profound adjustment. Especially since the Ukraine crisis, the international energy market pattern has been showing a period of turbulence and adjustment. Oil, natural gas, and new energy core technology may become an important weapon for the major countries to play in the future of the world's new pattern. In the long run, a new energy pattern will be formed, with energy technology as the core and a new energy industry chain as the main one. Therefore, beyond dealing with traditional oil and gas security, energy security also needs to deal with the construction of new energy as the main body of the energy system in the process of energy supply disruption risks (Ji et al. 2024). One is the risk that a new power system that is mainly based on new energy will not be able to provide a stable power output due to natural factors. The second is the risk of cyberattacks on the power system. The third is the risk brought by the development of a new energy industry chain (new energy vehicles, energy storage, etc.), such as lithium, cobalt, nickel, rare earths, and other critical mineral resources in the next two to three decades will continue to grow in demand, but the distribution of resources is more uneven than the oil and gas resources.

Against the background of a common response to global climate change, it is possible to realize common energy security at minimal cost to the country by fully leveraging the international energy market on the basis of the low-carbon transformation of the country's energy sources and carrying out in-depth cooperation in the fields of new energy technology and alternative energy development under the conditions of opening up at a higher level. However, in the joint response to climate change, the trade policies of major countries and measures to promote carbon neutrality have objectively increased the trade costs of developing countries, as well as the difficulty of reducing carbon emissions (Li et al. 2023). In 2022, EU countries reached an agreement on the Carbon Border Adjustment Mechanism (CBAM), which will impose a tax on the carbon emissions of imported industrial products, such as iron and steel, cement, fertilizers, and aluminum, and will particularly regulate countries with laxer climate rules. CBAM is one of the EU's mechanisms for encouraging trading partners to reduce carbon emissions from manufacturing and is seen by the EU as a key pillar of its climate policy. However, CBAM's substantive effect is to make imports bear the same carbon costs as EU products, negating the rationality of differences in carbon prices across countries and violating existing international trade rules.

2.2.4 Global Geopolitical Games Threaten International Energy Cooperation

Competition in overlapping areas of oil and gas resources has intensified, and geopolitical risks have increased (KPMG, 2024). Under the drive of the goal of decoupling from Russian energy, apart from the US and Australia, the Middle East and Central Asia will also become important sources to fill the gap in European oil and gas imports. These areas also play an important role in China's energy imports, with crude oil accounting for about 70% and pipeline natural gas accounting for about 80%. This has increased the risk of China's "competition for oil and gas."

China's deepening energy dependence on Russia has increased the potential threat of sanctions on energy security. In recent years, China's deepened energy cooperation with Russia has increased its reliance on Russian energy, while China's large energy import demand, coupled with excessive reliance on a single import channel, will amplify the impact of unexpected events on national energy security. Furthermore, China may also face secondary sanctions risks from the US and Western countries due to its energy cooperation with Russia. If the US and Western countries impose severe sanctions on China's energy sector, China will face severe challenges in obtaining overseas oil and gas resources, ensuring the security of oil and gas import channels, and safeguarding its overseas oil and gas assets.

The intensified US–China energy competition has increased the risks and uncertainties of international energy cooperation and trade (Xia et al. 2019). The Russia–Ukraine conflict may lead to a split in the global energy system, forming two relatively parallel energy systems: one dominated by China and India using Russian energy, and the other dominated by the US and Europe reducing their reliance on Russian energy. Under the current situation of the US' containment and exclusion of China, the intensified US–China energy competition may lead to more complex uncertainties and financial risks in international energy cooperation and trade. First, the US is likely to mobilize countries such as ASEAN, Japan, and South Korea to encircle China's main energy transport channels, increasing the risks of China's strategic energy channels, especially the Malacca Strait, which is a crucial route for China's oil imports. Second, the US may disrupt China's cooperation with major oil-producing countries in the Middle East through its dominance in the region and international political power, forcing suppliers in the region to stop supplying oil to China. Third, the US may include Chinese energy companies in its real-name sanctions list, leading to the freezing of China's offshore capital settlement accounts, and obstructing China's oil and gas trade with foreign countries. Fourth, the US may implement "long-arm jurisdiction," leading to a decrease in the willingness of some countries to cooperate with China on energy projects, and key energy technologies and core oil and gas equipment may face blockades. Existing and ongoing energy cooperation projects may face more uncertainties, and previous investment losses could be significant if projects are suspended or canceled.

2.3 Opportunities and Strategies

As mentioned above, threats to energy supply, fluctuations in energy prices, risks of energy transition, and geopolitical uncertainties in international energy cooperation and trade all require China to actively respond to the challenges faced by energy security in the context of international energy changes. However, at the same time, China currently has certain advantages in the field of new energy, with the manufacturing levels of photovoltaics, wind power, new energy vehicles, and energy storage equipment all in the first tier (Chadly et al. 2024). Therefore, the new changes in international energy after the Russia–Ukraine conflict and China's new energy technology advantages also bring China several new opportunities to deepen energy security.

China's cooperation with Russia in the energy sector is expected to move toward a higher level and closer relationship. On the one hand, in terms of fossil energy, China's growing demand can bear some of the sanctions-induced excess capacity of Russia, consolidating the "ballast stone" role of energy in bilateral trade and ensuring a relatively stable fossil energy supply. On the other hand, around low-carbon energy, such as nuclear energy, electricity, and downstream industries, cooperation between the two countries is expected to further expand, building a closer relationship and continuously enhancing their industrial competitiveness. In addition, the use of rubles and the RMB in the bilateral natural gas trade is of great significance for promoting the development of the two countries' bilateral currency settlement systems and financial institutions and accelerating the internationalization of the RMB.

China's cooperation with other developing countries in the energy sector is expected to continue to expand. Energy-rich developing countries in the Middle East, Central Asia, and other regions—China's vast consumer market and complete energy industrial system—are important in ensuring relatively stable consumption demand in the uncertain international energy market after the Ukraine conflict. Cooperating with these regions in upstream oil and gas development, storage, refining, and low-carbon innovative technologies not only benefits China in expanding the channels for fossil energy imports but also plays a positive role in promoting these regions to shift to low-carbon green development models. For regions such as ASEAN, Latin America, and Africa, China can use its experience and financial advantages in low-carbon infrastructure construction to provide replicable green solutions through a batch of overseas clean energy demonstration projects. Expanding overseas investments can also foster the alignment of industry and finance, driving mutual development. The joint construction of the green "Belt and Road," which strengthens South–South cooperation, and explores the sustainable development paths for developing countries, is of great significance.

China's energy industry upgrade is expected to accelerate, and industrial advantages are expected to be consolidated. On the one hand, the sustained energy crisis in Europe has forced the accelerated transfer of energy-intensive industries abroad, providing opportunities for China to absorb related industries. The investment of European multinational companies not only benefits China's related industries and technology upgrading but also promotes the regional development balance in China by encouraging these companies to invest in labor- and resource-rich regions in central and western China. On the other hand, guided by enhanced energy security, countries around the world are accelerating the development of new energy, which also brings more opportunities for China's export of related products. In 2022, China's new energy vehicle production increased by 96.9% year-on-year, and exports increased by 120%. Solar cells and lithium battery exports increased by 67.8% and 86.7%, respectively. Furthermore, by encouraging enterprises to invest their export income in enhancing the independent R&D capability of key components, China can further consolidate its technological advantages and improve the scale and development levels of the industry.

Based on a comprehensive consideration of the challenges and opportunities facing China's energy security, several response strategies are recommended, as presented below.

2.3.1 Compacting the Foundation of Energy Self-Sufficiency and Accelerating the Construction of a Strong and Reliable Energy Supply Guarantee System

China should optimize its energy supply system and promote cleaner use of fossil energy. Fossil energy will remain the main source of energy for a long time to come, and while controlling the total amount of energy and withdrawing it in an orderly manner, promoting the clean and efficient use of fossil energy is the top priority of the transition (Ji et al. 2022b). Coal is the dominant domestic reserve and production and an independent and controllable main source of energy. China must attach great importance to its strategic position of guaranteeing national energy security. To realize the combination of coal utilization, energy transformation under the goal of "double carbon" must adhere to the first-to-establish rule and then break or put an end to the “one-size-fits-all” “step-by-step” carbon reduction campaign. The withdrawal of coal and other traditional energy sources must be based on the safe and reliable substitution of renewable energy. In the field of oil and natural gas, it is necessary to vigorously implement the strategy of “stabilizing oil and increasing gas” and accelerating the transformation of the energy structure. Efforts should be made to realize stable oil production, and oil should gradually be transformed from “fueling” to “materializing,” allowing it to play the role of the “ballast” and “cornerstone” of raw materials for people’s livelihoods in guaranteeing the country’s energy security. Natural gas is recognized as a clean, low-carbon gas. It is the world’s recognized clean, low-carbon, flexible, and efficient fossil energy. Promoting natural gas reserves and production requires vigorous development of the natural gas industry during the low-carbon transformation of high-carbon fossil energy substitutions “complementary” for renewable energy power generation to provide peak support. Furthermore, we should promote energy saving and low-carbon transformation in the oil and gas industry, optimize its structure, and create a low-carbon chain.

Efforts should be made to promote large-scale utilization of renewable energy. This involves fully utilizing China’s abundant renewable energy resources, building a good clean energy supply system for wind, light, and water, focusing on new energy supply and consumption, accelerating the construction of a new type of power system, and significantly enhancing the ability of non-fossil energy sources to securely replace them. Furthermore, stakeholders should increase policy support, increase the proportion of installed renewable energy power generation, accelerate the construction of energy storage, smart grids, and other infrastructures, enhance the ability of the power system to accept large-scale renewable energy power generation, accelerate the effective substitution of traditional fossil energy power generation, and increase the proportion of renewable energy in the overall energy consumption structure.

An important direction is the acceleration of the construction of a resilient energy supply chain. On the one hand, this will enhance energy production and supply capacity, build on China’s energy resource endowment, improve the multi-wheel-driven energy supply system for coal, oil, gas, electricity, nuclear power, and renewable energy sources, and enhance the capacity for regional independent balance and cross-regional synergy and mutual assistance. During the transition period, the focus is on grasping the balance between old and new energy sources, accelerating the enhancement of new energy sources’ reliable substitution capability, and continuously enhancing the stability, security, and sustainability of the energy supply. On the other hand, the focus is on improving production and consumption forecasting capabilities, strengthening the construction of reserve regulation capacity, improving the layout of gas storage facilities, and enhancing the resilience and elasticity of the energy supply chain.

2.3.2 *Stabilize the External Supply of Energy and Prevent the Impact of External Input Factors on Energy Security*

China should improve its pattern of diversified energy imports. On the basis of maintaining existing import source countries, expand new energy import channels through energy diplomacy. Deepen and expand cooperation with key countries and regions such as the Middle East, Central Asia, and Russia, and promote the development of oil and gas resources and the construction of security infrastructure in the countries along the "Belt and Road," so as to reduce excessive dependence on a single country or region. Strengthen the construction of onshore oil and gas import channels, implement, and optimize the sources of onshore oil and gas imports, and ensure the safe and stable operation of the channels. Strengthen international multilateral energy dialogue and cooperation, further establish dialogue and exchange mechanisms with relevant international organizations, such as the International Energy Agency, and gradually expand China's influence on the international energy market and its rule-making. Various measures should be taken to encourage Chinese energy enterprises to go global and flexibly participate in all aspects of exploration, exploitation, smelting, and sales of foreign oil resources by means of wholly owned enterprises, joint ventures, and equity participation, thereby expanding their overseas business and setting up overseas energy supply bases (Odgaard and Delman 2014).

To enhance international energy pricing power, China's energy futures market plan should include expanding the depth and breadth of the commodity futures market. Drawing on the experience of energy futures development in the US, Europe, and other developed Western economies, China should improve its futures market system and promote the exchange rules to be in line with international standards. This encompasses innovative development of commodity futures and options varieties, stepping up the development of contracts for natural gas and other "missing" commodity categories, and intensifying efforts to research and develop new energy sources, carbon emission rights, and other new areas of trading varieties. On the premise of risk control, domestic and foreign financial institutions and spot enterprises should be encouraged to enter China's futures market to foster the formation of a more rational market trading system and reasonable equilibrium prices and enhance the influence of China's futures market. The country should steadily push forward the internationalization of RMB, use digital currency represented by blockchain technology to improve the convenience of RMB cross-border payment, increase the rate of RMB settlement for international business, and further enhance the international pricing ability of RMB for energy on this basis.

2.3.3 Increase the Scale of Strategic Energy Reserves and Enhance Energy Security Emergency Response Capacity

A sound plan should involve establishing and improving the coal reserve system. China should coordinate the "carbon reduction" and "coal pocket" supply guarantees and build a scientific strategic coal reserve system in accordance with the principle of "building up before breaking down," taking into full consideration a variety of scenarios. Combined with the goal of "double carbon," the country should scientifically evaluate various possible scenarios and maintain a reasonable scale of coal reserves. A three-tier coal reserve system of "resources, production capacity, and products" should be established, and a reasonable stockpile cycle for coal-fired power plants should be established, with enterprises as the main body.

Increasing the scale of oil reserves and building a strategic natural gas reserve system as soon as possible can offer several immediate benefits. Important steps include enhancing the capacity of strategic oil reserves, planning a number of new strategic reserves, and expanding the capacity of emergency oil reserves. China should accelerate the construction of natural gas reserve capacity, and form a natural gas reserve system that combines the three levels of reserves of the state, resource enterprises, and city gas enterprises, as well as strategic reserves and commercial reserves (Kang, 2021).

China should emphasize the positive role of renewable energy in emergency security. The nation should allow the full role of renewable energy in emergency supply security, and build an energy emergency supply system that includes multiple varieties of energy. This can be achieved by optimizing regional and provincial power grid contact lines, reforming the existing power grid dispatching rules, and accelerating the construction of the auxiliary service market system. This also involves improving the redundancy capacity of the existing power grid to cope with fluctuating wind power and enhancing the flexibility of the power system. China should encourage the rational, moderate, and effective development of various types of renewable energy sources, build a diversified and distributed energy emergency supply network with flexibility, give full play to the potential of various types of energy sources in different scenarios and areas to maintain emergency supply, and resolve the risk of impacts on the energy system caused by emergencies.

Planning a strategic mineral resource reserve system should be prioritized. The establishment of a new system of "production, supply, storage, circulation, and replacement" of strategic mineral resources should be accelerated while enhancing the ability to regulate market supply. The country should respond to emergencies, guarantee the security of resource supply, and emphasize the secondary resource recycling and utilization of strategic mineral resources. Consideration can be given to adopting tax, financial and industrial funds, and other policy tools to encourage large enterprises to haul domestic resources recycling and utilization and other supporting enterprises to develop, cultivate more "specialized, special, and new" enterprises, and continuously improve the high-quality supply capacity of nickel and cobalt materials to support the sustainable development of battery materials.

2.3.4 Strengthen International Cooperation and Continuously Improve Overseas Supply Chain Systems

In the face of the new global energy pattern that may be formed in the future, China should not only guard against the security risks of the traditional energy market but also play the role of a major energy-consuming country in the world. It should follow the principle of mutual benefit and win–win cooperation in international cooperation, actively participate in global energy governance, jointly safeguard the stability of the global energy market, and steer international cooperation in addressing climate change.

China should strengthen international cooperation in the traditional oil and gas sector, based on global resources, adhering to the strategy of diversifying oil and gas imports, and realizing a higher level of opening up to the outside world to ensure energy security. This may include smoothing energy trade and investments, relentlessly expanding openness to the outside world, substantially relaxing foreign investment access, and promoting the liberalization and facilitation of energy trade and investment (Bega and Lin 2023; Liu and Ding 2024). It should enhance the production of overseas oil and gas rights and interests, increase investment in oil and gas resources in key regions and important countries on the premise of guaranteeing the stability and security of China's overseas oil, gas, and chemical supply chain, take the initiative to participate in the exploration, development, and construction of oil and gas resources in the relevant countries, and explore flexible and diversified cooperative relationships to cultivate a new advantage in long-term and stable trade. The nation can solidify diversified channels for oil and gas imports from the Middle East, Africa, Australia, and South America and engage in dialogues and exchanges in the energy sector with countries with potential room for cooperation. It should explore with the US, Australia, and other countries in the field of LNG to explore forms of cooperation in line with the common interests of both sides and to optimize the structure of LNG imports by sea. It should promote "Belt and Road" cooperation, build overseas oil and gas supply bases, prioritize key partners, strengthen overall planning, adhere to mutual benefits and win–win situations, and continuously consolidate and deepen energy cooperation with "Belt and Road" countries.

Active participation in global energy governance is paramount. China should actively participate in international cooperation on energy under multilateral mechanisms, such as the G20, APEC, and BRICS. It should strengthen more pragmatic policy communication and coordination with Asian, African, and Latin American countries to create peaceful and stable expectations for cooperation and reduce geopolitical risks other than those led by the US. Relying on the SCO, BRICS, the China–Africa Cooperation Forum, and the China–ASEAN Economic and Trade Cooperation Mechanism, China can strengthen consensus, formulate pragmatic cooperation plans, and form a longer-term and closer cooperative relationship. Efforts should be made to promote “Belt and Road” energy cooperation, and cooperation with countries along the “Belt and Road” in the fields of energy investment, trade, production capacity, and technical standards should be widely encouraged, with a view to jointly establishing the “Belt and Road” energy partnership. In response to the United Nations 2030 Sustainable Development Goals, China should actively participate in international cooperation on energy accessibility, and support the construction of energy accessibility projects in countries along the Belt and Road to address the problem of access to electricity for people without electricity.

Another area is the strengthening of exchanges with developed countries in the field of new energy and seeking win–win cooperation. In the current turbulent international energy market adjustment process, China should not only actively participate in the governance of the international oil and gas market, and promote the restoration of the international market order, but also seek cooperation with the US and Europe in the field of new energy, and promote the formation of a long-term stable trade pattern as soon as possible. Stakeholders should insist on Chinese products “going out” and support Chinese enterprises in the export of photovoltaic and other products. They should encourage US and European new energy and high-tech enterprises to “come in” and support Chinese enterprises in carrying out cooperation with the US and Europe in the fields of energy storage, electric vehicles, hydrogen and fuel cell vehicles, nuclear power, and hydrogen energy in terms of equipment, standards, technology, and market. The nation should actively advocate and promote regional energy cooperation, and build regional energy cooperation platforms between China and ASEAN, the Arab League, the African Union, and Central and Eastern Europe. It should work together to address global climate change, uphold the concept of a community of human destiny, actively promote the low-carbon transformation of global energy, and support developing countries, such as the least developed countries and small island states, in addressing the challenges of climate change.

2.4 Conclusion

As the world’s largest energy producer and consumer, China has, in recent years, focused on building coal, oil, gas, nuclear, new energy, renewable energy, a multi-wheel-driven energy supply system, energy production, and its security capabilities. It has been strengthening the structure of energy consumption while engaging in clean and low-carbon transformation. The layout of the strategic energy import channels is continuously perfected, and the construction of the energy security reserve system has achieved initial results. Thus, the power and influence of international oil and gas discourse have been evolving.

However, along with economic development, energy transformation, and the increasingly complex international geopolitical environment, China’s energy security will face more potential risks and difficult challenges. First, traditional energy supply and price risks still exist. This is mainly manifested in an increasing dependence on oil and gas from foreign countries. Although China's energy supply diversification pattern has been expanded and the oil and gas supply system has improved the nation's toughness, the country cannot rule out the possibility of short-term imports of extreme shortages. The lack of international energy price discourse also leads to increased price risk. Second, the energy supply system is not sufficiently stable, mainly manifested in the lack of coordination in the energy system within coal and power development. This has resulted in upstream and downstream energy industries associated with poor convergence caused by regional phased supply shortages and a lack of control over part of the energy supply chain. There is a long-term external risk and a lack of reasonable energy supply reserve capacity; the market mechanism to regulate the role of supply and demand is also limited. Third, in addition to dealing with traditional oil and gas security, energy security also needs to deal with the risk of interruption of the energy supply that may arise in the process of building a new energy system with new energy as the mainstay, and the impact of energy transition on energy security is more complex. Fourth, China faces increased competition in overlapping areas of oil and gas resources, the threat of secondary sanctions, and intensified US–China energy competition, bringing more complex challenges to energy security.

China also has certain advantages in the fields of new energy, prioritizing the manufacturing level of photovoltaics, wind power, new energy vehicles, and energy storage equipment. Therefore, new changes in international energy have also created new opportunities for China to expand international energy cooperation and ensure energy security. For example, China has opportunities to deepen energy cooperation with Russia, expand cooperation with developing countries, and accelerate the upgrading of the energy industry. Based on the current situation, challenges, and opportunities for energy security in China, corresponding suggestions are proposed from the aspects of consolidating the foundation of energy self-sufficiency, stabilizing external energy supply, enhancing emergency response capabilities for energy security, and strengthening international cooperation. These recommendations provide a reference for preventing energy security risks in advance and ensuring China's energy security.

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Chapter 3
Power Games and Global Geopolitics of Critical Mineral Resources

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Abstract The scarcity and uneven geographical distribution of critical mineral resources have intensified the global competition for control and rights over these resources, becoming a focal point in contemporary geopolitical struggles. Led by the United States, Western nations have implemented various measures to strengthen the trend of "camp-based" global resource governance in pursuit of critical minerals supply chain security. Concurrently, there is a rising trend of resource nationalism among major mineral-producing countries, exacerbating the competition for critical minerals and the geopolitical rivalry among great powers. This chapter analyses the current state of global competition for critical minerals, systematically examines the emerging geopolitical landscape surrounding these resources, and outlines the strategies and policies of major economies regarding critical minerals. It also delves into the complex domestic and international environment faced by China, exploring opportunities for and challenges in ensuring national resource security. The aim is to provide insights and references for understanding the evolving geopolitical dynamics related to critical minerals both now and in the future.

Keywords Critical minerals · Geopolitical · Power games

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3.1 New Global Geopolitical Dynamics of Critical Minerals

3.1.1 Supply Chain Localization and "De-Chinaization"

Western countries, led by the United States, have continuously strengthened their policy deployment regarding critical mineral supply chain security by elevating it to the legislative level and emphasizing the localization of critical mineral supply. Four U.S. executive orders related to the critical mineral supply chain have been issued to strengthen the resilience of the domestic supply of critical minerals, and through federal government departments, loan support, financial subsidies, government investment, and other policy tools, the formation of a "whole-of-government, cross-sectoral" critical minerals policy network mechanism is in place to ensure the security of the U.S. critical minerals supply chain. In terms of departmental coordination, Executive Order 14,017 was issued in 2021 to review the vulnerability of the U.S. supply chain and require the Department of Defense to coordinate with the Departments of the Interior, Agriculture, Energy, and Commerce to ensure a sustainable supply of domestic critical materials and the development of domestic productivity. The U.S. government vitalized domestic production of critical minerals by invoking the Defense Production Act (DPA) to fund the mining, processing, and recycling of lithium, cobalt, nickel, graphite, and manganese ores and by naming Canadian entities as DPA-compliant sources of funding. Executive Order 14,057 proposes that the federal government leverage strong scale and sourcing capabilities to enhance the competitiveness of U.S. industries to create jobs and to support resilient supply chains to drive innovation, i.e., institutionalize supply chain resilience at the federal level and ensure homegrown green supply chains (The White House 2021). The Inflation Reduction Act of 2022 put US$369 billion into climate change and energy security. Under this law, the U.S. government will offer consumers up to $7500 in tax credits when purchasing an electric vehicle and up to $4000 in tax credits for purchasing a used electric vehicle. However, the final assembly of the purchased vehicle would have to take place in the United States or in a country with which the United States has signed a free trade agreement, and at least 40 per cent of the metallic raw materials and minerals (such as lithium and cobalt) used in the batteries would have to be mined and refined in the aforementioned countries (The White House 2023).

The EU also attaches great importance to strengthening its critical minerals strategy and securing the supply of raw materials. In order to reduce the geopolitical risks arising from external dependence on key raw materials, the EU released the Critical Raw Materials Action Plan in September 2020, including the establishment of the European Raw Materials Alliance, the strengthening of raw material recycling, the promotion of local raw material extraction and processing, and the diversification of supply channels. The Critical Raw Materials Act of 2023 was passed to ensure the security and sustainable supply of key raw materials, such as rare earths, lithium, cobalt, nickel, and silicon, to increase domestic production capacity at all stages of extraction, processing, and recycling of key raw materials, and to increase the resilience of the supply chain through the international network of key raw materials.

While strengthening the localization of supply chains, the U.S. and Western countries are actively "de-Chinaizing" critical mineral supply chains and standards in the areas of mineral extraction, clean energy technology, and rule-making. In June 2021, the U.S. government launched the U.S.-European Trade and Technology Council (TTC), which will focus on cooperation in supply chain security, technology development, and standards in the clean energy sector. China will be excluded from the global mineral supply chain through the development of national and industry standards and norms highlighting environmental, labour, and transparency criteria. At the same time, the United States government's critical minerals strategy is also tied to the issue of human rights, which it has used to accuse China of using "forced labour" in Xinjiang, and it has blocked imports of solar products containing polysilicon from the Xinjiang region.

3.1.2 Formation of International Cooperation

In the face of increasingly fierce competition, major Western economies have expanded their voice in the global supply chain of critical minerals by forging alliances. The "critical minerals diplomacy" of major economies has been heating up, and the United States has continued to embed the issue of critical minerals supply chain cooperation into the bilateral and multilateral cooperation system by diplomatic means, by signing cooperation agreements with Canada, Australia, the European Union, Japan, and other countries, and by committing itself to building a resilient supply chain led by the United States. Western powers led by the U.S. have established multiple critical mineral cooperation alliances globally to strengthen supply security and stability among allies, which has resulted in the camping of international cooperation in the field of critical minerals. In 2019, nine major mineral resource countries, including the U.S., Australia, Brazil, the Democratic Republic of the Congo (DRC), and Peru, launched the Energy Resource Governance Initiative. In 2022, the U.S., Canada, Australia, the European Union, and Japan established the Mineral Security Partnership (MSP) in an attempt to build an ideologically based "friend-shoring"[1] critical mineral supply chain (Vivoda 2023). To this end, the U.S. has built and strengthened bilateral and multilateral mechanisms such as the U.S.-Japan, U.S.-Korea collaboration, the U.S.-Japan-India-Australia Quadrilateral Dialogue, the U.S.-European TTC, the Indo-Pacific Economic Framework, and other multilateral platforms to promote the goal of supply chain resilience. At the same time, Western countries are also actively engaged in "resource diplomacy"

[1] Friendly-shoring refers to limiting supply chain networks to allied and friendly countries and strengthening trade cooperation with these countries to avoid overdependence on countries with geopolitical concerns. Friendly-shoring aims to address the vulnerability and lack of resilience of global supply chains, reduce U.S. economic risk by reducing dependence on countries with geopolitical risks, and build supply chains based on shared values.

with resource-rich countries and regions such as Africa and Latin America. On 7 February 2023, a meeting of deputy ministers of the key members of the MSP and mineral-rich countries such as Angola, Botswana, the DRC, and South Africa was held to discuss responsible mining and processing of minerals (Abrar 2024). The meeting was held to discuss priorities, challenges, and opportunities for responsible mining, processing, and recycling of critical minerals, with a view to strengthening cooperation on critical minerals. The strengthening of supply chain partnerships in the United States and Western countries and the establishment of energy and mineral resource alliances and other "small circle" approaches, which are characterized by exclusivity and camping, have led to increasing competition among global critical mineral powers (Calabrese 2024).

3.1.3 Rising Resource Nationalism

Resource nationalism in the world's major critical mineral resource countries is on the rise as the scarcity and strategic nature of critical mineral resources become increasingly evident (Dou et al. 2024). Specifically, the policy tools used by major resource countries range from traditional tariff and non-tariff barriers to trade to more extreme coercive official measures, such as promotion of the nationalization of resources, increased investment scrutiny, and enhanced regulatory efforts. Export restrictions, higher taxes, and royalties are the most common trade protection measures (Han et al. 2024). For example, in January 2020, a ban on the export of nickel raw materials came into effect in Indonesia, one of the world's largest nickel exporters. In addition, Indonesia announced an increase in nickel royalties in 2022. Subsequently, Indonesia banned the export of bauxite from June 2023 in order to boost the local aluminium-processing industry. Chile, the world's top copper producer and second-largest lithium producer, approved mining tax reforms in May 2023 that will require large copper and lithium producers to pay more taxes and royalties to the government.

In addition, against the backdrop of contradictions between resource countries and mining companies over issues such as taxation and benefit distribution, many mineral resource countries have begun to adopt asset nationalization policies—such as Mexico, which in April 2023 through the national franchise battery metal lithium development bill, officially started lithium industry nationalization. The initiative led to nine lithium mining concessions to Ganfeng Lithium being cancelled by the Mexican government. Chile has also announced intentions to promote the nationalization of the country's lithium mining industry and the establishment of a state-controlled lithium mining company. Prior to this, in January 2022, BYD had participated in lithium mine bidding activities. After it won, the bidding was stopped by the Chilean government. Argentina's foreign ministry proposed that Argentina, Bolivia, and Chile commit to promoting the establishment of a bloc similar to the Organization of the Petroleum Exporting Countries, "lithium Pec," in order to reach a "price agreement" in the case of lithium price volatility to enhance the added value of the industry and pricing power. It is foreseeable that with the rise of resource nationalism, China's overseas mining cooperation will face higher host country political risk, policy risk, and other challenges.

3.1.4 Financialization of Mineral Resource Markets

Financial instruments in resource markets have also become an important tool in geopolitical games. Financial power in the resource sector mainly refers to market manipulation through market pricing and standard-setting (Diego and Juan 2020). For a long time, developed Western countries led by the United States have made good use of financial means to control the origin, production, pricing, and supply of global minerals. *China Mining Finance Development Report 2023* points out that the financial attributes of energy resources are increasing in the global game, and at the beginning of the global spread of the new coronavirus in 2020, abundant global monetary liquidity pushed up the price of minerals significantly, and the financial "black swan" event triggered a huge shock in the price of bulk minerals, which damaged the industrial chain (Yu and Li 2023) and had a great impact on the global economic governance system. In 2022, global oil and gas prices were affected by geopolitical events such as the Russia–Ukraine conflict and changes in the EU demand structure, with oil and gas prices rising rapidly, energy prices pushing up production costs, and the risk of a global recession intensifying, making the security of the supply of primary commodities (such as energy resources) an important factor affecting the economy, and prices have become an important factor affecting the economy. Since 2020, international mineral prices have shaken sharply, also increasing the cost of China's energy resources imports. Imports of energy and major mineral products accounted for a rapid rise in the proportion of foreign exchange reserves, from 8.9% in 2005 to 21.5% in 2022. Commodities such as energy and minerals have the dual attributes of means of production and investment, so smooth operation of the financial market is also affected when their prices fluctuate significantly (Irfan et al. 2022). The financialization of the mineral resources market is increasingly visible.

3.2 Critical Mineral Strategies and Policies in Major Economies

Against the backdrop of intensified competition among major countries, the demand for strategic emerging industries and energy transformation has led to rising concerns about the security of critical minerals in major countries around the world. With the continued rise of global trade protectionism and deepening geopolitical conflicts, the United States government has successively released the Critical Minerals List, the

Federal Strategy for Ensuring the Safe and Reliable Supply of Critical Minerals, and the 100-Day Supply Chain Assessment Report, in an attempt to politicize the issue of the strategic mineral resources industry supply chain. The outbreak of the epidemic in 2020 further worsened the global economic situation, and the trend of localization and regionalization of the industrial supply chain became more and more obvious. In 2020, the European Union published the Critical Raw Materials Act. The goal of the regulation to strengthen the control of critical mineral resources. Japan, India, and Australia have launched the Supply Chain Resilience Initiative, which explicitly calls for the establishment of a strategic mineral resources industrial supply chain, with the aim of strengthening the supply chain to reduce dependence on China's supply chain in key areas. This has further exacerbated the risk of global production and allocation of strategic mineral resources, and the issue of supply chain security in the strategic mineral resources industry chain has long gone beyond the scope of economy and trade to become the core of national security issues. In this section, the United States, the European Union, Japan, and South Korea are selected as the major demand countries (regions), and Australia, Chile, Mexico, Indonesia, and the Philippines are selected as the major mineral suppliers to be studied in order to sort out the development of their critical mineral strategies and policies.

3.2.1 Major Mineral-Demanding Countries/Regions

The strategic importance of critical minerals is becoming increasingly prominent. With intensification of the great power game, the United States, other Western countries, and other major mineral-demanding countries are attaching greater importance to the security of critical minerals. They have launched a global layout to cope with supply chain risks by stepping up the launch of, and adjusting, critical mineral strategies and strengthening supply chain partnerships.

United States

(1) Critical Minerals Highlighted in U.S. Strategy

The United States was the first country to establish a strategic mineral reserve and to conduct critical mineral evaluations. As early as 1939, the United States enacted the Strategic and Crisis Raw Materials Reserve Act (1939), which formally put forward the concepts of strategic and crisis mineral resources. In recent years, the U.S. has elevated the security of its critical mineral supply chain to a high level of national strategy, continuously reviewing and identifying the risks of its critical mineral supply chain and releasing major critical mineral strategy documents as shown in Table 3.1. During the Trump administration, the "America First" concept began to drive the return of the supply chain to autonomy, and U.S.–China trade friction has triggered widespread concern in the U.S. about breakage of the critical mineral supply chain.

Executive Order 13,817 puts forward a strategy to reduce the country's dependence on critical minerals, including an assessment of the development of critical mineral recycling and reprocessing technologies and technological alternatives to critical minerals, as well as the acquisition and development of critical minerals through investment and trade with allies and partners. On this basis, the U.S. Departments of Commerce, Interior, and Defense jointly launched a Federal Strategy to Ensure a Safe and Reliable Supply of Critical Minerals to maintain the security of the critical minerals supply chain, guard against so-called Chinese control of the U.S. supply chain, and reduce external dependence on critical minerals. Documents released by the Trump administration, such as the 2017 National Security Strategy and the 2018 U.S. Leadership Strategy for Advanced Manufacturing, both call for autonomy in U.S. supply chain security.

Under the trend of counter-globalization, the risk of breaking the chain of critical mineral supplies has further increased. The banner of "rebuilding a better future" focuses on the domestic clean energy revolution and the great power game, highlights the strategic significance of the green mineral resources supply chain, and strengthens cooperation with allies and partners. A U.S.-led "green supply chain alliance" is on the horizon. Traditional competition for resources mainly centres around fossil energy, while future competition will focus more on key strategic mineral resources. Strong linkages between emerging energy technologies and critical minerals are seen as key to strategic resource planning. The green and low-carbon technological revolution (with such as battery technology, robotics and artificial intelligence systems), which represents the transition from fossil to renewable energy sources, is highly dependent on strategic mineral resources such as lithium, cobalt, and rare earths. The U.S. government released the report *Building Resilient Supply Chains, Revitalizing U.S. Manufacturing, and Promoting Broad-Based Growth: A 100-Day Review Under Executive Order 14,017*, which highlights the importance of critical minerals and raw materials to the national security of the United States and proposes a strategy to "de-Chinaize" the supply chain.

(2) Critical Mineral Supply Chain Projects in Green and Low-Carbon Development

The Center for Strategic and International Studies report *The Geopolitics of Critical Mineral Supply Chains* suggests that the critical minerals needed for clean energy are becoming increasingly strategic, affecting the competitiveness of countries' clean energy and low-carbon economies. However, the U.S. critical mineral supply chain lacks basic mineral resources, and the overall competitiveness is not strong. It is difficult to support the strong development of a green low-carbon economy, as the clean energy revolution requires solar photovoltaic panels; wind turbines and electric vehicle battery production rely heavily on rare earths, gallium and indium. And the U.S. foreign dependence on rare earths and germanium reaches more than 80%. Most of the lithium, cobalt and manganese required for the production of lithium-ion batteries in the United States also come from China, Australia and other countries (Wang and Wang 2023). In April 2021, the U.S. Senate Foreign Relations Committee introduced the Strategic Competitiveness Act of 2021, which recommended that the State Department integrate climate response, clean development, and other factors

Table 3.1 U.S. strategic deployment of critical minerals

ID	Name	Timing	Launching office	Key initiatives/Content
1	Rare Earth Supply Technology and Resource Conversion Act 2010 S.3521—Rare Earths Supply Technology and Resources Transformation Act of 2010	22 June 2010	United States Senate	Rare Earth Supply Technology and Resource Conversion Act of 2010. Congress stated that: (1) the United States faces shortages of critical rare earth materials that are the backbone of the defence and energy supply chains; (2) there is an urgent need to rebuild the domestic rare earth supply chain, and statutory priorities are needed to support such rebuilding; (3) there is an urgent need to support innovation, training, and workforce development in the domestic rare earth supply chain; and (4) the Departments of Energy, the Interior, Commerce, and Defense shall provide funding to academic institutions, federal laboratories, and private entities, respectively, for innovation, training, and workforce development in the domestic rare earth supply chain
2	2010 Critical Minerals Strategy	22 October 2010	U.S. Department of Energy (DOE)	Proposes that the U.S. Critical Minerals Strategy should promote the extraction, production, recovery, and reuse of critical minerals. Increase supply chain security for critical minerals and improve market transparency and information sharing on critical minerals
3	Rare Earths and Critical Materials Revitalization Act of 2011 H.R. 618—Rare Earths and Critical Materials Revitalization Act of 2011	10 February 2011	United States Congress	Rare Earths and Critical Materials Revitalization Act of 2011—Establishes a programme of research, development, and commercial application in the DOE to ensure the long-term, secure, and sustainable supply of rare earth materials to meet U.S. national security, economic well-being, and industrial production needs. Directs the Secretary of Energy to (1) support new or significantly improved processes and technologies (as compared to those currently used in the rare earth materials industry); (2) encourage multidisciplinary collaborations to provide opportunities for students at institutions of higher education, and (3) submit an implementation plan to Congress. Amends the Energy Policy Act of 2005 to authorize the Secretary to enter into loan guarantee commitments for the commercial application of new or significantly improved technologies for specified projects. Amends the National Materials and Minerals Policy, Research, and Development Act of 1980 to: (1) direct the Director of the Office of Science and Technology Policy to coordinate federal materials research and development through the National Science and Technology Council (rather than, as is now required, the Federal Coordinating Council for Science, Engineering, and Technology, which no longer exists); (2) modify the Secretary of Commerce's responsibilities with respect to critical needs assessments; (3) repeal the specified reports and other responsibilities of the Secretaries of Defense and the Interior. Repeals the National Critical Materials Act of 1984
4	American Mineral Security Act of 2015	26 March 2015	Adopted by the United States Congress	This bill amends the National Materials and Minerals Policy, Research, and Development Act of 1980 to direct the President to: (1) establish an analytical and forecasting capability to identify critical mineral market factors to avoid supply shortages, mitigate price volatility, and prepare for demand growth and other market changes; and (2) encourage federal agencies to promote the development and production of domestic resources to meet the Nation's critical materials and mineral needs

(continued)

Table 3.1 (continued)

ID	Name	Timing	Launching office	Key initiatives/Content
5	Executive Order 13,806	21 July 2017	The Trump Administration 2017–2021	Requires the Secretary of Defense, in coordination with the Departments of Commerce, Labor, Energy, and Homeland Security, and in collaboration with other Departments, to conduct an assessment of U.S. manufacturing capabilities, the defence industrial base, and supply chain resilience
6	Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resilience	5 October 2018	Led by the Department of Defense's Office of Manufacturing and Industrial Base Policy, with participation from multiple government departments, including the Departments of Commerce, Labor, Energy, and Homeland Security	At the request of Trump's Executive Order 13,806, nine working groups focus on traditional sectors, including aircraft, biological, chemical, nuclear, and radiological, land systems, munitions and missiles, warheads for nuclear material, radar and electronic warfare, shipbuilding, man-portable systems, and space; and seven additional working groups assess cross-cutting capabilities, including manufacturing cybersecurity, electronics industry, machine tools and industrial controls, materials, organics fundamentals, and software engineering workforce. The report concludes that there are five major challenges to the U.S. manufacturing and defence industrial base and supply chain: uncertainty about deficit reduction and government spending; declining manufacturing capabilities and capacity; disruption of government business and procurement practices; industrial policies of competitor nations; and shrinking science, technology, engineering, and mathematics and professional skills human resources. It is also suggested that the five challenges mentioned above have changed the industrial base and future trends of the United States, resulting in the impairment of U.S. capabilities; and that the risks and challenges facing the United States have led to insecurity in the supply chain of the U.S. Department of Defense
7	Executive Order 13,817	20 December 2017	The Trump Administration 2017–2021	Requires the Secretary of the Interior to take the lead in developing a list of critical minerals and the Secretary of Commerce to take the lead in developing a strategy to reduce dependence on critical minerals
8	Critical Minerals List 2018	February 2018	United States Department of the Interior	Lists 35 critical minerals on which the U.S. has a high level of foreign dependence and which are critical to U.S. economic development and national security
9	Federal Strategy to Ensure a Safe and Reliable Supply of Critical Minerals	4 June 2019	U.S. Department of Commerce	The supply chain for critical minerals was assessed, and ways to strengthen the supply chain through recycling, reprocessing and identifying alternative minerals and materials, diversifying the supply chain through trade with allies and partners, and streamlining the permitting and review process were identified. It is recommended that the U.S. government take measures to promote domestic production of rare earths and other critical minerals, including by advancing the transformation of the critical minerals supply chain, strengthening cooperation with allies, and reducing restrictions on the authorization of domestic mineral resource development

(continued)

Table 3.1 (continued)

ID	Name	Timing	Launching office	Key initiatives/Content
10	Energy Resource Governance Initiative	June 2019	U.S. Department of State	Nine countries—the Democratic Republic of the Congo, Zambia, Namibia, Botswana, Peru, Argentina, Brazil, the Philippines, and Australia—have joined the United States–sponsored Energy Resources Governance Initiative. The United States will share its mining experience with these countries to help them explore and develop minerals such as lithium, copper, and cobalt
11	Executive Order 13,953	September 2020	The Trump Administration 2017–2021	Arranges for the Departments of the Interior, Treasury, Defense, and Commerce to investigate the extent of U.S. dependence on critical minerals, establish a secure supply chain for critical minerals, and prioritize the expansion and protection of the domestic mineral supply chain to reduce the potential for supply chain disruptions
12	Energy Bill 2020	December 2020	Adopted by the United States Congress	Defines "critical minerals" as non-fuel minerals or mineral materials that are critical to the United States economy or national security and for which the supply chain is vulnerable
13	Executive Order 14,017	1 March 2021	The Biden–Harris Administration 2021–2024	Call for an immediate review of vulnerabilities in the supply chain of critical minerals and high-capacity batteries, including electric vehicle batteries
14	Energy Resources Governance Initiative Act of 2021	22 April 2021	Adopted by the United States Congress	The bill establishes the Energy Resource Governance Initiative within the Department of State to promote responsible and sustainable mining practices through international cooperation. The initiative must seek to promote integrated and resilient supply chains, responsible sourcing of critical minerals, and good governance in the mining sector. It must also seek to minimize the potential adverse impacts of increased demand for renewable energy on mineral-rich countries
15	Building Resilient Supply Chains, Revitalizing U.S. Manufacturing, and Promoting Broad-based Growth	June 2021	U.S. White House Report	As requested by the Biden Administration in Executive Order 14,017, an assessment of supply chains for four key product categories, including high-capacity batteries and strategic and critical minerals, concluded that China's comparative resource advantage and so-called "unfair competition," among other things, severely exacerbated supply chain risks in the United States
16	List of Critical Minerals 2022	31 January 2022	United States geological survey (USGS)	The catalogue of critical minerals was adjusted from 35 types in 2018 to 50 types, with 20 types added and 5 removed. The main changes are as follows: First, the "rare earth elements" in the old catalogue are now 15 minerals, including "cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, terbium, thulium, ytterbium and yttrium." "Scandium" is still retained separately as a rare earth element, but "promethium" is not retained as a rare earth element. Secondly, the "platinum group elements" in the old version of the catalogue are now "iridium, platinum, palladium, and rhodium." In addition, the "platinum group elements" in the old version of the catalogue were changed to "iridium, platinum, palladium, rhodium, ruthenium" and five other minerals, but "osmium" as a platinum group element did not enter the catalogue. Thirdly, two minerals, such as nickel and zinc, were added. And fourthly, five minerals, namely helium, potassium, rhenium, strontium, and uranium, were excluded

(continued)

Table 3.1 (continued)

ID	Name	Timing	Launching office	Key initiatives/Content
17	Ensuring a Made-in-America Supply Chain for Critical Minerals	February 2022	U.S. White House	Major investments in the domestic production of critical mineral materials, such as lithium, graphite, and rare earths, are announced, with the explicit aim of "strengthening reserves of critical minerals."
18	U.S., Canada, others establish Minerals Security Partnership	June 2022	U.S. Department of State	The United States establishes mineral security partnerships with Canada, Australia, Finland, France, Germany, Japan, South Korea, Sweden, the United Kingdom, and the European Union to promote cooperation with allies and strengthen indigenous processing capacity to reduce dependence on Chinese products
19	Draft Critical Mineral Independence Act of 2022 S.5195 -critical mineral independence act of 2022	December 2022	Senator Dan Sullivan	To enhance the national security of the United States by reducing the Department of Defense's dependence on critical minerals from China, and for other purposes. Expanding the mining and processing of critical minerals, including rare earth elements, in the United States and allied countries to meet the needs of the U.S. Department of Defense so that the Department of Defense achieves independence in the critical mineral supply chain by 2027

into regional security planning to ensure that the U.S. has a decidedly dominant position in the global competition for green tech. In June, the U.S. Senate passed the high-vote 2021 American Innovation and Competition Act, which originated from the Endless Frontier Act proposed during the Trump administration and which integrates a number of China-related technological competition bills such as the 2021 Strategic Competition Act and the 2021 Responding to China's Challenges Act. The bill makes numerous references to building the resilience of critical mineral supply chains, covering a variety of dimensions such as mining research, technological innovation, recycling, as well as the development of the mineral workforce and the promotion of international cooperation in minerals. As the Biden administration pushes for a Green New Deal to develop new energy vehicles, energy storage, wind power, and photovoltaic industries, the vulnerability of the U.S. in terms of its heavy dependence on foreign countries for critical mineral resources such as rare earths, lithium, platinum, zinc, nickel, manganese, chromium, molybdenum, vanadium, and graphite has been further accentuated (Dou et al. 2023). The U.S. federal government has stepped up coordinated, issue-led, "whole-of-government, cross-sector" actions.

(3) Strategy Centres on Promoting Supply Chain Alliance-Building

A critical minerals supply chain alliance is a key link for the U.S. to strengthen its own supply chain security, as well as its ability to dominate the global green economy and compete with China (Home 2022). The U.S. and its allies have a common interest in mineral resource cooperation. In June 2019, the Trump administration launched the Energy Resources Governance Initiative (ERGI) in partnership with Australia, Botswana, Canada, and Peru. Under the ERGI, the U.S. will share mining expertise with other countries to help them explore and develop their mineral resources. The initiative is in effect a U.S.-led "critical minerals coalition," in which the U.S. will work with resource-based allies, such as Canada and Australia, to deepen cooperation in the supply chain and propose regulatory standards for management and governance frameworks. In December 2019, the U.S. Geological Survey, along with Geoscience Australia and the Geological Survey of Canada, proposed the Critical Mineral Mapping Initiative, which aims to increase the reliable supply of critical minerals by identifying their current distribution through a deeper understanding of known critical mineral resources. The initiative released a global mineral map in June 2020 to help the United States and its partner countries secure supply chains as global demand for critical minerals accelerates. The Interim National Security Strategic Approach integrates allies and partners in a united front through a values-based approach, with the goal of reshaping the supply chain to create an interest-based approach that strengthens supply chain security internally and enhances U.S. competitiveness externally. During the Earth Leaders Climate Summit in April 2021, the U.S., along with Canada, Norway, Qatar, and Saudi Arabia, announced the formation of a Net-Zero Producer Forum in the fall of 2021 to coordinate the production of critical energy and minerals. In June, the U.S. and the European Union signalled a concerted effort to address global supply chain risks in areas such as critical minerals and semiconductors at the G7 Summit, and the G7 Resilience Group identified supply chain resilience as a key point in its report. In its report, the G7 Economic Resilience

Group identified supply chain resilience as a key point and proposed the establishment of a "Critical Supply Forum" to identify risks and strengthen coordinated responses.

European Union

The European Union is also active in the strategic guidance of critical minerals and the supply of raw materials, and its relevant policy documents tend to use the concept of "critical raw materials." As early as 2008, the EU put forward the Raw Materials Initiative. In March 2023, the European Commission promulgated the Critical Raw Materials Act, which specifies the need to strengthen production capacity for 34 critical raw materials, including lithium, cobalt and nickel, and to set benchmarks for intra-EU production capacity in the raw materials supply chain. The Act stipulates that by 2030, 10% of the EU's annual raw material consumption should come from domestic mining, 40% from processing in the EU, and 25% from recycling. For 17 of these "strategic raw materials" (magnesium is also listed), the bill requires that no more than 65% of the supply come from a single third country (Hool et al. 2024). Similar to the U.S., the EU seeks to strengthen its indigenous mining and processing capabilities and build stronger trade relationships in the minerals sector with countries in other parts of the world by issuing a number of strategic initiatives to increase its control over raw materials and related technologies. Also in March 2023, the EU issued the Net-Zero Industry Act to improve the competitiveness and resilience of its net-zero technology industrial base. The EU has also proposed a number of measures to stimulate investment in net-zero technologies and improve their competitiveness. In addition, the bill refers to tools such as the introduction of sustainability and resilience criteria in procurement procedures, increased training and education in net-zero technology skills, and the creation of a regulatory sandbox to stimulate innovation. The EU introduced the Act mainly to ease the pressure on European industry from national subsidy policies such as the Inflation Reduction Act in the United States and to get rid of the high dependence on imports in some clean industries.

In addition to strengthening local supply, the EU is promoting supply chain diversification. In terms of strategic partnerships, the EU has strengthened technology development and standards cooperation with Western countries and enhanced supply chain diversification through cooperation with developing countries. In June 2022, the EU joined the U.S.-led Partnership for Mineral Security in an attempt to build a so-called "strong and responsible" supply chain for critical minerals, and in June 2023, the EU agreed with the U.S. on a negotiating directive for the Critical Minerals Agreement, which will facilitate EU-U.S. supply chain cooperation. At the same time, the EU also cooperates with developing economies such as India and with African countries. In April 2022, the EU and India set up the Europe-India Trade and Technology Committee, in which the Working Group on Green and Clean Energy Technologies is dedicated to R&D and innovation in green technologies and standards cooperation, and the Working Group on Trade, Investment and Resilient Value Chains is dedicated to green and resilient supply chains and the security of supply of key components and raw materials. In October 2023, the EU signed an agreement on cooperation on value chains for key raw materials with the DRC and an agreement on cooperation on sustainable value chains for raw materials with Zambia, pursuing five areas of cooperation: integration of sustainable value chains for raw materials, financing of infrastructure development, sustainable and responsible production, R&D cooperation, and capacity-building for compliance.

Japan

Japan has attached great importance to the issue of securing its supply of mineral resources for many years, and it has accelerated its efforts in the following areas.

First, review of critical mineral investments was strengthened to reduce the vulnerability of the country's industries. In August 2021, the Japanese government took measures to strengthen control of (restricting) foreign investors from exploring and mining 34 rare metals, including tungsten, molybdenum, rare earths, lithium, cobalt, and indium, and added important mineral industries such as tungsten, molybdenum, and rare earths to the list of the key review of foreign investments in the Amendments to the Foreign Exchange Law with the aim of minimizing the vulnerability of the country's supply chain for key raw materials. The bill provides that foreign investors will be subject to pre-screening when acquiring 1 per cent or more of a company in a core sector, significantly lower than the previous 10 per cent share acquisition requirement.

Second, international cooperation is being strengthened to ensure the supply of critical minerals in the country. Japan has signed cooperation agreements with mineral resource countries, such as Brazil and the DRC, to strengthen cooperation on the supply of mineral resources. In January 2021, Japan and Brazil signed a cooperation agreement aimed at promoting the production of niobium and graphene in Brazil through new technologies. In December 2022, the Japanese government signed a joint statement with the DRC, which included cooperation in the field of mining, with the aim of securing interests and concluding long-term supply contracts in the southern mines of the DRC, among other goals.

Third, Japan also maintains good cooperative relations with the United States to enhance diversification of the supply chain for critical minerals and to ensure the overseas interests of its own companies. In October, the Japanese and U.S. governments announced a trade agreement on minerals related to clean energy technologies, in which the two countries agreed not to impose export tariffs on trade in critical minerals between them and to harmonize standards for the production of critical minerals. The agreement will be reviewed every six months. The mineral agreement will be reviewed every two years thereafter to determine whether it should be renewed or changed. Meanwhile, the agreement also prohibits the two countries from imposing bilateral export restrictions on the minerals most critical to electric vehicle batteries, including lithium, nickel, cobalt, graphite, and manganese. Under the agreement, electric vehicles using critical minerals sourced or processed in Japan will be subject to U.S. Inflation Reduction Act tax credits.

Fourth, Japan will strengthen the recycling of critical minerals and enhance the ability to sustainably secure resources. In May 2022, in order to secure the supply of metal resources, the Ministry of the Environment of Japan strengthened the recycling of used home appliances, etc., and it plans to increase the amount of domestic recycling, as well as importing and processing home appliances from overseas, in an effort to raise the amount to be processed in 2030 to double the current amount.

Korea

Like Japan, South Korea is highly concerned about the supply of critical mineral resources, and recent years have seen a succession of government policies and corporate initiatives.

First is strengthening the management of critical minerals and ensuring the supply of critical minerals in the country. In August 2021, the South Korean government convened the 42nd Emergency Economic Central Countermeasures Headquarters Meeting and released "Countermeasures for the Development of the Rare Metals Industry, Version 2.0," in which it is decided to increase the reserves of tungsten, molybdenum, rare earths, and other rare metals by one-fold to ensure 100 days of usage. This is a significant increase from the previous reserve of 57 days.

Second is to strengthen international industrial cooperation to secure access to mineral resources overseas. In January, South Korea and Australia signed a memorandum of understanding on cooperation in critical mineral supply chains, which will build on the two countries' previous commitments to further strengthen cooperation in the resource and energy sectors, particularly by expanding cooperation in technology, trade, and investment. In September 2021, the leaders of South Korea and Canada announced in a joint statement that they would deepen their strategic partnership on supply chain resilience, seeking to position the two countries as globally competitive players in critical mineral supply chains as well as in the battery and electric vehicle value chains. Through a memorandum of understanding, they intend to build a value chain between the two countries that includes critical minerals and supports the clean energy transition and energy security.

Thirdly, South Korea will strengthen cooperation in overseas investment by enterprises to ensure the security of the supply of critical minerals. In order to encourage private enterprises to actively develop overseas mineral resources, the South Korean government will expand preferences in finance and taxation, reintroduce tax credit benefits for investment projects in overseas resource development, and expand the scope of compensation for losses. The government will also expand the amount of and items in critical mineral reserves by investing 270 billion won (1.43 billion yuan) to establish a dedicated reserve base for critical minerals in the Saemangeum Industrial Complex (Yonhap News Agency 2023).

3.2.2 Main Mineral-Supplying Countries/Areas

In the context of the current great power game, major mineral resource countries around the world have adopted nationalization, export bans, and higher tax rates to strengthen their resource sovereignty and control the flow of resources in order to enhance the value of resources. The following are the latest developments in major mineral resource countries.

Australia

As a globally significant mineral resource country, Australia has focused heavily on the security of critical mineral resources in recent years. Its Critical Minerals Strategy, first released in 2019, defines critical minerals as minerals used in a range of emerging high-tech applications in a variety of sectors, including renewable energy, aerospace, and defence. Since its initial release, the Australian government has updated it (in 2022 and 2023) to reach corresponding objectives, including: creating diverse, resilient, and sustainable supply chains through strong and secure international partnerships; building sovereign capacity in the processing of critical minerals; utilizing its own critical mineral resources to make Australia a renewable energy superpower; and keeping more of the value extracted from critical mineral resources within Australia to create jobs and economic opportunities. In the new Critical Minerals Strategy 2023, the Australian government wants to unlock its significant potential as a major supplier of the critical minerals needed to decarbonize the global economy. Specifically, the government hopes to expand Australia's presence in the global critical minerals chain by driving the country's critical minerals industry into downstream processing, thereby creating economic opportunities and jobs.

Australia wants to reshape the supply chain of the critical mineral industry chain in the Indo-Pacific and seeks to become a critical mineral supply chain power in the region. To this end, its government is focusing on domestic critical minerals industry research and development and the construction of regional centres to build a localized industry chain ecosystem; secondly, it is to radiate to the Indo-Pacific to give play to the competitive advantage of the supply chain. Focusing on critical minerals, Australia wishes to increase the localization layout, hoping to change from a single critical mineral resources supplier to the core country of the Indo-Pacific critical mineral industry supply chain.

At the same time, the Australian government has actively pursued cooperation with allied countries. In Australia's Critical Minerals Strategy, the term "like-minded countries" appears several times, reflecting its intention to reduce the current "high degree of concentration" in the critical minerals industry chain by strengthening cooperation with allies such as the United States, and to regard critical minerals as an important means of competing for supply chain dominance. For example, in November 2019, Geoscience Australia and the U.S. Geological Survey signed the U.S.-Australia Critical Minerals Partnership Agreement to deepen understanding and expand the supply of critical minerals, and in March 2020, Australia and the United States advanced a joint action plan to increase the resilience and diversity of the critical minerals global supply chain. In particular, the U.S. and Australia are closely enhancing the strength and depth of cooperation in sustainable development and the utilization of rare earth, lithium, and cobalt resources, and have developed a more consistent approach to China. This has accelerated transformation of the U.S.-Australia alliance into an exclusive and competitive "de-Chinaization," with Australia becoming an indispensable fulcrum in U.S. global geopolitics. In addition, the Australian government has placed special emphasis on cooperation with the Indo-Pacific countries, and it believes it can seize the strategic initiative and expand strategic space in Indo-Pacific affairs with its critical minerals.

Chile

Chile has been pushing forward with nationalization of its lithium mines in recent years (Financial Times 2023). In April 2023, Chilean President Gavriel Borich said he would push for the nationalization of Chile's lithium industry and the establishment of a state-controlled lithium company, while emphasizing that future lithium development contracts would only be open to public–private partnerships under the control of the state. In addition, Chile launched a mining tax reform in 2023 in order to increase government revenues, a move that will require Chile's large copper and lithium producers to pay more taxes and royalties to the government in order to increase government revenues.

Mexico

Mexico, a globally important mineral resource country, is also actively promoting the nationalization of lithium mining (Reuters 2023a, b). In April 2022, the Senate of the Mexican Congress passed President Obrador's bill on the state's monopoly on lithium battery metal development with 87 votes in favour, 20 votes against, and 16 abstentions, formally beginning nationalization of the industry. The bill upgrades lithium to a "strategic mineral" and declares that the state has a monopoly on the exploration, development, and utilization of lithium resources. In addition, the bill allows the state to enjoy the franchise of other minerals classified as strategic minerals. Lithium, after nationalization of its reserves, will be handed over to Ministry of Energy management, no longer granted any mineral rights, licences, contracts, approvals, or management authority. At the same time, Mexico also set up a state-owned lithium company (LitioMx), and the Mexican Ministry of Energy is responsible for its operation and management.

Indonesia

In order to develop the mineral resources processing industry, attract foreign investment to the mineral industry, increase employment opportunities, and raise the proportion of high-value-added products and export revenues, Indonesia, a major mining country, has in recent years banned the export of many kinds of raw minerals and required that metal minerals be exported only after completion of high-value-added processes in the country. In January 2020, Indonesia's ban on the export of nickel raw materials came into effect. In December 2022, Indonesian President Joko Widodo announced a ban on the export of bauxite ore starting from June 2023 in order to boost the development of the local aluminium-processing industry. In January 2024, the ban came into effect. On 26 January 2024, the President of Indonesia announced at the Saratoga Investment Summit that after a ban on copper exports came into effect, tin exports would also be banned in the short term (Nangoy and Christina 2022). The ban on tin exports is expected to come into effect in the near future. These policies are aimed at enhancing domestic mineral processing in Indonesia and bringing added value to the mineral supply chain for its economy, thereby boosting employment and economic development.

Philippines

The Philippines, a major global supplier of nickel ore, has also undertaken mining tax reforms through high mining taxes and fees in order to encourage domestic processing of minerals (Reuters 2023a, b). In August 2022, a Philippine House of Representatives committee approved a new mining fiscal regime that would increase the country's mining tax rate from 38 to 51%. This adjustment will help the Philippine government increase mining revenues to US$37.5 billion in the first year of implementation. Under the proposed measure, the Philippine government will also impose a 5 per cent royalty tax on the market value of total production from large-scale mining operations.

3.3 Strategic Opportunities and Challenges for China's Critical Mineral Security Strategy

3.3.1 Strategic Minerals Have Strong Industry Chain Relevance, Becoming the Focus of the Game of Big Countries

With the global energy transition and a new round of scientific and technological revolution and industrial change advancing in depth, critical minerals or strategic mineral resources have become a new area of strategic game for major global powers (Vivoda et al. 2024). The industrial supply chain structure of strategic mineral resources, including resource extraction, refining and processing, material manufacturing, and end-use applications, spans a number of material industries and manufacturing industries and involves complex international trade flows. On the one hand, the global competition for strategic mineral resources has spread from the primary mineral resources to the whole of the industrial supply chain and has become the focus of big countries. The U.S., Japan, and European and other countries have clearly pointed out that their critical mineral needs and China's have a competitive relationship and that they regard China as the primary competition for resources. On the other hand, the Russia–Ukraine conflict has had an impact on the global mineral supply chain, leading to significant fluctuations in mineral prices, which will promote reconstruction of global energy and mineral resource patterns. Currently, the global supply and demand situation of strategic minerals is characterized by scarcity of resources and their relatively concentrated distribution, explosive growth in demand due to the low-carbon energy transformation, and the tightening of mining policies by resource-exporting countries, which further intensifies the global competition for strategic mineral resources. The security of strategic minerals has risen to become a global and strategic issue related to national economic and social development.

3.3.2 China Faces the Risk of "Decoupling" as the World Intensifies Its Strategic Layout of Strategic Minerals

At the strategic level, the world has stepped up its strategic placement of strategic minerals. The U.S. and other major countries around the world have successively released strategies or lists of critical minerals. In June 2021, as a response to President Biden's "100-Day Review Order" in Executive Order 14,017, the U.S. White House released a report entitled *Building Resilient Supply Chains, Revitalizing U.S. Manufacturing, and Promoting Broad-Based Growth*, which comprehensively analyses the supply chain vulnerabilities of four key products, including high-capacity batteries and critical mineral materials, from a risk assessment of the global situation to opportunities and challenges, and makes countermeasure recommendations. In February, the U.S. Geological Survey published a new catalogue of 50 critical minerals and stated that these minerals are vital to the U.S. economy and national security. In addition, some countries led by the United States have adopted alliances to suppress China and to attempt to "decouple" from China. The U.S., Australia, and European and other countries have proposed building a domestic supply chain for critical minerals, and in June 2022, the U.S. established the Mineral Security Partnership with Canada, Australia, Finland, France, Germany, Japan, South Korea, Sweden, the UK, and the European Union to promote cooperation with allies and strengthen local processing capacity in order to reduce the dependence on China in the field of critical minerals. Major global economies such as Japan, the EU, the UK, and Australia have also released resource and mineral strategies to make strategic plans to enhance critical mineral security. For example, the EU released the *Strategic Technology and Product Supply Chain Assessment Report* in 2020 to assess the security of the supply chain of nine key technologies such as lithium-ion batteries and fuel cells related to the EU's three strategic sectors of renewable energy, electric mobility, defence and aviation. Currently, China, the United States, and the European Union have a high degree of overlap in strategic minerals, including chromium, lithium, cobalt, nickel, beryllium, zirconium, niobium, tantalum, and manganese, which are in short supply in China and have a higher supply risk, and there is a greater potential competition and risk of being "strangled." The risks and challenges posed by the global competitive situation to the security of supply of China's strategic mineral resources cannot be ignored.

3.3.3 Continued Strong Demand for Strategic Minerals, High External Dependence on Some Minerals, and Supply Risks

With its rapid development of strategic emerging industries, China's demand for critical minerals continues to increase. China is currently the world's largest mineral resource consumer and trader, with 36 kinds of mineral consumption ranking first in the world, and 20 kinds of minerals whose consumption accounts for more than 50% of the world's. In 2021, China was dependent on the outside world for 28 kinds of minerals, and 16 kinds of major solid mineral resources were net imports; among the minerals with larger net imports were iron ore, aluminium, manganese, copper, sulphur, and chromium. It is externally dependent for more than 70% of niobium, beryllium, zirconium, nickel, manganese, tantalum, cobalt, platinum group, chromium, oil, copper, and other 11 kinds of minerals it uses. Specifically, the degree of foreign dependence on iron ore is 82%, chrome ore is 98%, manganese ore is 96%, cobalt ore is 95%, nickel ore is 90%, and copper ore and petroleum are both 78%. Taking cobalt, nickel, and lithium as examples of three important mineral resources in new energy industrial technology, 80% of China's cobalt resources come from the DRC, lithium comes mainly from Australia, and nickel resources come mainly from the Philippines and Indonesia. These minerals have high degrees of external dependence and concentrated sources, with potential supply risks. Influenced by the geopolitical factors of the resource countries, the security challenges of China's critical mineral resources will become more prominent in the complex and uncertain global competitive situation and with the rapid development of the new energy industry.

3.3.4 Difficulty in Coordinating and Balancing the New Round of Mineral Resource Planning and Ecological Protection

At present, China has a relatively systematic and complete planning and implementation norms and guarantee system, but there is room for improvement in the articulation of related planning. The coordination between the ecological protection red line and national strategic mineral exploration and development has become a key issue to be solved. In August, the Ministry of Natural Resources, the Ministry of Ecology and Environment, and the State Forestry and Grassland Administration jointly issued the Notice on Strengthening the Management of the Ecological Protection Red Line (for Trial Implementation) (Natural Resource Issuance [2022] No. 142) (hereinafter referred to as "Circular 142"). Circular 142 stipulates:

> within the ecological protection red line, strategic mineral prospecting rights for chromium, copper, nickel, lithium, cobalt, zirconium, potash, and (medium-) heavy rare earth ores and other strategic minerals that have been established and newly established in accordance with the law to carry out prospecting activities may be subject to the prospecting right registration, and where mining activities are required due to the national strategic needs, they may be subject to the registration of the mining right. Measures to mitigate ecological and environmental impacts need to be implemented, and the relevant requirements for green exploration, mining and ecological restoration of the mining environment need to be strictly enforced.

However, as the existing Regulations of the People's Republic of China on Nature Reserves (the "Regulations") stipulate that mining is prohibited in nature reserves, despite the state's issuance of the "Opinions on Delineating and Strictly Abiding by the Ecological Protection Red Line" and the "Letter on Doing the Preliminary Relevant Work on Optimizing and Adjusting the Scope and Functional Zones of Nature Reserves" in February 2017 and March 2020, respectively, which are aimed at resolving through adjustment of unreasonable spatial layouts, villages, towns, mining rights, and other realistic conflicts and historical problems in nature reserves. However, as the adjustment of protected areas requires strict procedures and a high level of approval, coupled with the fact that some administrative organs do not have a clear understanding of the shortage of important strategic minerals, some provinces and municipalities are currently neglecting the security of resources. They are one-sidedly emphasizing environmental protection and promoting the withdrawal of mining rights across the board in the implementation of Circular 142, resulting in difficulties in the continuation of mining rights with their "one-size-fits-all" approach. This has led to the continuation of mining rights becoming a practical problem faced by many mining enterprises, which is not conducive to the breakthrough of mineral search, increase of reserves and production, and security of mineral resources.

3.4 Conclusion

This chapter deeply and systematically explores the complex game dynamics among global mineral resource powers and the strategic and policy movements behind them, thus presenting a multi-dimensional and multi-layered geopolitical picture of mineral resources.

First, the chapter focuses on the new dynamics of global mineral geopolitics, revealing a global trend in the localization and "de-Chinaization" of supply chains. This trend reflects the importance that countries attach to resource security, but it exacerbates the volatility of the international mineral resources market. At the same time, international cooperation is becoming increasingly obvious, with countries forming cooperative alliances based on common interests, further shaping the competitive landscape in the sector. The rise of resource nationalism, on the other hand, reflects countries' resolute defence of their own resource sovereignty and poses restrictions on the free flow of global mineral resources. In addition, the trend towards the financialization of the mineral resources market has been significant, and the role of financial capital in resource allocation has become increasingly prominent, adding new uncertainties and complexities.

Second, the chapter analyses the strategies and policy trends of major economies in the area of critical minerals from the perspective of mineral demand and supply countries. On the demand side, the major economies of the United States, the European Union, and Japan have been placing increasing emphasis on the security of critical mineral supply and have sought to occupy a favourable position in the competition for resources by diversifying their supply strategies, strengthening international cooperation, and reinforcing supply chain partnerships. The major mineral-supplying countries, on the other hand, have adopted nationalization, export bans, and higher tax rates to strengthen resource sovereignty and to control resource flows in order to enhance resource value. These strategic and policy adjustments reflect the urgent need of countries for resource security.

Finally, the chapter provides in-depth discussion of the strategic opportunities and challenges facing China's critical mineral security. China's demand for strategic minerals continues to be strong, and some minerals have a high degree of dependence on the outside world. Against the backdrop of global intensification of the layout of strategic minerals, China faces the risk of "decoupling" from the supply chain. In addition, there is an urgent need to explore the coordination and balance between the protection of ecological resources and the breakthrough of national strategic mineral search. China should strengthen international cooperation, optimize resource allocation, and promote the security and stability of the critical mineral industry chain. At the same time, it is also necessary to be alert to the uncertainty of the international environment, especially the potential threat to China's resource security posed by resource nationalism and supply chain localization.

To summarize, through its in-depth analysis of the global mineral resource big power game, this chapter reveals the new situation of mineral resources geopolitics, the strategies and policy trends of major economies, as well as the challenges and opportunities faced by China, thus providing useful references and perhaps inspirations for scholars, policymakers, and practitioners in related fields.

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Chapter 4
Solar Industry and Critical Mineral Trade Network Security

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Abstract The rapid expansion of the solar industry, which is the core part of the sustainable energy system, has made the stable supply of critical minerals a topic of attention globally. In this chapter, the growth trends of the solar industry in China and globally, the global distribution of critical minerals, and the major countries' strategic positions in international trade patterns are discussed. The chapter also establishes a trade security index to measure the security of the global trade network and the strategic importance of countries. The study reported here shows that selenium has the highest trade risk, and risks in the trade network are gradually increasing. The countries that affect the stability of critical mineral trade in the solar industry are mainly major countries such as China, the United States, Japan, and South Korea, as well as those with a wealth of resources and major transit countries. In terms of policy, the United States has invested funds in tellurium and cadmium. China pays attention to bulk mineral energy resources, and European countries attach importance to rare metals.

Keywords Solar energy · Critical minerals · Complex networks · Trade risk

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4.1 Development Trends in the Solar Industry

The solar industry encompasses two main fields: solar thermal utilization and solar photovoltaic (PV) power generation. Solar thermal utilization refers to the process of converting solar energy into other forms of energy, such as heating and hot water production, or to meet thermal energy demands in industrial processes. Solar PV power generation, on the other hand, involves the use of photovoltaic cells to directly convert solar radiation into electricity, and it holds a significant position in the clean energy sector. PV systems can be widely deployed on various types of buildings and terrains, ranging from small residential rooftop systems to utility-scale power plants. These systems are characterized by high energy conversion efficiency, environmental friendliness, and renewability. As technology advances and costs decline, the market for PV power generation continues to expand, making it one of the key drivers of the global energy transition. While solar thermal utilization still plays a role in certain specific areas, solar PV power generation is considered the most promising and significant application in the energy industry, providing strong support for achieving sustainable energy development goals.

4.1.1 Development of the Global Solar Industry

According to the report *Renewables 2023 Analysis and Forecast to 2028,* the solar PV industry experienced significant cost reductions from 2010 to 2022. During this period, the global average levelized cost of electricity (LCOE) for solar PV decreased from US$105 per megawatt-hour to US$35 per megawatt-hour, while the LCOE for utility-scale solar PV plummeted from US$450 per megawatt-hour to US$50 per megawatt-hour, a reduction of nearly 90%. Since 2019, variable renewable energy projects in many countries have become more cost-effective than many existing fossil fuel power plants, a trend that became particularly evident in 2022, as the Russia–Ukraine conflict resulted in significantly higher fossil fuel costs. In this price environment, the cost of utility-scale PV in most of the European Union has already fallen below that of coal and natural gas generation. Looking ahead, solar PV costs are expected to continue their downward trend.

Solar PV technology is the form of power generation most heavily invested in (Statista 2023). In 2022, global investments in new solar PV capacity increased by more than 20%, reaching a record high of US$320 billion. As of 2022, solar PV accounted for nearly 45% of global power generation investments, three times the total investment in all fossil fuel technologies. Given the policy support from governments and the increasing competitiveness of PV technology, investment in solar PV is expected to continue growing.

Despite the increasing cost competitiveness of the solar PV industry, policy support remains the primary driver for solar PV deployment and investment attraction in most regions worldwide. Policy-driven deployment refers to investment decisions primarily influenced by government policies, including auctions, feed-in tariffs, net-metering, and contracts for difference, among other policy types. Globally, several key policies implemented in recent years have significantly impacted the growth of solar PV capacity: During COP26 in November 2021, India announced new targets for 2030 aiming to achieve 500 GW of non-fossil power generation and a 50% share of renewable energy in its power generation mix, with solar PV being among the main technologies to meet these goals. In May 2022, the European Commission proposed raising the EU's 2030 renewable energy target to 45% as part of the REPowerEU plan, which will require a total installed capacity of 1236 GW of renewable energy, including 600 GW of solar PV. Many European countries have already expanded their solar PV support mechanisms to accelerate capacity growth, aiming to meet the 2030 targets and address the energy crisis caused by the Russia–Ukraine conflict. In February 2023, the European Commission announced the *Green Deal Industrial Plan*, which aims to support the expansion of clean energy technology manufacturing, including solar PV. In August 2022, the U.S. federal government introduced the Inflation Reduction Act, which significantly expands support for renewable energy over the next decade through measures such as tax credits.

In 2021 and 2022, the installed capacity of solar PV systems increased significantly (IEA 2024). In 2023, solar PV accounted for three-quarters of the world's new renewable energy power generation capacity. China contributed approximately 38% to global solar PV power generation growth in 2022. The European Union was the second-largest contributor (17% of the total), followed by the United States (15%). The resilience of the solar PV industry was demonstrated by its ability to overcome supply chain bottlenecks, high commodity prices, and rising interest rates in 2022, when it set a new annual record for additional capacity (220 GW).

Distributed systems are playing an increasingly important role in the global deployment of solar PV technology. The International Energy Agency (IEA)'s *Renewables 2023* report details the distribution of solar PV installed capacity across various sectors from 2015 to 2022 (Fig. 4.1). In 2022, utility-scale solar power plants accounted for approximately half of global new solar PV installed capacity, followed by distributed generation capacities in the commercial and industrial (25%) and residential (23%) sectors. The share of utility-scale solar power plants that year was at its lowest level since 2015. This trend is partly due to substantial policy incentives for distributed PV provided by China, Brazil, the United States, and the European Union during 2020–2021, which spurred growth in distributed PV installed capacity.

Among all renewable energy technologies, solar PV power generation saw the largest absolute increase in power output, surpassing wind power for the first time in history. Figure 4.2 shows the solar PV power generation from 2015 to 2022, where a record increase of 270 terawatt-hours (TWh) was observed in 2022, representing a 26% growth compared to 2021 and reaching nearly 1300 TWh. In the same year, solar PV accounted for 4.5% of total power generation globally, making it the third-largest renewable energy generation technology after hydropower and wind power. The continued growth in the economic appeal of PV, the large-scale development of supply chains, and increased policy support, particularly in China, the United States,

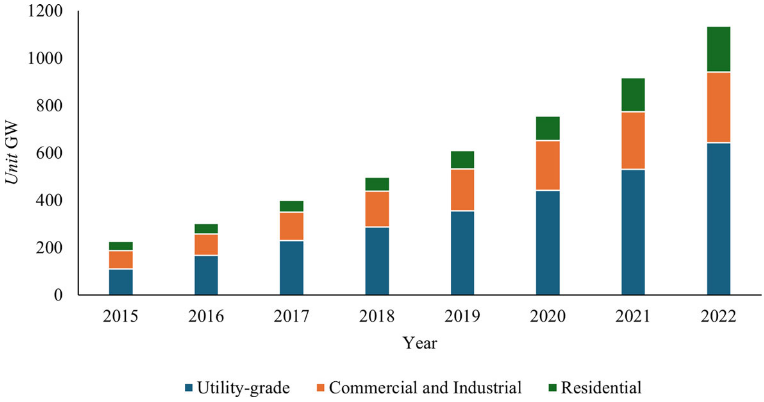
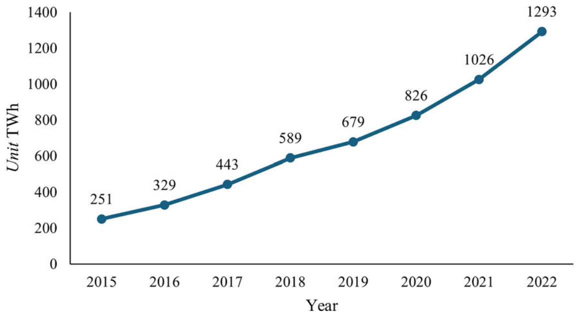


Fig. 4.1 Solar PV installed capacity by sector from 2015 to 2022. (*Source* IEA)

Fig. 4.2 Solar PV power generation from 2015 to 2022. (*Source* IEA)



the European Union, and India, are expected to further accelerate capacity growth in the coming years.

To meet the growing demand for clean energy, the solar manufacturing industry has undergone significant expansion over the past decade, with global growth increasing tenfold (Ballif et al. 2022). From the production of polysilicon to wafers and solar cells, the rapid expansion of solar PV power generation has been closely linked with the supply chain, which will undoubtedly accelerate the global clean energy transition. Specifically, the solar PV market is dominated by crystalline silicon technology, and its production process involves four main steps: (1) the production of high-purity polysilicon; (2) crystallization into ingots and slicing into thin wafers; (3) solar cell production; and (4) PV module assembly. In 2022, global solar PV capacity grew by over 70%, with an increase of nearly 200 GW. Polysilicon capacity reached 450 GW, while module capacity reached 640 GW. Looking ahead, based on manufacturers' investment announcements and the expected impact of industrial policies such as the U.S. Inflation Reduction Act of 2022, India's production-linked incentives, and the EU's Green Deal Industrial Plan, global capacity is expected to more than double over the next five years. During this period, China is likely to maintain its share of 80% to 95% of solar PV manufacturing capacity.

Crystalline polysilicon, as the core technology in PV module manufacturing, holds over 97% of the market share. This technology encompasses solar products using various types of wafers and cells, with some products achieving higher efficiency than others, giving their manufacturers a competitive advantage in a tight market. Currently, although PERC technology maintains its dominant position with nearly 60% market share, the market share of the more efficient TOPCon solar cell technology is gradually increasing. In 2022, approximately 25% of PV module production utilized TOPCon technology, and this proportion is expected to grow further (Solar Magazine 2023).

4.1.2 Development of China's Solar Industry

According to data provided by the China Photovoltaic Industry Association, the LCOE for PV power stations under the overall investment model is closely related to the initial investment, operation, and maintenance costs and to the number of power generation hours. Data from 2022 show that for different equivalent utilization hours (1800, 1500, 1200, 1000 h), the LCOE of ground-mounted PV power stations was 0.18, 0.22, 0.28, and 0.34 CNY/kWh (28.3, 34.6, 44.1, and 53.5 USD/MWh), respectively. Under the same conditions, the LCOE for distributed PV power systems was 0.18, 0.21, 0.27, and 0.32 CNY/kWh (28.3, 33.1, 42.5, and 50.4 USD/MWh), respectively. This indicates that despite differences in power generation efficiency, distributed systems can achieve economic benefits similar to those of ground-mounted stations at higher utilization hours. Currently, the main regions for distributed solar PV in China include Shandong, Hebei, Henan, and Zhejiang provinces, with economic viability already extending to most parts of the country. Bloomberg data further confirm that in 2022, the unit cost of solar PV power generation in China was 0.29 CNY/kWh (about 41.43 USD/MWh), which is already lower than the cost of coal power in 2010. This cost comparison highlights the economic advantage of solar PV power generation over traditional energy sources.

According to the IEA's *Renewables 2023 Analysis and Forecast to 2028*, policy-driven factors have contributed to approximately 95% of China's domestic economic growth. In 2020, China held competitive auctions with a national budget cap, but as the government gradually phased out subsidies for utility-scale solar PV projects, such auctions have ceased. Nevertheless, with the implementation of new green certificate regulations in 2022 and 2023, aimed at promoting interprovincial trade and effectively monitoring the achievement of renewable energy targets in each province, national policies will continue to drive the expansion of the solar PV industry.

China has maintained its global leadership in new solar PV installed capacity. According to data from the China Photovoltaic Industry Association, the newly installed capacity in 2022 reached a staggering 100 gigawatts, representing an increase of nearly 60% compared to 2021. In that year, distributed PV stations accounted for 58.5% of the total, surpassing the 41.5% of large-scale ground-mounted power stations. Among distributed stations, residential PV made up nearly half (49.4%). Additionally, due to persistently high supply chain prices in 2022, the actual growth of centralized installations fell short of expectations.

In the field of PV manufacturing, China's capacity growth has been particularly notable. According to IEA data, global solar PV capacity saw significant growth in 2022, with polysilicon capacity reaching 450 gigawatts and module capacity reaching 640 gigawatts. China accounted for over 95% of this global capacity expansion. As stated in the IEA's *The State of Clean Technology Manufacturing* report, approximately 85% of announced new solar PV manufacturing projects are located in China. It is evident that China plays a crucial role in advancing PV technology and optimizing the global energy structure as it continuously drives the transition towards a cleaner and more sustainable global energy system.

According to the IEA's *Renewables 2023 Analysis and Forecast to 2028*, China's solar PV industry is demonstrating strong momentum, overshadowing the slower progress in this field by other countries. The report points out that the current shortage in PV-grade polysilicon production capacity has been a major bottleneck in the PV supply chain. However, a significant increase in China's polysilicon capacity in the coming years is expected to fill this gap. Notably, the energy crisis triggered by the Russia–Ukraine conflict, along with the growing clean energy ambitions of many countries, will further drive global demand for PV. While the outlook for China's PV industry remains positive, close attention must be paid to technological innovation, policy support, and changes in market demand to ensure sustainable development and greater contributions to combating climate change (Bai et al. 2024).

Furthermore, during China's 14th Five-Year Plan period, the PV industry is expected to develop with a balanced focus on both centralized and distributed PV. As solar power fully enters the era of grid parity, coupled with the "carbon neutrality" goal and the development model of large-scale bases, centralized PV power stations are expected to experience a new wave of growth. On the other hand, with the integration of PV technology into sectors like construction and transportation, and the role of policy-driven factors, distributed PV projects are likely to retain a significant share in the market.

4.2 Global Distribution of Critical Minerals for the Solar Industry

4.2.1 Types of Critical Minerals

To better analyse the global trade competition landscape of critical minerals for renewable energy, we first identify the types of critical minerals required by technology based on data from the International Institute for Environment and Development (IISD 2018) and the International Renewable Energy Agency (IRENA 2019).

We also compile statistics on the major reserve countries and their cumulative global shares for each critical mineral in 2020, as shown in Table 4.1. It can be observed that gallium, germanium, indium, tellurium, cadmium, selenium, silver, and tin are specific minerals needed for the solar industry; molybdenum, cobalt, and chromium are specific to the wind energy industry; and graphite, lithium, and titanium are specific to the electric vehicle industry. The subsequent analysis will focus only on the specific minerals required by these industries.

The critical minerals specifically needed for the solar industry are cadmium, gallium, germanium, indium, selenium, silver, tin, and tellurium. Among these, gallium, germanium, indium, selenium, tellurium, cadmium, tin, and silicon are used in the production of semiconductors for solar cells. Nickel is commonly used for anodes in battery production, while zinc is often used for cathodes. Their specific applications in the solar industry are as follows.

Gallium, Germanium, Indium

Gallium is a soft, silver-coloured metal that is typically used in semiconductor components, making it crucial for the electronics industry (Shen et al. 2024). Gallium arsenide materials, known for their excellent energy conversion efficiency and outstanding luminescent properties, show significant application potential and research value in energy storage systems and solar cells. Its unique physical and chemical properties make gallium arsenide a key candidate material for current and future renewable energy technologies. Germanium's application in the PV field is particularly notable in concentrator cells and silicon–germanium thin-film cells, where it is primarily used as a substrate material for gallium arsenide solar cells (Osterthun et al. 2021). Indium is a metal widely used in the energy industry, particularly in solar PV devices. Statista's forecast for 2050 indicates that about 97.4% of indium used in energy technologies will be allocated to solar PV power, mainly for the construction of CIGS (copper indium gallium selenide) solar cells (World Bank 2020).

Cadmium, Tellurium

Cadmium telluride (CdTe) is a notable material for solar systems, showing significant potential in the solar cell field (SETO 2024). CdTe thin-film solar cells offer advantages of rapid production and low cost, providing an effective alternative to traditional silicon-based solar cell technology. The excellent photoelectric performance and material stability of cadmium telluride make it a hotspot in renewable energy research, with the potential for significant breakthroughs improving solar energy conversion efficiency and reducing costs. According to the U.S. Department of Energy, cadmium telluride solar cells are the second-most common PV technology in the global market, following crystalline silicon, and currently account for 5% of the

Table 4.1 Critical minerals required for solar energy, wind energy, and electric vehicle applications

	Solar power	Wind power	EVs	HS	Major reserve countries
Aluminum (Al)	√	√	√	2606	Guinea, Vietnam, Australia, Brazil, Jamaica, Indonesia (76%※)
Copper (Cu)	√	√	√	2603	Chile, Australia, Peru, Russia, Mexico, United States (60%※)
Iron (Fe)	√	√	√	2601	Australia, Brazil, Russia, China, Ukraine (75%※)
Lead (Pb)	√	√	√	2607	Australia, China, Peru, Mexico (74%※)
Rare Earth Elements (RE)		√	√	2846#	China, Vietnam, Russia (72%※)
Manganese (Mn)		√	√	2602	South Africa, Brazil, Australia (78%※)
Nickel (Ni)	√		√	2604	Australia, Indonesia, Brazil, Russia, the Philippines, China (76%※)
Silicon (Si)	√		√	280,461△	NA
Zinc (Zn)	√	√		2608	Australia, China, Russia, Mexico, Peru, Kazakhstan (74%※)
Cadmium (Cd)	√			8107	China, Peru, Mexico, Russia, India, United States (61%※)
Chromium (Cr)		√		2610	Kazakhstan, South Africa (75%※)
Cobalt (Co)		√		2605	Democratic Republic of the Congo (DRC), Australia, Indonesia, Cuba (78%※)
Gallium, Indium, Germanium (Ga +)	√			8112*	NA
Graphite (Gr)			√	2504	Turkey, China, Brazil, Madagascar (80%※)
Lithium (Li)			√	282,520△	Chile, Australia, Argentina (77%※)
Molybdenum (Mo)		√		2613	China, United States, Peru (83%※)
Selenium (Se)	√			280,490△	China, Russia, Peru, United States, Canada (75%※)
Silver (Ag)	√			261,610△	Peru, Australia, Poland, Russia, China, Mexico (75%※)
Tellurium (Te)	√			280,450△	China, United States, Canada, Sweden (37%※)

(continued)

Table 4.1 (continued)

	Solar power	Wind power	EVs	HS	Major reserve countries
Tin (Sn)	√			2609	China, Indonesia, Myanmar, Australia, Brazil, Bolivia (81%※)
Titanium (Ti)			√	2614	China, Australia, India, Brazil (74%※)

Source IISD, IRENA, USGS
Notes (1) √ indicates that the mineral is indispensable for the corresponding renewable energy technology. (2) *, 8112 represents Beryllium, Chromium, Germanium, Vanadium, Gallium, Hafnium, Indium, Rhenium, Niobium, Thallium, and their products. Since Gallium, Indium, and Germanium do not have individual HS codes, 8112 is used instead. (3) #, 2846 represents rare earth metals, yttrium, scandium, and their inorganic or organic compounds. Since neodymium and praseodymium do not have individual HS codes, 2846 is used. Dysprosium is also included in 2846 to avoid double-counting trade values. (4) NA indicates that data is not available. (5) △, Silicon, Germanium, Lithium, Selenium, Silver, and Tellurium are represented by six-digit HS codes, as four-digit codes are unavailable. (6) Bauxite is used to represent aluminum reserves, and ilmenite is used to represent titanium reserves. (7) ※ indicates cumulative reserve percentage

global market. According to the U.S. Geological Survey (USGS), 40% of cadmium's end products are used in solar energy.

Selenium

Selenium is a PV material, meaning it can convert light into electrical energy. Due to this property, it is used in solar panels, also known as PV panels (Fiducia et al. 2019).

Silver

Silver is a key component in the production of solar cells (Silver Institute 2023). Silver powder is transformed into a paste and applied to silicon wafers. When sunlight hits the silicon, electrons are released, and silver, being the world's best conductor, carries the electricity for immediate use or storage in batteries for later use. According to Statista, approximately 96.3% of silver used in energy technologies will be allocated to solar PV power, mainly for crystalline silicon technology.

Tin

Tin is an important component of the solar industry. According to the International Tin Association, it is expected that the solar industry will use over 20,000 tons of tin in 2022 (International Tin Association 2022). Tin is used to produce solar panels, coating copper wires to form “solar ribbons” that connect individual solar cells. These ribbons carry the charge to the edges of the panel and then to the junction box. Additionally, tin oxide, a material made from tin and oxygen, is used to manufacture semiconductors for solar panels and computer chips. Tin-based perovskite solar cells have been developed and are considered highly promising active materials in the field of lead-free perovskite solar cells. Their unique physical and chemical properties, such as excellent photoelectric conversion efficiency and stability, make tin-based perovskite solar cells a focal point in renewable energy technology research (Cao and Yan 2021).

4.2.2 Major Importers/Exporters and Producers of Critical Minerals

Major Importers and Exporters

Table 4.2 lists the major importing and exporting countries for critical minerals required by the solar industry and their trade volumes. As shown in Table 4.2, India is the largest importer of cadmium, followed by China, Sweden, Belgium, and France, with India’s net imports far exceeding those of other major importers. The primary exporting countries are South Korea, China, Canada, Japan, and the UAE. India is the largest and fastest-growing importer of cadmium globally, primarily importing from China, South Korea, Japan, the UAE, and Uzbekistan. According to USGS data, India’s apparent consumption accounts for approximately 37% of consumption worldwide (USGS 2024). In India, cadmium is obtained as a byproduct of zinc smelting and refining. The increased demand for cadmium, due to its extensive use in industrial products like batteries, has led to a substantial volume of cadmium imports (Statista 2022). China, the second-largest importer of cadmium, is also among the countries with the richest cadmium resources. It holds approximately 92,000 tons of cadmium reserves, accounting for 18.4% of the global total (USGS 2014). Cadmium mainly occurs as a byproduct in lead and zinc ores, with significant deposits concentrated in central, southwestern, and eastern China. These regions account for 88% of the country’s proven reserves and 87.1% of the reserved reserves. Cadmium production is primarily concentrated in the southwest, contributing 59.4% to total production. However, cadmium is highly polluting, necessitating careful management and utilization of cadmium resources. Despite China’s significant potential in cadmium resources, proper management and sustainable use are essential for environmental protection.

The major importing countries for gallium, germanium, and indium include Malaysia, the United States, Germany, the Netherlands, and Japan, while the primary exporting countries are the United States, China, Russia, the United Kingdom, and France. The Indium Corporation, a global supplier of materials for electronic assembly and semiconductor packaging, has announced an investment of 250 million

Table 4.2 Major importing and exporting countries and import and export quantities of critical minerals for solar energy (*unit* tons)

Importing country	Import volume	Exporting country	Export volume
Chromium			
India	9569	South Korea	4701
China	3929	China	3418
Sweden	1072	Canada	2750
Belgium	560	Japan	1619
France	349	UAE	693
Gallium, Germanium, Indium			
Malaysia	24,708	USA	25,456
USA	18,203	China	17,834
Germany	13,298	Russia	16,827
Netherlands	11,401	UK	8086
Japan	5885	France	7686
Selenium			
China	1128	Netherlands	858
Italy	857	Japan	751
India	376	Canada	663
USA	354	South Korea	652
Pakistan	323	China	428
Silver			
China	1,431,378	Peru	612,243
Namibia	71,036	Mexico	286,747
South Korea	44,682	Bolivia	131,255
Japan	24,524	Mongolia	104,301
Bulgaria	8930	Spain	88,527
Tin			
China	243,629	Myanmar	188,394
Malaysia	20,391	DRC	27,094
Thailand	12,532	Australia	16,437
Belgium	2070	Nigeria	12,121
Myanmar	1374	Republic of the Congo	6201
Tellurium			
Spain	1653	France	1386
Germany	1526	China	924
Philippines	564	Canada	719
Canada	408	Germany	682
Malaysia	203	Luxembourg	395

Source UNcomtrade and Author

Malaysian Ringgit to establish a manufacturing facility in Malaysia. The Indium Corporation is a major refiner, smelter, manufacturer, and supplier of materials for the electronics, semiconductor, and thin-film markets (which require metals such as indium, gallium, germanium, and tin), leading to significant imports of gallium, germanium, and indium into Malaysia.

The major importing countries for selenium are China, Italy, India, the United States, and Pakistan, while the primary exporting countries are the Netherlands, Japan, Canada, South Korea, and China. In recent years, China has become one of the world's leading importers of selenium. China's selenium imports primarily come from countries with significant selenium reserves, such as Japan, Canada, and South Korea. In 2022, these three countries exported 279.1 tons, 258.3 tons, and 222.9 tons of selenium products to China, accounting for 24.7%, 22.9%, and 19.8% of global selenium imports, respectively. Recently, as domestic selenium production has increased, China's import volume of selenium products has declined. According to data from the General Administration of Customs, China's selenium products mainly include hydrogen selenide, inorganic selenium (selenium salts and selenites), and other selenium compounds. In 2021 and 2022, imports of selenium products (selenium salts and selenites, and other forms of selenium) decreased consecutively, totalling 1130.8 tons and 709.4 tons, respectively. Of these, imports of other forms of selenium accounted for over 99%, with imports of selenium salts and selenites totalling around 3 tons. Conversely, exports of selenium salts and selenites were relatively high, reaching 31.3 tons in 2022.

The major importing countries for silver are China, Malaysia, Thailand, Belgium, and Myanmar, while the primary exporting countries are Peru, Mexico, Bolivia, Mongolia, and Spain. Due to insufficient domestic reserves to meet demand, China relies heavily on imports of silver ore and concentrates. According to trade data from the United Nations Commodity Trade Statistics Database, China's imports of silver ore and concentrates exhibited a fluctuating upward trend from 2014 to 2022, reaching 1.43 million tons in 2022. This increase is largely attributed to the COVID-19 pandemic's impact on global shipping, which led to a decline in silver ore and concentrate prices, thereby boosting China's demand for imports. In recent years, domestic investment in silver exploration has decreased, and although new silver resources have been discovered, exploration activities have diminished. As a result, despite having abundant silver mineral resources, China still needs to import silver to meet domestic demand.

The major importing countries for tin are China, Malaysia, Thailand, Belgium, and Myanmar, while the primary exporting countries are Myanmar, DRC, Australia, Nigeria, and the Republic of the Congo. According to USGS data, global tin reserves were 4.3 million tons in 2023, with major resources concentrated in China (25.58%), Myanmar (16.28%), and Australia (14.42%). Due to limited progress in resource exploration in recent years and the gradual depletion of existing mines from long-term extraction, global tin reserves have started to decline. In China, tin reserves are geographically concentrated. According to the Ministry of Natural Resources report, in 2022, tin reserves in Yunnan, Guangxi, Hunan, and Jiangxi provinces accounted for 78% of the national total. In 2022, China imported a total of 244,000 tons of tin ore and concentrates, a 32% increase year-on-year. Despite China's abundant tin resources, domestic production still falls short of meeting demand, leading to a high dependency on imports, with Myanmar being the primary source.

The major importing countries for tellurium are Germany, the Philippines, Canada, and Malaysia, while the primary exporting countries are France, China, Canada, Germany, and Luxembourg. In 2022, Germany accounted for 64.6% of global tellurium imports, while Canada accounted for 9.1%. Previously, China was the largest importer of tellurium.

Major Producers

This section, based on USGS data, summarizes the major producing countries and production volumes for cadmium, gallium, germanium, indium, selenium, silver, tin, and tellurium, as shown in Table 4.3. The major producers of cadmium are China, South Korea, and Canada, which are also the leading exporters. South Korea is the largest exporter of cadmium and one of the largest primary cadmium metal production areas in Asia, with a refined cadmium production of approximately 4000 tons in 2023. Canada is also a significant primary cadmium metal producer, with refined cadmium production increasing annually. Canada's refined cadmium production is about 1800 tons, accounting for approximately 7.8% of global production. Major production areas in Canada include Ontario, Quebec, and British Columbia. Despite its relatively small share in global cadmium production, Canada's refined cadmium output continues to grow steadily. China is the largest producer of cadmium, with proven reserves in central, southwestern, and eastern China accounting for 88% of total proven reserves and 87.1% of the total remaining reserves in the country.

The major producers of gallium include China, Russia, and Japan. China is the largest producer, consumer, and exporter of metallic gallium globally. Since 2018, driven by the growth of the LED industry, China has surpassed Japan to become the world's largest consumer of metallic gallium. China has supplied nearly all of the global demand for gallium, although in 2019, due to a domestic production decline and reduced exports by companies, the price of metallic gallium faced significant uncertainty. This led to a sharp decrease in export volumes by nearly half as foreign downstream users became more cautious and increased inventory consumption. The market for metallic gallium in China has shown considerable volatility due to fluctuations in product prices and demand. According to UN commodity trade data, in 2022, China imported approximately $118 million worth of gallium and exported about $550 million. Due to gallium export controls in China in 2023, the U.S. and other countries are considering restarting domestic primary gallium production.

Germanium resources are globally scarce and highly concentrated. The major producing countries for germanium are China, the United States, Russia, and Canada, with significant Chinese production in Yunnan, Inner Mongolia, Guangdong, Guizhou, and Sichuan. Although the United States has the largest germanium resource reserves globally, it has been protecting germanium as a strategic defence reserve since 1984 and has largely ceased germanium mining in recent years. Since

Table 4.3 Major producing countries and production of critical minerals for solar industry in 2022 (*unit* tons)

Major producing country	Production	Major producing country	Production
Cadmium		Gallium	
China	8700	China	600
South Korea	4000	Japan	5
Canada	1800	South Korea	3
Japan	1800	Russia	2
Mexico	1170		
Germanium		Indium	
USA	/	China	670
Belgium	/	South Korea	180
Canada	/	Japan	66
China	/	Canada	39
Russia	/	Belgium	19
Selenium		Silver	
China	1290	Mexico	6195
Japan	710	China	3480
Russia	340	Peru	3079
Germany	300	Poland	1316
Belgium	200	Russia	1280
Tin		Tellurium	
China	71,000	China	380
Indonesia	70,000	Russia	70
Myanmar	47,000	Japan	68
Peru	28,200	Sweden	33
DRC	18,600	Canada	24

Source USGS

2013, China has maintained a global share of over 60% in germanium production, establishing itself as a key global supplier.

The major producers of indium include China, South Korea, and Japan. Global indium resources are relatively limited, with significant concentrations in China, Peru, the United States, Canada, and Russia, with China having the largest reserves. According to USGS data, China holds 72.7% of the world's indium reserves, ranking first globally; Peru holds 3.3%; and the United States holds 2.5%. In terms of global indium production, the global output increased steadily from 2015 to 2019 due to growing downstream demand. However, in 2020 and 2021, overall indium supply decreased slightly due to less overall demand and the impact of the pandemic, with production volumes of 957 tons and 920 tons, respectively.

The major producers of selenium include China, Japan, and Russia. In 2023, China was a leading producer of refined selenium, accounting for approximately 42% of global estimated production. One of its largest importers, China's demand for selenium has become increasingly prominent. In 2022, China imported 1128 tons. Additionally, global selenium resources are estimated to be approximately 95,000 tons, with relatively abundant reserves found in Chile, Russia, Peru, and the United States.

The major producers of silver are Mexico, China, and Peru. China's silver resources have been increasing annually, with reserves reaching 3400 tons in 2023, distributed across Inner Mongolia, Jiangxi, Anhui, Hubei, and Guangdong. However, silver production declined between 2014 and 2020, mainly due to decreased zinc-lead mining and environmental protection regulations. In 2020, China's silver production was 3200 tons, a decrease of 240 tons or 7% compared to the previous year. Peru's silver production is approximately 4500 tons, with known reserves of 93,000 tons, making it the top country in terms of reserves. Mexico, which regained its position as the world's largest silver producer in 2017, produced 5600 tons of silver. Mexico also has numerous companies operating silver mines and conducting exploration within the country.

The major tin-producing countries include China, Myanmar, and Indonesia. Since 2018, global tin production (measured in metal) has gradually decreased due to the global economic downturn and declining tin reserves in major producing countries. Additionally, the concentration of tin ore resources in economically underdeveloped regions like Africa and South America, coupled with political instability in these regions, has also impacted tin production. According to USGS data, global tin production fell to 290,000 tons in 2023.

The major tellurium-producing countries include China, Russia, and Japan. According to USGS data, by the end of 2023, global proven tellurium reserves were 36,000 tons. Although China holds the largest share of global tellurium reserves, its tellurium industry is still in the early stages of development compared to other countries. Tellurium resources in China are relatively concentrated, with significant reserves located in Guangdong, Jiangxi, and Gansu provinces. These provinces account for 93.08% of the country's total tellurium resources. Furthermore, China's tellurium development heavily relies on host deposits.

Policies

Relying on the IEA policy database, this section summarizes policies related to critical minerals for solar energy, focusing on relevant policies in the European Union, China, the United States, the United Kingdom, and the Philippines. The details are presented in Table 4.4. Different countries or regions target various critical minerals: The United States has allocated funds for two materials used in solar cell production (tellurium and cadmium); China emphasizes resources such as gold, silver, copper, lead–zinc, aluminium, iron ore, coal, natural gas, and oil, and, as a major producer of gallium and germanium, has begun to restrict their exports; European countries focus on rare-earth metals, including tin, tantalum, tungsten, selenium, neodymium, indium, and gallium.

4.3 Global Trade Network Security of Critical Minerals in the Solar Energy Industry

4.3.1 Trade Disruption Risk Index

In this section, we construct a new type of global mineral trade security index to measure the stability of the global mineral trade network and the importance of each trading country in the event of trade disruptions. Before constructing the index, we first describe the overall characteristics of the network using indicators such as degree, degree distribution, and clustering coefficient, as discussed in the "New Trends in Global Energy Security Geopolitics" chapter. Subsequently, we use the following indicators to evaluate the risks in the trade network and the importance of countries.

Network Risk Indicator

Since many mineral-exporting countries are concentrated in regions with unstable political situations and high political risks, local wars and regime changes could lead to interruptions in mineral supplies, resulting in significant uncertainty and risks in mineral provision (Dou et al. 2023; Nomkhosi and Nelson 2024). Therefore, in this section, the safety of importing countries is defined as the extent of the impact faced by importing nodes in the trade network when export nodes are attacked and different levels of supply disruptions occur. Here, safety refers to the likelihood that the importing nodes can quickly secure alternative supplies to meet their import demand. The specific definition is as follows:

$$R(i) = \sum_{j=1}^{N_{direct}} p_j \times \frac{T_{ij}}{E_w} \times (1 - r_j) \times d_{ij}^{-1} + \sum_{k=1}^{N_{indirect}} p_k \times \frac{T_k}{E_w} \times (1 - r_k) \times (d_{ik} \times d'_{ik})^{-1} \tag{4.1}$$

where $R(i)$ represents the trade security of importing country v_i; N_{direct} is the number of exporting countries that have direct trade relations with importing country v_i; N_{indirect} represents the number of exporting countries that do not have direct trade relations with importing country v_i; p_j and p_k represent the political risk coefficients of exporting countries v_j and v_k, respectively; T_{ij} represents the trade volume between importing country v_i and exporting country v_j; T_k represents the total export volume of exporting country v_k; E_w represents the total world export volume; r represents the proportion of trade disruption in exporting countries; d_{ij} represents the spatial

Table 4.4 National policies on critical minerals for the solar industry

Country or area	Time	Policy
EU*	2020	EU Regulation 2017/821 outlines supply chain due diligence obligations for EU companies importing tin, tantalum, tungsten and their ores, as well as gold, from conflict-affected and high-risk areas
China*	2015	On 9 June 2015, the Belt and Road Mining Development Fund, the first private equity fund focusing on Belt and Road mineral resources and related industries, was officially launched in Beijing. The fund aimed to complete its fundraising by the end of 2015 and raise RMB 10 billion. The fund mainly invests in high-quality mineral resources, infrastructure, and related industrial chains along the "Belt and Road." The projects are mainly located in countries along the "Silk Road Economic Belt," especially in Kazakhstan, Kyrgyzstan, and Tajikistan. The Fund has set up projects involving gold, silver, copper, lead and zinc, aluminium, iron ore, coal, natural gas, oil, and other resources
China*	2023	On 1 August 2023, China imposed export controls on gallium- and germanium-related items
United States of America*	2022	The Inflation Reduction Act of 2022 grants a tax credit of 10 per cent of the cost of production to producers of the following critical minerals applicable to the manufacturing industry: aluminium, antimony, barite, beryllium, cerium, caesium, chromium, cobalt, dysprosium, europium, fluorite ore, gadolinium, germanium, graphite, indium, lithium, manganese, neodymium, nickel, niobium, tellurium, tin, tungsten, vanadium, ytterbium, and others. Eligible minerals must be produced in the United States. The tax credit for production of critical minerals began in 2023 and is exempt from the phase-out that applies to other eligible components beginning in 2023

(continued)

Table 4.4 (continued)

Country or area	Time	Policy
United States of America*	2021	The U.S. Department of Energy (DOE) has announced a goal of reducing the price of solar energy by 60 per cent over the next decade and will invest US$128 million to do so. The DOE wants to reduce the current price of 4.6 cents per kilowatt hour to 3 cents per kilowatt hour by 2025 and to 2 cents per kilowatt hour by 2030. Funding announced through the DOE's Solar Energy Technology Office will support the development of two materials used to make solar cells totalling US$63 million: perovskites, an emerging family of solar materials with the potential to make highly efficient thin-film solar cells at very low production costs; and cadmium telluride (CdTe) thin films, which account for 20 per cent of the country's installed modules and is an alternative to traditional silicon-based technologies. Unlike photovoltaic (PV) technology, concentrating solar thermal captures heat from sunlight and uses that heat to spin a turbine or power an engine to generate electricity. In addition, the DOE announced a new funding opportunity of $7 million for projects that extend the useful life of silicon-based PV systems from approximately 30 to 50 years to reduce energy costs and minimize waste
United Kingdom of Great Britain and Northern Ireland	2012	Supply of Mineral Resources (SoS MinErals) is a research programme supported by the Natural Environment Research Council and the Engineering and Physical Science Research Council, in partnership with industry and academia. The SoS MinErals programme consists of four fully funded projects covering the study of all the elements of electronics: cobalt, tellurium, selenium, neodymium, indium, gallium, and heavy rare-earth elements
Philippine	2021	Executive Order No. 2021-40 issued by the Ministry of Environment and Natural Resources (MENR) eliminated the open pit mining method for copper, gold, silver, and composite ores that was prohibited under MENR Executive Order No. 2017-10

Note * are countries rich in mineral resources for solar energy

distance between importing country v_i and exporting country v_j, while $d_{ik}{'}$ represents the trade distance between importing country v_i and exporting country v_k, which is the shortest directed trade path between the importing and exporting countries in the trade network. If no shortest path exists between the importing and exporting countries, d_{ij} is set to infinity (∞).

This section measures three aspects of security against disruption risks faced by importing country v_i: "security of supply acquisition," "likelihood of supply acquisition," and "timeliness of supply acquisition." The political risk coefficient p_j of exporting country v_j is used to measure the security of importing country v_i in acquiring supplies from exporting country v_j. If exporting country v_j has a relatively secure political environment, then the risk of importing country v_i not obtaining stable mineral supplies is relatively low. If there is already a direct trade relationship between the importing and exporting countries, the stability of the trade relationship between exporting country v_j and importing country v_i is measured by the indicator T_{ij}/E_w. Clearly, the larger the T_{ij}/E_w value, the more stable the relationship between the two countries. If no direct trade relationship exists between the importing and exporting countries, then the supply capacity of other exporting countries in the network is reflected by T_k/E_w.

Systemic security in trade networks refers to the overall ability of the system to withstand disruptions, encompassing the average security of all importing nodes. This metric assesses the stability of current mineral trade operations. Given the significant disparities in trade volumes among mineral-importing countries, major trading nations evidently contribute more substantially to the security of the trade network. Therefore, this section evaluates each country's contribution to the overall trade network's security by using its trade volume as a proportion of the world's total imports as weights. The calculation formula is as follows:

$$NV = \sum_{i=1}^{N_{im}} \frac{M_i}{M_w} \times R(i) \tag{4.2}$$

where NV represents the systemic security of the trade network; N_{im} denotes the number of importing countries; M_i refers to the import volume of importing country v_i; and M_w represents the total world imports. The larger the value of this indicator, the higher the security of the trade system and the greater the stability of the trade network's operations.

Node Importance Indicator

Export nodes are the driving force of the trade network. Trade disruptions in exporting countries will directly introduce risks to the network. Due to differences in resource endowments and trade relationships, the trade positions of exporting countries within the network also vary significantly. Therefore, identifying key export nodes in the network is crucial for studying and responding to trade network risks. In this section, the change in the systemic security of the trade network when an exporting country experiences a supply disruption is used as the standard to measure the trade importance of that exporting country. The specific expression is as follows:

$$M(i) = \frac{NV(S, v_i) - NV(S)}{NV(S)} \tag{4.3}$$

where $M(i)$ represents the importance of exporting country v_i; $NV(S, v_i)$ represents the systemic security of the trade network when exporting country v_i experiences a disruption; and $NV(S)$ represents the systemic security of the network when no trade disruption occurs. $M(i) \in [0, 1]$, and the larger the value of this indicator, the more important exporting country v_i is in the oil trade network.

4.3.2 Overall Characteristics of the Trade Network

Figure 4.3 illustrates the evolution of the degree distribution of the trade networks for various critical minerals required by the solar energy industry in the years 2000, 2005, 2010, 2015, and 2020, examining the heterogeneity of different trade network nodes. The power-law characteristics of the trade networks for gallium, germanium, indium, selenium, and tellurium gradually became more pronounced between 2000 and 2015, exhibiting the features of a scale-free network. This means that most nodes have relatively few connections, while a small number of nodes possess many connections, highlighting the heterogeneity among network nodes and significant differences in node importance. This indicates an uneven distribution of resources, with resources monopolized by a few countries and regions. The heterogeneity of the trade networks for critical minerals in the solar energy industry reached its peak in 2015.

Figure 4.4 presents the evolution of the relationship between clustering coefficient and degree in the trade networks of various critical minerals required by the solar energy industry for the years 2000, 2005, 2010, 2015, and 2020. The clustering coefficient is an important indicator that describes the local tightness of network nodes, and it can also effectively measure whether there is a clear hierarchical structure within the network. If the distribution of $c(k)$ follows a power-law form ($c(k) = k^{-\beta}$), it indicates the existence of a hierarchical structure within the network. The power-law characteristics of the trade networks for cadmium, gallium, selenium, silver, and tellurium have become increasingly apparent, with the clustering coefficient decreasing as the degree increases, indicating a relatively clear hierarchical structure. This suggests that in these networks, countries with smaller degrees tend to have higher local trade tightness, forming tightly connected smaller clusters, while countries with larger degrees engage less frequently in trade with their partners. This characteristic has become increasingly prominent. Nodes with higher degrees connect smaller clusters into larger, looser clusters, which are then linked together through nodes with even higher degrees, forming the overall network. Therefore, nodes with higher degrees play a crucial "bridge" role in the formation of trade networks.

4.3.3 Trade Network Security

Figure 4.5 clearly illustrates the evolution trend of trade risks for critical minerals in the solar energy industry from 2000 to 2020. It can be observed that the trade risk for selenium remained consistently high, showing a year-on-year upward trend.

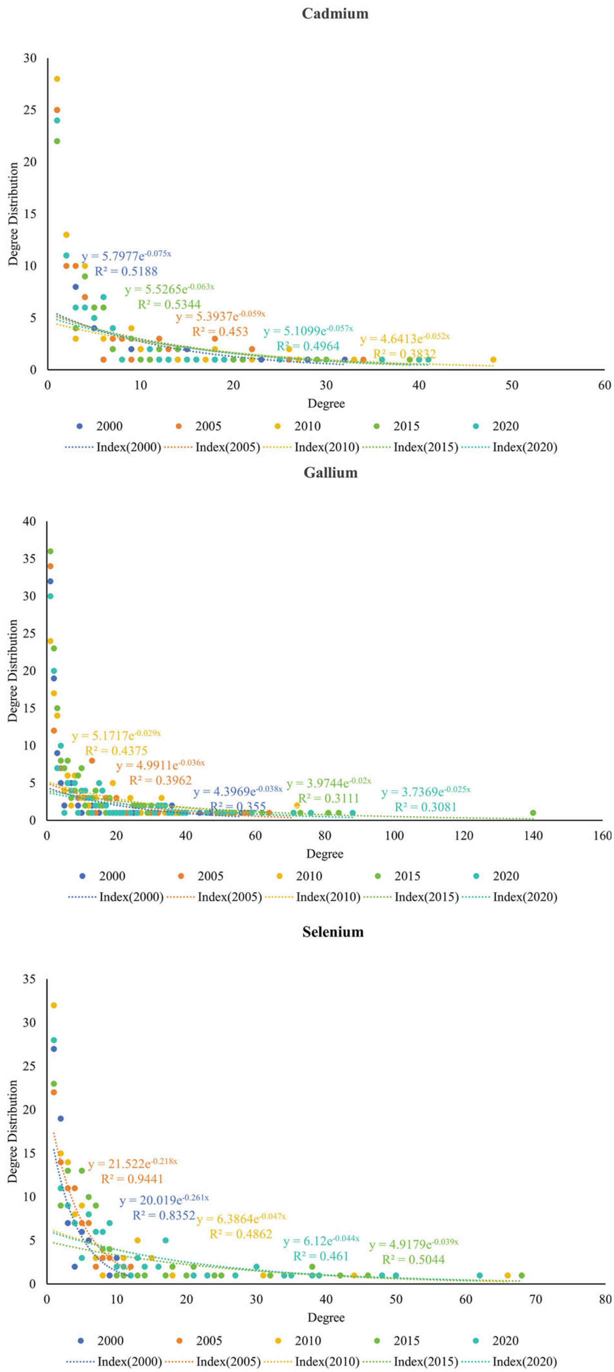


Fig. 4.3 Evolution of the degree distribution in the trade network of critical minerals for the solar energy industry

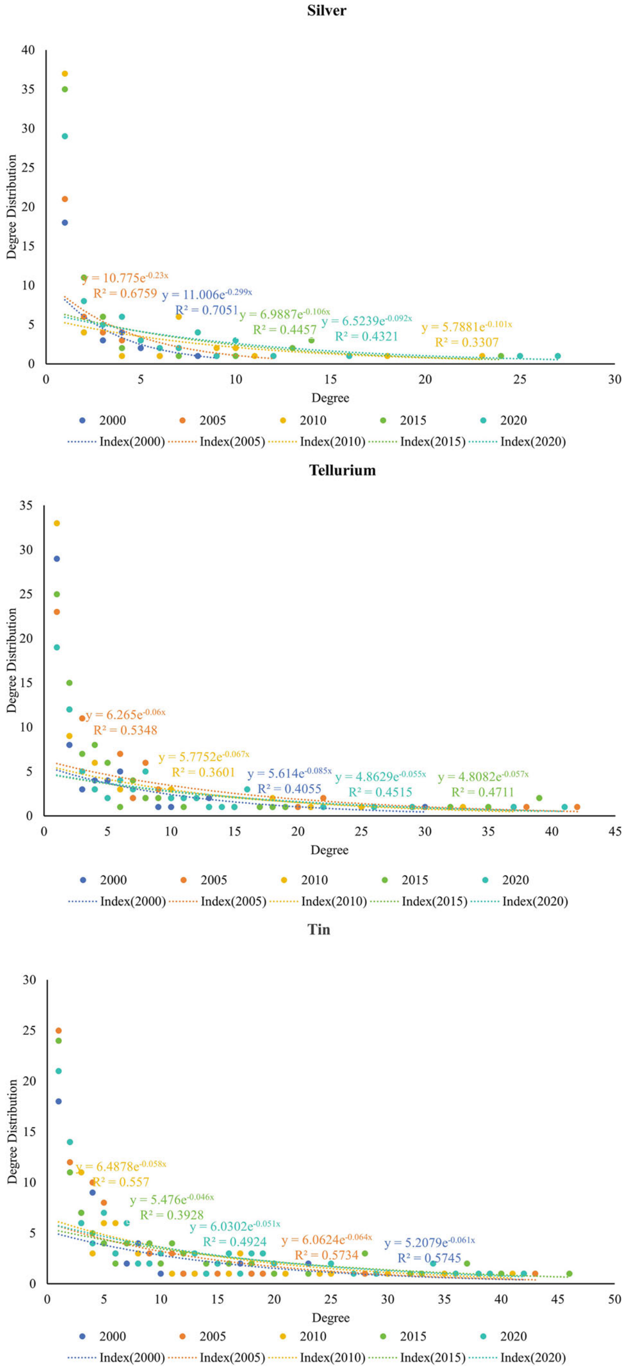


Fig. 4.3 (continued)

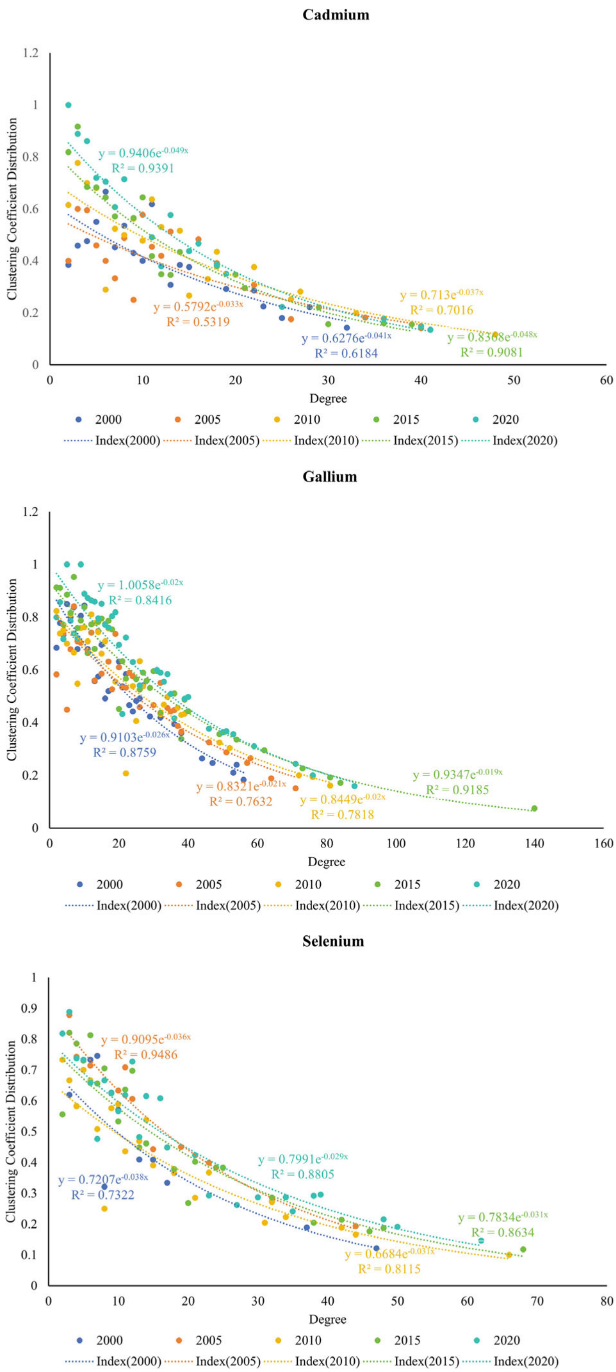


Fig. 4.4 Evolution of the relationship between clustering coefficient and degree in the trade network of critical minerals for the solar energy industry

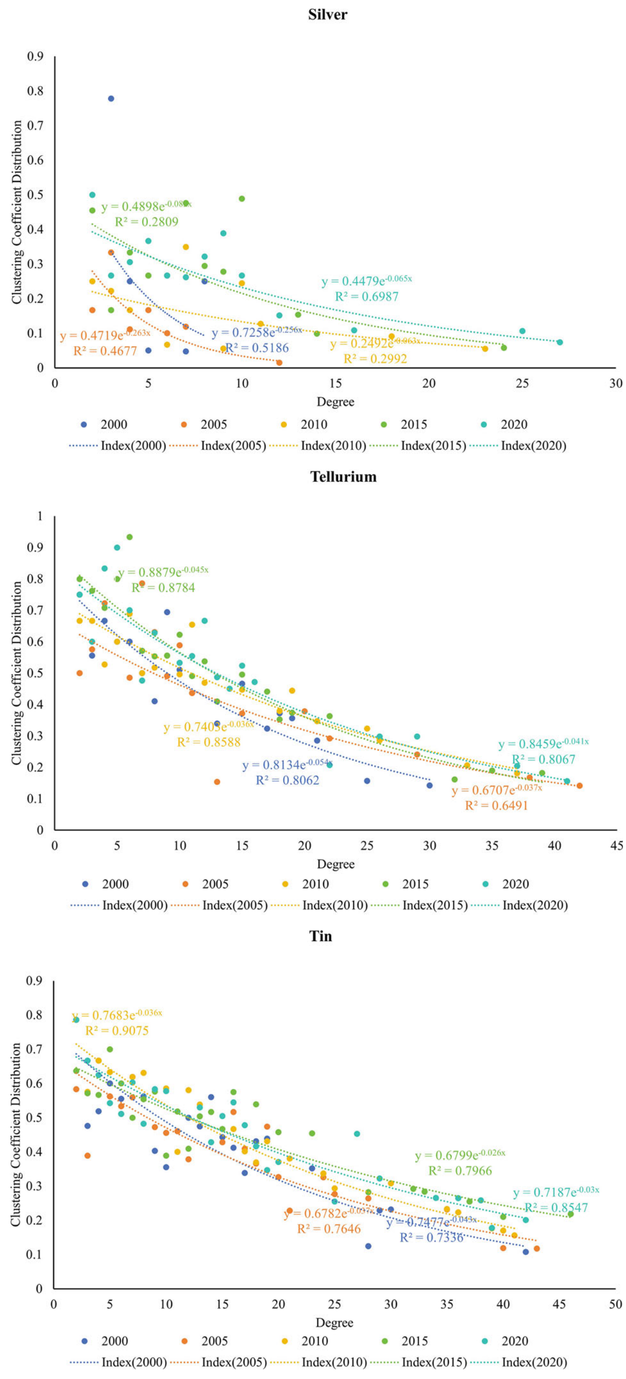


Fig. 4.4 (continued)

Following closely are tin and tellurium, which also exhibit relatively high trade risks. In contrast, the trade risk for chromium appears to be relatively low.

4.3.4 Major Trade Countries

This section measures the position of exporting countries in the trade network of critical minerals required by the solar energy industry (as shown in Table 4.5). The exporting countries affecting the stability of critical mineral trade for the solar energy industry are primarily concentrated in major countries such as China, the United States, Japan, and South Korea, as well as resource-rich countries and those on strategically important trade routes. For example, in the tin trade network, key countries include China, the United States, Myanmar, and Malaysia. As mentioned in Sect. 4.2 above, China and Myanmar are resource-rich countries for tin; the United States is neither a major exporter nor a primary resource or production country, but it holds significant importance in the tin trade due to its status as a global power; Malaysia, while not a resource or production country, consistently ranks among the top five due to its strategic location. The Strait of Malacca, an important passage between the Indian Ocean and the Pacific Ocean, is controlled by Malaysia, Singapore, and Indonesia, making Malaysia a key transit point for trade.

4.4 Conclusion

This chapter explores development trends in the solar energy industry and investigates the trade patterns, trade security, and key countries involved in the critical minerals required for the industry. The study finds that the power-law characteristics of the trade networks for gallium, germanium, indium, selenium, and tellurium became increasingly prominent from 2000 to 2015. The power-law features of the trade networks for cadmium, gallium, selenium, silver, and tellurium are becoming more evident, with countries having smaller degrees showing higher local trade tightness and forming tightly connected smaller clusters, while countries with larger degrees exhibit less frequent trade interactions. Selenium has the highest trade risk, which has been gradually increasing over time, followed by tin and tellurium with relatively high trade risks, and chromium with the lowest trade risk. The stability of trade in critical minerals for the solar energy industry is most significantly influenced by exporting countries such as China, the United States, Japan, and South Korea and by resource-rich countries or those on a strategically important trade route. In terms of policies, there are differences in focus among countries and regions: the United States invests in two materials used for manufacturing solar cells (tellurium and cadmium); China focuses on resources such as gold, silver, copper, lead–zinc, aluminium, iron ore, coal, natural gas, and oil, and as a resource-rich country for gallium and germanium, has

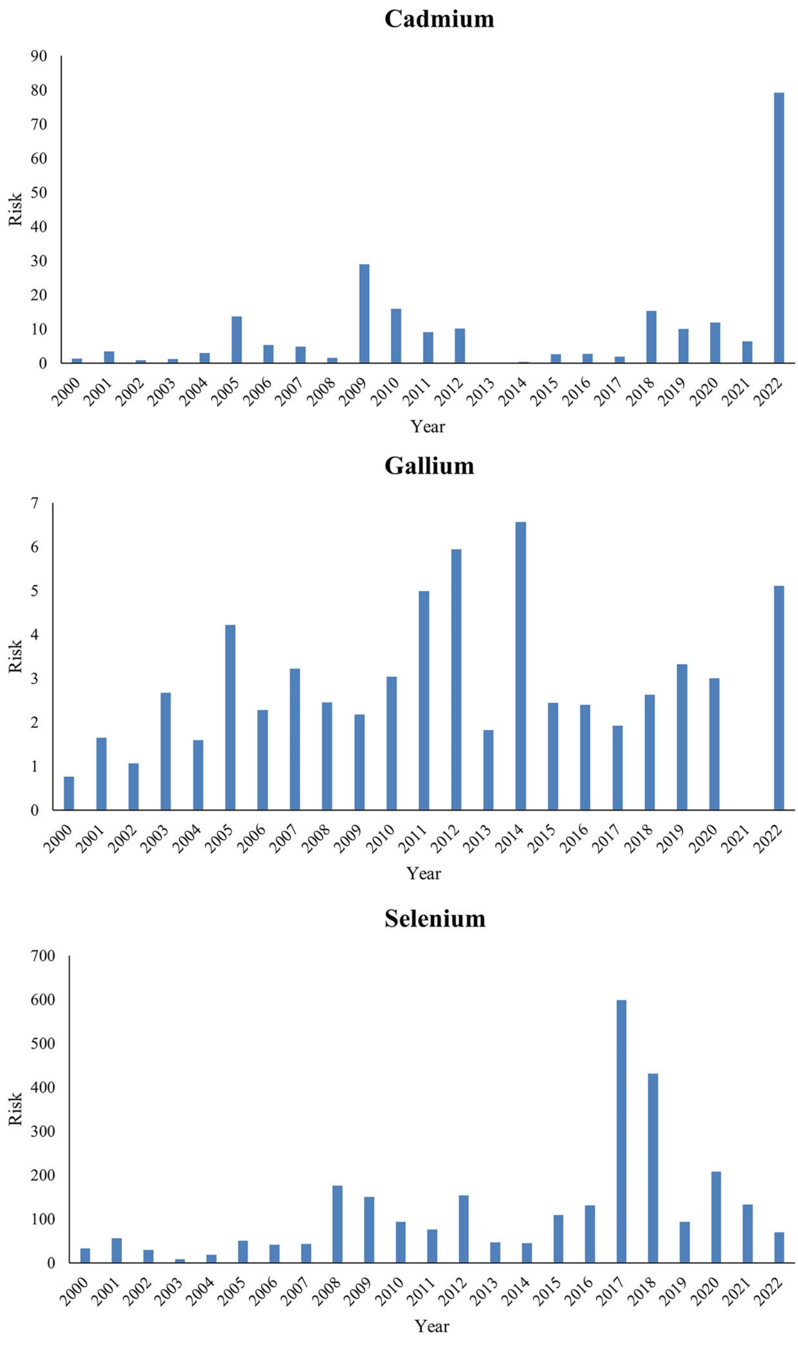
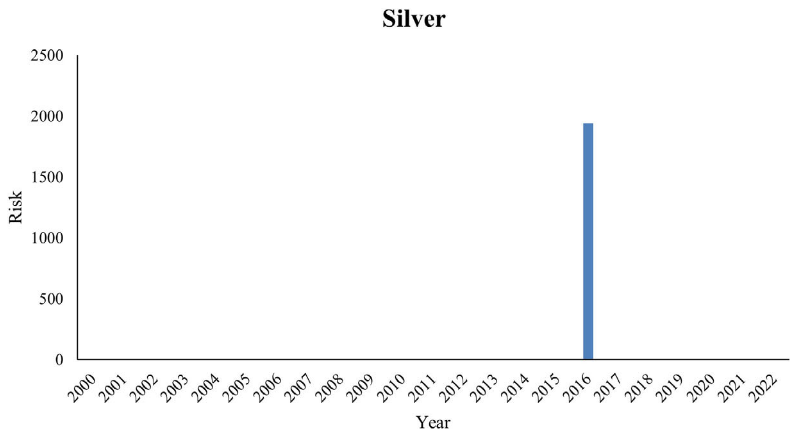
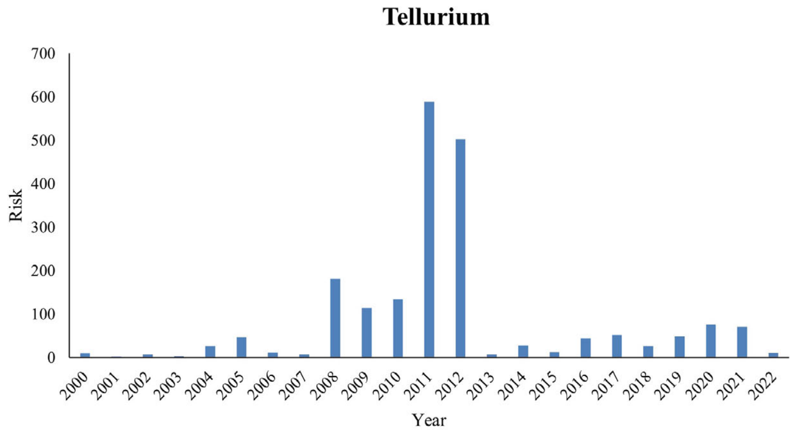


Fig. 4.5 Evolution of trade network risks for critical minerals in the solar energy industry





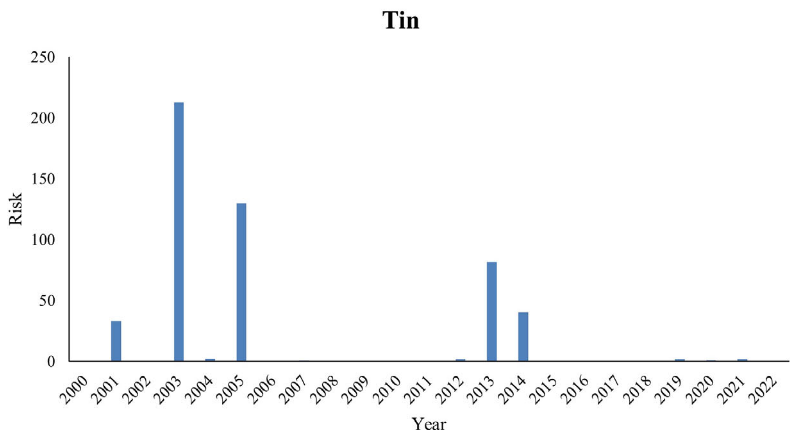


Fig. 4.5 (continued)

Table 4.5 Evolution of the order of importance of exporting countries of critical minerals for the solar industry

2000	2005	2010	2015	2020
Cadmium				
Belgium	Belgium	China	Japan	South Korea
China	China	Canada	India	India
France	India	Japan	Kazakhstan	Japan
UAE	South Korea	Belgium	South Korea	Belgium
Uzbekistan	France	Mexico	Australia	Australia
Gallium, Germanium, Indium				
UAE	France	UAE	France	UAE
USA	China	France	China	Germany
Singapore	Russia	Netherlands	UAE	Netherlands
Saudi Arabia	UAE	China	Germany	China
France	Singapore	USA	Russia	Spain
Selenium				
Japan	Australia	UK	Germany	Netherlands
UK	Japan	Brazil	Belgium	Germany
South Korea	Belgium	Japan	China	France
USA	Norway	USA	Japan	Canada
Russia	China	Poland	Russia	Spain
Silver				
South Africa	Benin	Zambia	Canada	Zambia
France	Belgium	China	China	China
USA	Netherlands	North Korea	UK	Bolivia
North Korea	South Africa	Australia	Turkey	France
Germany	Germany	South Korea	France	Spain
Tin				
UAE	Malaysia	China	USA	China
Malaysia	Rwanda	Malaysia	China	Myanmar
USA	Kenya	UAE	Myanmar	USA
China	Tanzania	Germany	Malaysia	Japan
Belgium	DRC	Myanmar	Australia	Malaysia
Tellurium				
Japan	Belgium	Germany	Germany	Philippines
UK	India	Philippines	China	Germany
Peru	Philippines	China	Philippines	Canada
Belgium	Morocco	Thailand	South Korea	Laos
Philippines	Canada	Italy	Belgium	China

Source UNcomtrade and Author

started to restrict their export; European countries concentrate on rare-earth metals such as tin, tantalum, tungsten, selenium, neodymium, indium, and gallium.

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Chapter 5
Wind Energy Industry and Critical Mineral Trade Network Security

Haoran Li and Jiayue Yang

Abstract The wind energy industry is an important part of the sustainable energy system, and its rapid development requires a stable supply of critical minerals. This chapter analyses the development trend of the global wind energy industry, the global distribution pattern of critical minerals, and the strategic position of a country that has a core role in international trade. The chapter uses the trade network security index built in Chapter 4 to evaluate critical minerals in the industry, the supply stability of molybdenum, cobalt, and chromium, and the influence of various countries in the global trade network. The study reported here shows that among the critical minerals required by the wind energy industry, cobalt has the highest trade risk. The main countries affecting the cobalt trade network include the Democratic Republic of the Congo (DRC), China, and African countries. China, the United States, the United Kingdom, and Finland have formulated critical mineral policies on the wind energy industry. These policies are focussed on rare earth resources.

Keywords Wind energy · Critical minerals · Complex networks · Trade risk

5.1 Development Trends in Wind Energy Industry

Wind energy, as an abundant and widely distributed natural resource, plays a crucial role in the energy transition and sustainable development (Sadorsky 2021). Wind power generation technology, which harnesses the kinetic energy of wind and converts it into electrical energy, can be categorized into two main types: onshore and offshore. Onshore wind power, a proven and mature technology, benefits from

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a globally extensive supply chain and has seen continuous growth in recent years. The goal in developing it is to enhance power generation efficiency per megawatt of installed capacity, thereby expanding the utilization of areas with lower wind speeds. As wind turbine sizes increase, the development trend in onshore wind power is shifting towards greater hub heights and larger rotor diameters. Meanwhile, offshore wind power holds tremendous potential in harnessing stronger wind resources and is expected to experience rapid growth in the coming years (World Economic Forum 2022). Wind power is one of the fastest-growing renewable energy sources and is expected to generate 20% of global electricity by 2035. With ongoing technological advancements and cost reductions, the wind energy industry is gradually becoming a mainstream global renewable energy source providing critical support for the energy transition and for sustainable development goals.

5.1.1 Development of Global Wind Energy Industry

According to data from *World Energy Outlook 2023*, the levelized cost of electricity (LCOE) for the wind energy sector experienced a significant reduction between 2010 and 2022, with onshore costs falling by 70% and offshore costs by 60% (IEA 2023a). This shift marks a major advancement in the cost-efficiency of wind energy technologies. However, the industry currently faces challenges related to supply chain constraints and the poor financial performance of major Western manufacturers, which has kept investment costs at a relatively high level in the short term. For onshore wind, this trend is expected to raise power generation costs by only 10%–15%, a margin insufficient to alter its competitive edge over fossil fuel–based generation, where it still maintains a cost advantage. In contrast, offshore wind, particularly outside the European Union, has yet to achieve cost parity with fossil fuel generation (IEA 2023b). Compared to onshore wind, offshore wind entails higher construction and maintenance costs. Nevertheless, as technological advancements continue and economies of scale are realized, wind energy generation costs are expected to decline further, enhancing its economic viability over time.

After slowing in 2021, investment in the wind energy sector rebounded with a 20% increase in 2022, with total investments reaching US$185 billion. This made wind energy the second-largest recipient of investment among all power generation technologies, second only to solar photovoltaics (IEA 2023c). Driven by ambitious government targets, supportive policies, and the sector's strong competitiveness, investment in wind power is expected to continue to grow steadily (Wei et al. 2021).

Policy support remains the primary driver of wind energy deployment in most regions worldwide. Various types of policy are fuelling capacity growth, including auctions, feed-in tariffs, contracts for difference, and renewable energy portfolio standards. In addition to the EU's goal of increasing the share of renewable energy to 45% by 2030, as mentioned in "Solar Industry and Critical Mineral Trade Network Security", and the Green Deal Industrial Plan, several key policies were implemented in 2022–2023 that have significantly impacted wind energy growth: In August 2022, the

U.S. federal government introduced the Inflation Reduction Act, which has strongly supported the domestic offshore wind industry through tax credits and other incentives (U.S. Department of the Treasury 2022). In April 2023, nine European countries announced plans to significantly accelerate offshore wind deployment with the aim of increasing installed capacity from 30 GW in 2022 to over 120 GW by 2030, and further to over 300 GW by 2050 (WindEurope 2023). In October 2023, the European Commission announced the EU Wind Power Action Plan, which is aimed at accelerating installation growth and supporting local manufacturers by simplifying permitting processes, improving auction design, facilitating financing, and expanding workforce training programmes (European Commission 2023).

Onshore wind technology continues to lead the growth in installed wind power capacity, while the share of offshore wind is expanding more gradually. A mature technology, onshore wind is widely deployed across 115 countries worldwide. In contrast, offshore wind is still in its early stages of development, with only 20 countries having installed capacity. Figure 5.1 illustrates the installed wind power capacity from 2015 to 2022, showing that, by 2022, the total global wind power capacity had reached 900 GW, with 93% located onshore and the remaining 7% in offshore wind farms. As more countries develop or plan their first offshore wind projects, the coverage of offshore wind is expected to expand significantly in the coming years.

In 2021 and 2022, the growth rate of newly installed global wind power capacity slowed. In 2022, total installed wind power capacity increased by 74 GW, with offshore wind accounting for 18% of this growth. The newly installed wind capacity in 2022 was 20% lower than in 2021, and compared to the high growth in 2020, the decline amounted to 32%. This slowdown was primarily caused by project delays due to the COVID-19 pandemic and a reduction in installations following the gradual phase-out of tax incentives in the United States. However, with increased policy support from the U.S. and the EU, along with China's policy targets and strong

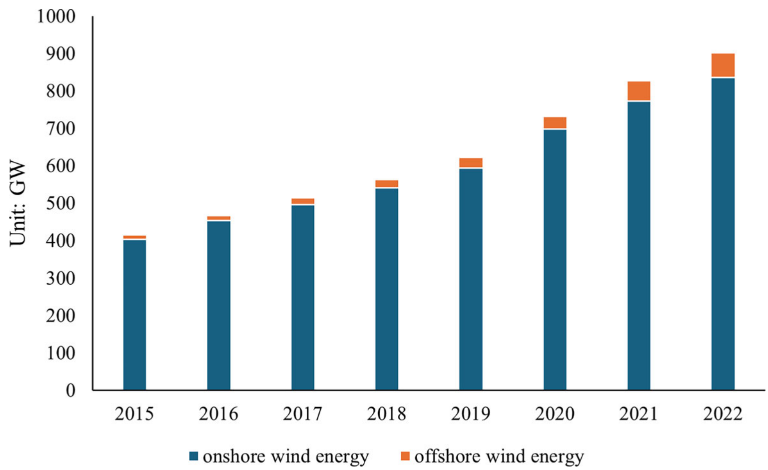

Fig. 5.1 Installed wind energy capacity from 2015 to 2022. (*Source* IEA)

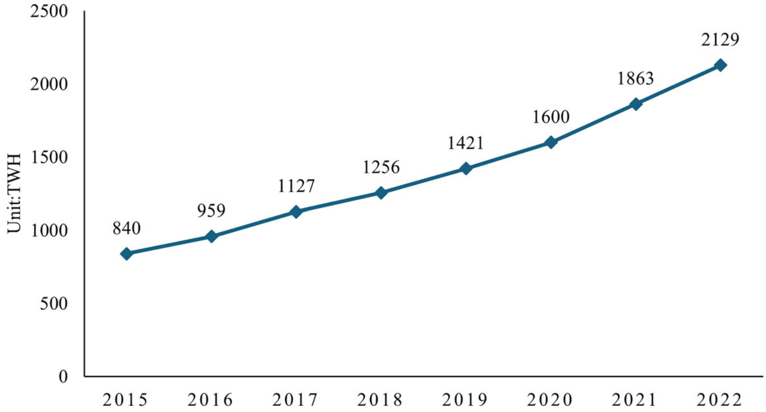

Fig. 5.2 Wind energy generation from 2015 to 2022. (*Source* IEA)

economic competitiveness, the growth of new wind power installations is expected to rebound and accelerate.

Figure 5.2 shows the trajectory of power generation within the wind energy industry from 2015 to 2022. As a predominant form of renewable energy technology, excluding hydropower, wind energy experienced unprecedented expansion in capacity during 2022 (Summerfield-Ryan and Park 2023). Specifically, wind energy generation increased by 265 TWh in 2022, a 14 percent increase from the previous year, ranking it second among all generation technologies. By the end of 2022, total wind energy generation reached 2129 TWh, surpassing the combined total of all other non-hydro renewable energy technologies.

At the national level, China made the largest contribution to wind power growth in 2022, accounting for nearly 40% of the global increase, followed by the United States at 22%. After experiencing prolonged low wind conditions in 2021, the European Union saw a 14% rebound in wind power generation in 2022. However, due to the decline in global wind power capacity additions in 2021 and 2022, growth may slow in the coming years. This trend suggests that while significant progress has been made in the short term, the long-term development of wind energy still faces challenges.

According to the *Renewables 2023 Analysis and Forecast to 2028*, the expansion of the wind turbine manufacturing industry in 2022 showed signs of slowing. Manufacturing capacity for major wind components, including nacelles, towers, and blades, remained stable at 110–120 GW, similar to the previous year. Faced with an uncertain policy environment, wind turbine manufacturers outside China have largely paused their expansion plans. Western manufacturers, in particular, have been hit by a combination of cost inflation and significantly lower prices in the Chinese market. First, logistical challenges caused by lockdowns and other disruptions during the COVID-19 pandemic drove up costs for turbine manufacturers in the EU and the U.S. Second, the sharp rise in raw material and transportation costs from 2021 to 2022 exacerbated the situation, resulting in a 20% increase in the average price per megawatt for turbines from the first half of 2020–2023. Meanwhile, prices in the

Chinese market fell by more than 50%, driven by a concentrated local supply chain, dynamic market growth, attractive raw material pricing, low-cost financing, and intense competition among domestic manufacturers. Additionally, the wind energy industry has faced project delays and cancellations. In Europe and North America, several offshore wind projects have encountered significant challenges, including overcapacity, complex government approval processes, and supply chain bottlenecks (Financial Times 2023). These challenges have delayed investment decisions and impacted project timelines. As costs continue to rise, projects have been postponed or cancelled, reflecting the uneven development of the offshore wind sector globally.

The development of wind power technology continues to focus on enhancing efficiency and reducing costs. At the core of technological innovation is the design of wind turbines with longer blades and taller towers to boost turbine productivity, especially in areas with weaker wind conditions. However, for onshore wind power, the maximum height of turbines is often restricted in certain regions due to environmental protection and public acceptance concerns, which limit the potential for innovation. Offshore wind power is not constrained by such size limitations, allowing innovation to focus on larger turbines and thus lower overall generation costs. At the same time, the development of safe, cost-effective floating offshore wind technology is accelerating. Floating wind farms can tap into the vast potential of ocean areas, particularly in regions where the water is too deep for traditional fixed turbines, and they are expected to become a key tool in advancing the energy transition. Countries like France, Japan, South Korea, Norway, Portugal, the UK, and the U.S. (west coast), which have deep waters close to shore, are expected to be the first to deploy this technology on a large scale (IEA 2023d).

5.1.2 Development of China's Wind Energy Industry

Since 2006, China's wind energy industry has experienced explosive growth, rapidly becoming the third-largest source of electricity in the country and steadily advancing towards a dominant energy position. Since 2010, China has witnessed two significant waves of wind power expansion. The first occurred in 2015, driven by an impending reduction in onshore wind subsidies, which spurred rapid onshore wind farm development. The second wave took place between 2019 and 2020 for onshore wind and in 2021 for offshore wind, both triggered by policy shifts and adjustments in subsidy mechanisms (Xu et al. 2022; Zhang et al. 2020). Currently, policy support for wind energy technology in China is strengthening (Zhang et al. 2024). In February 2022, the National Development and Reform Commission issued *Opinions on Improving the Institutional Mechanism and Policy Measures for Green and Low-Carbon Energy Transition*, which set green and low-carbon goals for the future energy transition; the Commission prioritized offshore wind development and thus laid a solid policy foundation for the industry's future. In June 2022, China released the *14th Five-Year Plan for Renewable Energy Development*, which set a target for renewable energy to account for 33% of total electricity generation by 2025 (up from approximately 29%

in 2021). Within this target, wind and solar power are set to achieve a combined share of 18%. In terms of spatial planning, the focus is on accelerating the construction of large wind farms in desert, Gobi, and arid regions while steadily advancing the development of offshore wind power bases.

According to the *Battle for the Future 2022: Asia Pacific Power and Renewables Competitiveness Report* (Wood Mackenzie 2023), the LCOE for wind power projects in China decreased in 2022, in stark contrast to the rising LCOE trends observed in other markets in the Asia–Pacific region. This phenomenon is closely linked to the localization of China's supply chain, its price competitiveness, and the low-interest-rate environment. In 2022, China's onshore wind LCOE saw a significant 26% reduction. Meanwhile, the LCOE for offshore wind dropped to $72 per megawatt-hour (US$72/MWh), a 22% year-on-year decrease, which is significantly lower than the average offshore wind LCOE of US$171/MWh elsewhere in the Asia–Pacific region.

According to IEA data, in 2022, China's wind energy sector continued to lead globally in newly installed capacity, with an increase of 37 GW, representing an 11.2% year-on-year growth. This addition accounted for 50% of total global capacity growth. Of this, offshore wind contributed 7 GW, solidifying China's leadership in the global offshore wind market and making a significant contribution to industry growth. In the same year, the global wind energy sector saw an increase of 265 terawatt-hours in electricity generation, with China contributing nearly 40% of the total, followed by the United States at 22%. These figures highlight China's critical role in driving global wind energy growth.

Simultaneously, according to the *Renewables 2023 Analysis and Forecast to 2028* report, two-thirds of the expansion projects announced by major wind turbine component manufacturers were based in China and aimed at meeting the growing market demand. China's original equipment manufacturers have supplied more than 95% of the turbines for the domestic market, but their penetration into overseas markets remains limited. In contrast, outside China, approximately 95% of the global market demand is met by companies based in Europe and the United States. Although turbines manufactured in China are priced on average at only one-third of their European and American counterparts, their competitiveness in the international market needs improvement.

According to the forecast data provided by the IEA in *Renewables 2023 Analysis and Forecast to 2028*, China's wind energy sector is the only one globally demonstrating a stable, positive development trajectory. Based on *China Wind Power Development Roadmap 2050*, it is projected that by 2050, China's installed wind power capacity will reach 1 billion kilowatts, capable of meeting 17% of the country's electricity demand. This goal envisions comprehensive development of onshore wind in the eastern, central, and western regions, as well as both nearshore and offshore wind power. To achieve this ambitious target, the construction and optimization of a national-level wind power technology and innovation system, along with strengthening basic research and public service capabilities, are crucial. These efforts will both sustain the development of China's wind energy industry and contribute to advancements in renewable energy.

5.2 Global Distribution of Critical Minerals for the Wind Energy Industry

5.2.1 Types of Critical Minerals

The wind energy industry requires several specific critical minerals, including molybdenum, cobalt, and chromium. Cobalt, manganese, rare earth elements, and zinc are also essential for the development of wind energy (IEA 2021). In the industry, cobalt is primarily used in battery cathodes, while manganese and rare earths are integral to the production of wind turbine generators. Manganese is also used to produce high-strength steel for wind turbine towers and other components. Zinc coatings protect wind turbines from corrosion and rust, extending their operational life. The following sections detail the specific applications of molybdenum, cobalt, and chromium in the wind energy sector.

Molybdenum

Molybdenum-containing steels are known for their high strength, toughness, corrosion resistance, and long service life and are widely used in key wind turbine components such as main shafts, gears, and towers (Summerfield-Ryan and Park 2023). For each GW of wind power installed, approximately 110 tons of molybdenum are required. By 2025, the demand for molybdenum for wind turbines is expected to reach 17,000 tons, with a compound annual growth rate of 11.3% from 2022 to 2025.

Cobalt

According to IEA reports, clean energy technologies, including wind turbines, require a wide range of minerals and metals, including cobalt. Cobalt is a critical component in the rechargeable batteries used in wind turbines (Yacoub et al. 2024). These batteries store electricity generated by the turbines for use when wind is not blowing. In addition, to produce electricity, wind turbines rely on magnetic fields, and cobalt is used in wind turbine magnets.

Chromium

While chromium is used in some battery technologies, its primary application in renewable energy is in steel alloys. Chromium-based iron alloys have high corrosion resistance, making them particularly valuable in wind turbines and geothermal facilities. By 2050, the demand for chromium in green energy technologies is projected to reach 366,000 tons per year (Lund and Toth 2020), which represents only 1%

of global production in 2018. Since 90% of chromium is used in the steel industry, which serves various sectors, the growing demand from renewable energy is unlikely to have a significant economic impact on chromium's broader market.

5.2.2 Major Importers/Exporters and Producers of Critical Minerals

Major Importers and Exporters

Table 5.1 lists the major importing and exporting countries for critical minerals required by the wind energy industry, along with their import and export volumes. The major importers of molybdenum are China, South Korea, Japan, the United States, and the Netherlands, while the major exporters are Chile, Peru, the United States, the Netherlands, and Mexico. According to the Ministry of Natural Resources, China's molybdenum reserves in 2022 were 5.9 million tons, an increase of 51,600 tons compared to 2021, with concentrations in Henan, Inner Mongolia, Tibet, Heilongjiang, and Jilin. Additionally, annual molybdenum exploration funding reached 73 million yuan, with drilling reaching 60,000 m, reflecting respective growths of 32.7% and 20.0% and thus marking significant progress. As the largest molybdenum consumer, China's consumption reached 122,000 tons (about 270 million lb.) in 2022, accounting for 42.6% of global demand, followed by Europe (19.67%), the United States (9.71%), and Japan (8.06%) (IMOA 2024). In terms of trade, China's molybdenum product imports in 2021 amounted to 57,800 tons, valued at $772 million, while exports totalled 45,600 tons, valued at $961 million.

The main importers of cobalt are China, Morocco, Finland, Malaysia, and Zambia, while the primary exporters are the DRC, Austria, South Korea, the United States, and Canada. China is one of the largest consumers and processors of cobalt globally. However, cobalt resources within China are relatively scarce. According to the Ministry of Natural Resources, China's identified cobalt resources stood at 158,700 tons in 2022, mainly located in Gansu, Shandong, Yunnan, Hubei, Hebei, Qinghai, and Shanxi provinces, with Gansu accounting for the largest share at 29.68% of national reserves (Ministry of Natural Resources 2024).

The primary importers of chromium are China, Indonesia, Turkey, Germany, and India, while the major exporters are South Africa, Turkey, Zimbabwe, Albania, and Pakistan. In 2021, global reserves of marketable-grade chromite ore amounted to 570 million tons. Chromite resources are highly concentrated, with five countries—South Africa, Kazakhstan, India, Finland, and Turkey—holding over 99% of the world's reserves. China, in contrast, has limited chromium resources, and the quality of its chromite ores is relatively poor. As of the end of 2020, China's proven chromite ore reserves totalled 2.7697 million tons, concentrated in Tibet, Gansu, Xinjiang, and Hebei, with respective shares of 75.61%, 17.73%, 5.60%, and 1.06%. From 2006 to 2019, China's proven chromite resources grew at an average annual rate

Table 5.1 Major importing and exporting countries of critical minerals for wind energy and their trade volumes (*Unit* tons)

Importing country	Import volume	Exporting country	Export volume
Molybdenum			
China	41,194	Chile	79,375
South Korea	36,057	Peru	59,963
Japan	35,369	USA	47,795
USA	32,037	Netherlands	31,357
Netherlands	31,972	Mexico	23,290
Cobalt			
China	26,272	DRC	28,881
Morocco	2332	Austria	1310
Finland	1350	South Korea	417
Malaysia	1020	USA	172
Zambia	297	Canada	135
Chromium			
China	14,967,456	South Africa	13,434,665
Indonesia	485,270	Turkey	995,659
Turkey	174,810	Zimbabwe	475,943
Germany	142,038	Albania	403,520
India	141,469	Pakistan	340,861

Source UN Comtrade and research team calculations

of 1.42%. In 2019, exploration efforts led to an additional 244,000 tons of proven chromite resources, though overall reserves have slightly declined since 2010. Due to low domestic production and reserves, China is heavily reliant on chromite imports. From 2015 to 2021, China's chromite ore and concentrate imports remained between 10 and 16 million tons annually, with imports increasing yearly as demand from downstream industries like stainless steel and specialty steel continued to rise. The primary sources of these imports are South Africa, Turkey, and Zimbabwe, with South Africa being the largest supplier.

Major Producers

This section compiles data on the major producers and production volumes of molybdenum, cobalt, and chromium based on U.S. Geological Survey (USGS) data, as shown in Table 5.2.

Molybdenum: The major producing countries of molybdenum are China, Chile, and Peru. China is the largest producer, accounting for approximately 40% of global production in 2022. South America is the second-largest molybdenum-producing region, with a production volume of 75,613 tons in 2022. Molybdenum resource

Table 5.2 Major producing countries and production of critical minerals for the wind energy industry in 2022 (*Unit* tons)

Major producing country	Production
Molybdenum	
China	106,000
Chile	45,600
USA	34,600
Peru	31,600
Mexico	15,500
Cobalt	
DRC	144,000
Indonesia	9600
Russia	9200
Australia	5790
Philippines	3900
Chromium	
South Africa	19,100,000
Kazakhstan	6,000,000
Turkey	5,410,000
India	4,000,000
Finland	2,000,000

Source USGS

development in China is concentrated in Henan, Heilongjiang, Shaanxi, Inner Mongolia, and Hebei. In 2021, these five provinces accounted for over 80% of China's total production, with Henan contributing the highest share at 34.3%, followed by Inner Mongolia (17.7%) and Heilongjiang (15.9%).

Cobalt: The primary cobalt-producing countries are the DRC and Indonesia. According to USGS data, global cobalt reserves were 8.3 million tons in 2022, an increase of just 1.1 million tons from 2013. The DRC holds the largest share of cobalt reserves, with 3.5 million tons in 2022, representing 48.2% of global reserves. Global cobalt production has continued to grow, with the DRC accounting for nearly 70% of this output. Due to the DRC's large, high-grade reserves and its improved political stability since 2001, the country has become the world's largest and fastest-growing cobalt producer, driving the rapid growth of global cobalt production. In 2022, global cobalt production was approximately 190,000 tons, a 15.15% year-on-year increase. Of this, the DRC produced around 130,000 tons, accounting for 68.4%, while production in other countries was below 10,000 tons in each.

Chromium: The major chromium-producing countries are South Africa, Turkey, and Kazakhstan. According to the USGS report, between 1958 and 2022, the cumulative global production of chromite ore (raw ore) amounted to 6.1294 million tons (equivalent to 1.8744 million tons of chromium content). Chromite ore production initially grew and later declined. From 1958 to 1987, annual production grew slowly, fluctuating between 3000 and 75,000 tons. From 1988 to 2007, production increased rapidly, rising from 37,000 tons in 1988 to a historic high of 281,500 tons in 2007. Production then gradually decreased, reaching 23,000 tons in 2018, though there was a growth trend from 2019 to 2022. China's domestic chromite ore resources are limited, with small, scattered deposits and challenging development conditions. Reserves are roughly split between low- and high-grade ores, and most accessible high-grade deposits have already been mined. Major chromite mines in China include the Luobusha chromite mine in Tibet, the Dadaoerji chromite mine in Gansu, and the Saltuohai chromite mine in Xinjiang, though production remains very low, with an import dependency rate exceeding 90%. According to USGS data, China's chromite ore production in 2022 was approximately 160,000 tons.

Policies

Based on the IEA policy database, this section summarizes the policies related to critical minerals required by the wind energy industry, as outlined in Table 5.3. Countries such as China, the United States, the United Kingdom, and Finland have implemented specific policies focused on the protection, development, and use of rare earth resources. These policies are designed to promote sustainable development of the wind energy sector and enhance national economic competitiveness.

5.3 Global Trade Network Security of Critical Minerals in the Wind Energy Industry

5.3.1 Overall Characteristics of the Trade Network

Figure 5.3 illustrates the evolution of the degree distribution in the trade networks of critical minerals required by the wind energy industry for the years 2000, 2005, 2010, 2015, and 2020. The figure displays the heterogeneity of the different nodes within trade networks. The power-law characteristics of the molybdenum, cobalt, and chromium trade networks peaked in 2015, with the power-law behaviour of molybdenum and chromium being significantly higher in 2015 compared to other years. Cobalt's power-law distribution became increasingly pronounced between 2000 and 2015, indicating that the distribution of resources has become more unequal over time, with control of cobalt resources increasingly concentrated in a small number of countries and regions. This growing concentration of resources suggests that trade network security has been increasingly affected by the dominance of a few key players, which could lead to vulnerabilities in global supply chains for critical minerals essential to the wind energy industry.

Figure 5.4 depicts the evolution of the relationship between clustering coefficient and degree in the trade networks of critical minerals required by the wind

Table 5.3 Policies on critical minerals for the wind energy industry by country

Country or area	Year	Policy
China*	2011	Issued *Recommendations on Promoting the Sustainable and Healthy Development of the Rare Earth Industry*, aiming to enhance understanding of the importance of effective protection and rational use of rare earth resources and to promote sustainable development of the rare earth industry. The document established national policies for the rare earth industry, including measures to strengthen the regulatory system, such as strict control over illegal mining, exports, pollution, and new rare earth smelting and separation projects
China*	2021	The state-owned Assets Supervision and Administration Commission announced the establishment of the China Rare Earth Group to consolidate the advantages of rare earth resources and promote coordinated development of the industry. As the world's largest strategic producer of rare earth elements, the group aims to enhance the central government's direct control over the rare earth sector
USA*	2015	The National Energy Technology Laboratory (NETL) provided funding for research on innovative midstream processing technologies to extract, separate, and refine high-purity rare earth elements and other critical minerals from coal, coal by-products, and alternative non-coal raw materials. By 2017, NETL had allocated more than US$20 million for related research
USA*	2021	The Department of Energy Office of Science allocated US$30 million to research projects led by 13 national laboratories and universities, aimed at developing new technologies to ensure the security and diversity of the domestic critical material supply chain. This includes efforts to improve recycling and reuse of key components like rare earths and platinum group elements for clean energy and high-tech applications
USA*	2022	The Inflation Reduction Act of 2022 grants a 10% tax credit to manufacturers for production costs associated with critical minerals, including aluminium, antimony, barium, beryllium, cerium, caesium, chromium, cobalt, dysprosium, europium, fluorspar, gadolinium, germanium, graphite, indium, lithium, manganese, neodymium, nickel, niobium, tellurium, tin, tungsten, vanadium, and ytterbium. Eligible minerals must be produced in the United States. The tax credit applies starting in 2023 and is exempt from the phase-out applicable to other qualifying components

(continued)

Table 5.3 (continued)

Country or area	Year	Policy
UK	2012	The SoS Minerals research programme, supported by the Natural Environment Research Council and the Engineering and Physical Science Research Council, collaborates with industry and academia. The SoS Minerals programme includes four fully funded projects focused on critical elements for electronic technologies, including cobalt, tellurium, selenium, neodymium, indium, gallium, and heavy rare earth elements
Finland*	2021	In 2020, the Ministry of Economic Affairs and Employment began developing the National Battery Strategy to encourage projects in the battery sector and position Finland as a key player in electrification and battery production. The strategy emphasizes the responsible sourcing and processing of raw materials and research into battery materials and recycling. Finland aims to become the world's leading expert in battery minerals, focusing on cobalt, nickel, lithium, copper, and graphite

Note * denotes countries rich in critical minerals required for wind energy

energy industry for the years 2000, 2005, 2010, 2015, and 2020. The trade networks for molybdenum, cobalt, and chromium exhibit power-law characteristics, with the clustering coefficient decreasing as degree increases, indicating a clear hierarchical structure. The power-law characteristics of the molybdenum and chromium trade networks were most pronounced in 2015, whereas cobalt displayed weaker power-law behaviour. This suggests that in the molybdenum and chromium trade networks, countries with lower degrees (those trading with fewer partners) tend to have higher clustering coefficients, meaning they form tightly connected smaller clusters with high local trade density. In contrast, countries with higher degrees (those trading with many partners) do not exhibit frequent trade interactions among their partners, highlighting a more hierarchical structure. On the other hand, the cobalt trade network demonstrates weaker clustering overall, and countries with higher degrees engage in more frequent trade interactions compared to those in the molybdenum and chromium networks. This indicates that the cobalt trade network is less clustered, with more globalized and widespread trade among the major players.

5.3.2 Trade Network Security

Figure 5.5 illustrates the evolution of trade risks for critical minerals required by the wind energy industry from 2000, 2005, 2010, 2015, and 2020. Overall, cobalt presents the highest trade risk among these minerals, followed by molybdenum, while chromium shows the lowest trade risk. Between 2010 and 2020, trade risks for cobalt and chromium show a clear upward trend, indicating increasing vulnerability in global supply chains. In contrast, the trade risk for molybdenum has been decreasing, suggesting improvements in the security of its trade network. This could be attributed

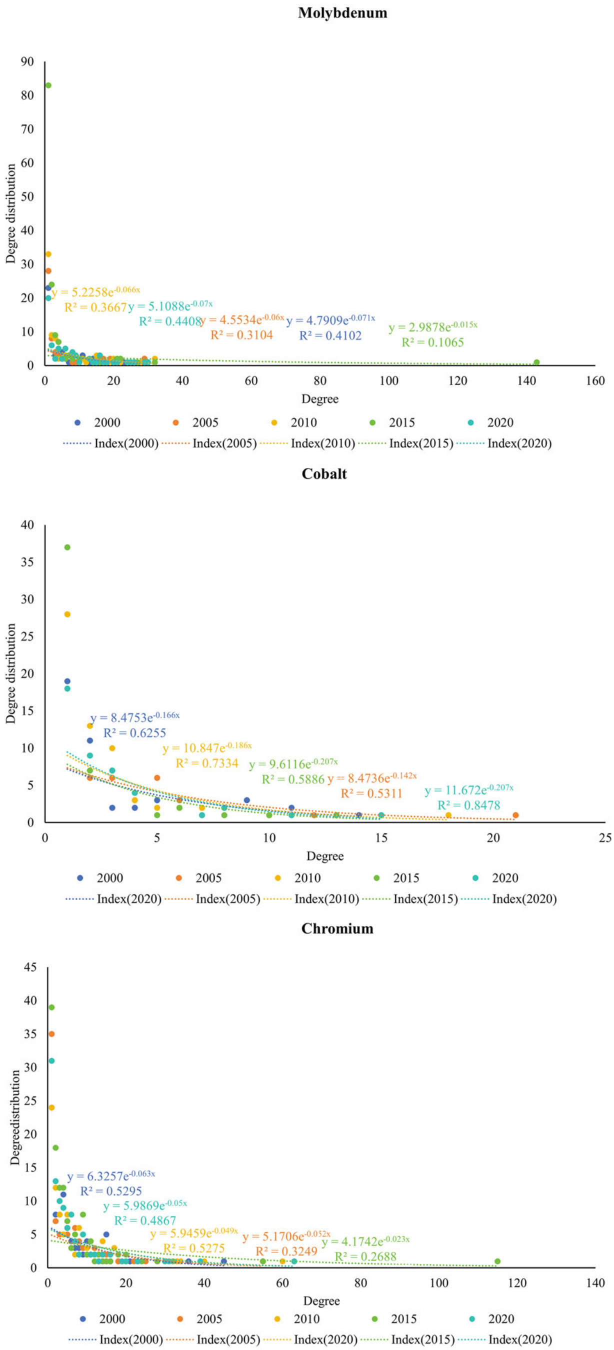

Fig. 5.3 Evolution of degree distribution in the trade network of critical minerals for the wind energy industry. (*Source* the authors)

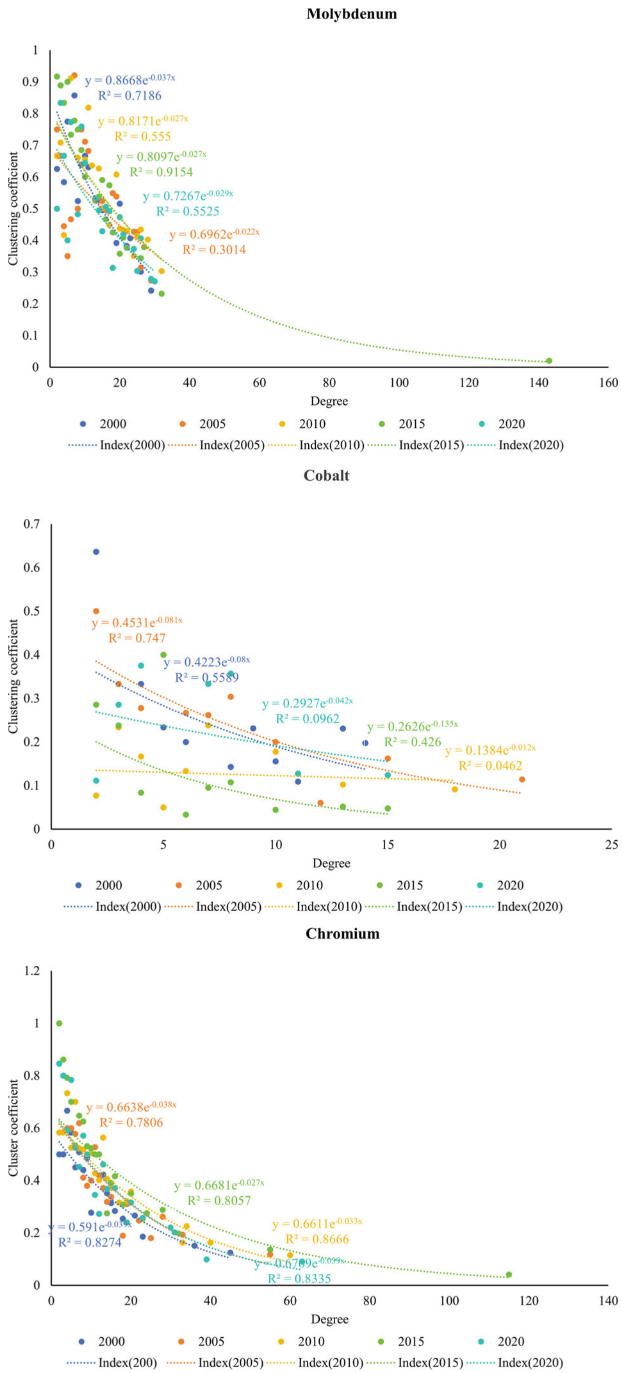

Fig. 5.4 Evolution of clustering coefficient and degree relationship in the trade network of critical minerals for the wind energy industry. (*Source* the authors)

to stabler global supply patterns or diversification in molybdenum production and trade partners, whereas cobalt's growing demand and supply concentration have heightened its trade risks.

5.3.3 Major Trade Countries

This section assesses the positions of key exporting countries within the trade networks for critical minerals required by the wind energy industry (as shown in Table 5.4). The findings indicate the following.

The countries that play a critical role in stabilizing the molybdenum trade network are concentrated among major producers or exporters, including the Netherlands, Chile, the United States, and China. These countries are pivotal in maintaining the security and flow of molybdenum within the global trade network.

In the cobalt trade network, key countries include the DRC, China, and several African nations. The DRC is the largest producer of cobalt, while China is the largest importer, underscoring its critical role in the cobalt trade network and its global importance in cobalt processing and consumption.

These countries' roles in the trade network highlight their strategic importance in ensuring a stable supply of critical minerals necessary for the growth and security of the global wind energy industry.

5.4 Conclusion

This chapter has explored development trends in the wind energy industry, focusing on trade patterns, trade security, and key countries involved in the supply of critical minerals required by the industry. The study reported here found that the power-law characteristics of the molybdenum, cobalt, and chromium trade networks peaked in 2015, with molybdenum and chromium showing much stronger power-law behaviour compared to other years. The cobalt trade network exhibited relatively weak clustering, and trade between high-degree countries was more frequent compared to molybdenum and chromium. Among the critical minerals required by the wind energy industry, cobalt presented the highest trade risk, followed by molybdenum, with chromium having the lowest risk. The countries critical to the stability of molybdenum trade were concentrated among key producers and exporters, such as the Netherlands, Chile, the United States, and China. In terms of policy, China, the United States, the United Kingdom, and Finland have implemented policies related to critical minerals for wind energy. These policies primarily focus on the protection, development, and use of rare earth resources with the dual aim of promoting the sustainable development of related industries and enhancing national economic competitiveness.

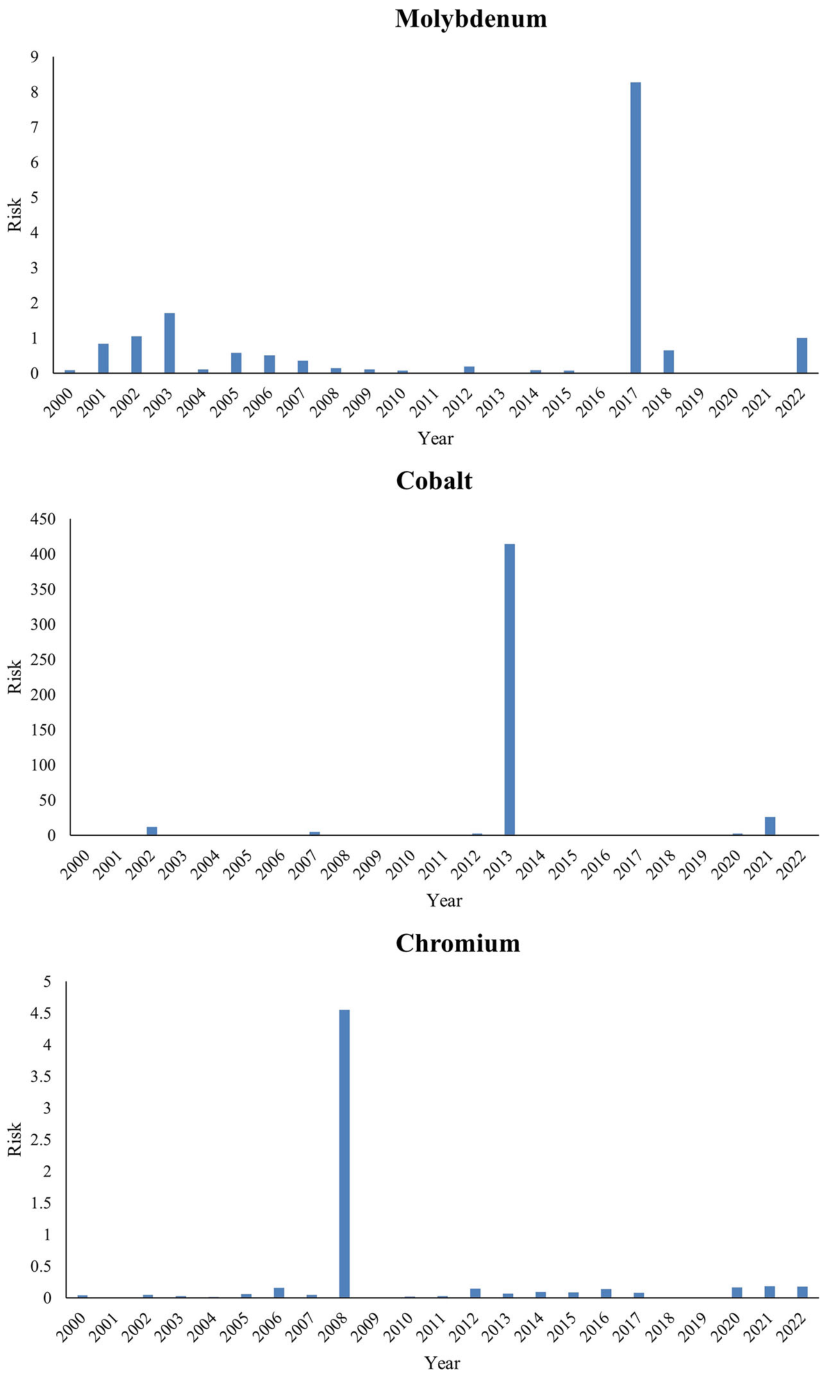

Fig. 5.5 Evolution of trade risks in the trade networks of critical minerals for the wind energy industry. (*Source* the authors)

Table 5.4 Evolution of exporting countries' importance in the trade network of critical minerals for the wind energy industry

2000	2005	2010	2015	2020
Molybdenum				
Netherlands	Japan	Netherlands	Netherlands	UAE
Russia	Belgium	Chile	Belgium	USA
China	Netherlands	China	Chile	India
USA	Germany	USA	USA	France
Chile	Peru	Russia	Nepal	Chile
Cobalt				
Germany	China	DRC	DRC	DRC
UK	DRC	China	China	China
France	USA	UAE	South Africa	Morocco
Belgium	Republic of the Congo	Zambia	Belgium	USA
South Africa	Finland	Pakistan	Zambia	Dominican Republic
Chromium				
Iran	China	China	China	China
Netherlands	UAE	Iran	Oman	UAE
China	South Africa	UAE	Iran	Oman
India	Turkey	Turkey	UAE	Iran
South Africa	Kazakhstan	South Africa	South Africa	Russia

Source UN Comtrade and calculations by the research team

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Chapter 6
Electric Vehicle Industry and Critical Mineral Trade Network Security

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Abstract As a key driving force for sustainable energy transformation, the rapid development pace of the electric vehicle industry has stimulated global attention to the stable supply of its key raw materials. This chapter has deeply analysed the development of the global electric vehicle (EV) industry, critical minerals—such as graphite, lithium and titanium—and the strategic position of countries that play a key role in international trade. By applying the trade network security index constructed in Chapter 4, this chapter comprehensively evaluates the stability of the supply of these raw materials and identifies countries that have great influence on global trade stability. The study reported here shows that among the critical minerals required by the EV industry, lithium faces the highest trade risk. China, the United Arab Emirates (UAE) and Iran are among the countries that influence the stability of the graphite trade. The United States and China attach great importance to rare earth elements, while Germany and Finland attach more importance to cobalt, nickel, lithium, copper and graphite.

Keywords Electric vehicles · Critical minerals · Complex networks · Trade risk

6.1 Development Trends in the Electric Vehicle Industry

The electric vehicle (EV) industry is hugely important for decarbonizing road transport, which accounts for about one-sixth of global carbon emissions. In recent years, the EV market has shown a dynamic growth trajectory—with sales increasing exponentially—an expanding product range, a wide variety of models and continuously

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improving performance. This trend is driven by heightened global awareness of emissions reduction and air quality improvement, along with support from governments and businesses, as well as market demand fuelled by technological innovation and cost reductions. The competition in the EV industry involves not only traditional automakers but also emerging EV companies, which are focused on developing more advanced, high-performance, and environmentally friendly products. These efforts contribute positively to achieving the Sustainable Development Goals in the clean energy sector.

6.1.1 Development of the Global Electric Vehicle Industry

According to the report, "Global EV Outlook 2023", global expenditure on EV surpassed US$425 billion in 2022, marking a US$40 billion of this expenditure can be attributed to government support, with the remainder stemming directly from consumer purchases of vehicles. Between 2017 and 2022, the proportion of government contributions to total EV expenditures declined from over 20% to less than 10%. Looking ahead to 2023 and beyond, governments in major EV markets were poised to gradually phase out subsidies for EVs, signifying a reduction in government expenditures on these markets. Nevertheless, in markets with relatively low EV adoption rates, such as emerging markets and developing economies like India, Indonesia and Thailand, government incentives are anticipated to increase, potentially raising overall government expenditures.

Concurrently, investors maintain a high level of confidence in the EV sector. Since 2019, the stock performance of companies associated with the EV industry has consistently outpaced that of traditional automakers (USITC 2024; Giray and Rabeh 2023). Venture capital investments in startups developing EVs and their battery technologies have also continued to grow, reaching nearly US$2.1 billion in 2022, a 30% increase from 2021. Furthermore, investments in batteries and critical mineral resources are on the rise.

Since 2019, the global rise in commodity prices has put pressure on battery manufacturing costs. Supply chain disruptions during the COVID-19 pandemic, heightened demand spurred by the global economic recovery, and events such as the Russia–Ukraine conflict have all contributed to the escalation of commodity prices. According to the report, "Global EV Outlook 2023" (IEA 2023a), in 2022, the average price of batteries approximated US$150 per kilowatt-hour (kWh), with battery assembly costs accounting for a reduced share of 20%, down from the previous 30%. Nevertheless, the surge in material and energy costs has led to an increase in battery cell production costs. Different battery chemistries have been impacted unevenly by these cost shifts; for instance, lithium iron phosphate (LFP) battery prices rose by over 25%, while nickel manganese cobalt oxide (NMC) battery prices increased by less than 15%. As LFP batteries forgo the use of costly nickel and cobalt, opting for iron and phosphorus instead, lithium prices contribute a larger proportion to their costs. However, in terms of unit energy capacity, LFP batteries remain less expensive than lithium nickel cobalt aluminium (NCA) and NMC batteries. Battery prices also vary across global regions, with China generally offering the lowest prices, primarily due to its share of approximately 65% of battery cell production and nearly 80% of cathode material production.

Newly adopted and proposed greenhouse gas standards and zero-emission vehicle (ZEV) policies (USEPA 2024; EU Council 2024; Government of Canada 2023) will facilitate the widespread adoption of EVs in the future. California, a pioneer in ZEV policies, has set goals of minimum ZEV sale shares for light-duty vehicles (LDVs) between 35% in 2026 and 100% by 2035. It has also established milestones for the sale of zero-emission heavy-duty vehicles, aiming for 100% penetration between 2035 and 2042. The United States Environmental Protection Agency introduced new greenhouse gas emission standards in April 2023, targeting light- and medium-duty vehicles. This new standard aims to achieve significant emission reductions compared with the current 2026 model year standards: a 56% reduction for LDVs and a 44% reduction for medium-duty vehicles by 2032. This series of policies and regulations underscore a global commitment to advancing EV adoption, mitigating greenhouse gas emissions, and fostering environmental sustainability.

Policies are increasingly focused on fostering the development of manufacturing rather than on mere deployment. The European Union's "Net-Zero Industry Act" proposed in March 2023 aims to enable EU battery manufacturers to meet nearly 90% of annual battery demand, with a production capacity of at least 550 gigawatt-hours by 2030. Similarly, India aims to boost domestic EV and battery manufacturing through the Production-Linked Incentive scheme for advanced chemistry cell battery storage. In the United States, the Inflation Reduction Act (U.S. Department of the Treasury 2022) introduces conditions for consumer tax credits for clean vehicles, including the requirement that final vehicle assembly must occur in North America. Meeting these criteria can yield a credit of up to $7500 per vehicle; an additional $3750 is available if the battery meets critical mineral requirements and a further $3750 if component requirements are met (IEA 2023a).

According to International Energy Agency (IEA) data, global EV battery demand surged by approximately 65% in 2022, reaching around 550 gigawatt-hours (GWh), which roughly aligned with EV battery production. Specifically, global lithium-ion battery production capacity stood at around 1.5 terawatt-hours (TWh) in 2022, indicating a utilization rate of approximately 35% compared with 43% in 2021. Anticipating further growth in demand, there is an urgent need to optimize and expand EV manufacturing capabilities to meet escalating market demands. Moreover, EV manufacturers are intensifying their research and development efforts, offering a broader range of brands and models to cater to the diverse needs of consumers. In 2022, the number of EV models available on the global market soared to 500, more than doubling since 2018. This trend underscores manufacturers' proactive approach to expanding their market share and fulfilling consumer expectations.

EV sales achieved a historic breakthrough in 2022 despite numerous challenges facing the global automotive market that year. These challenges included supply chain disruptions, macroeconomic volatility, geopolitical uncertainties, and rising commodity and energy prices (IEA 2022), which led to an overall contraction of the global automotive market, with total vehicle sales declining by 3% from 2021. Nevertheless, EV sales hit a new record high, with over 10 million units sold globally, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). These accounted for 14% of total vehicle sales, marking a 55% increase from 2021. This leap is particularly noteworthy in the long run, as it took just five years for EV sales to skyrocket from approximately 1 million units in 2017 to over 10 million in 2022. Notably, it took the same five years for EV sales to grow from around 100,000 units in 2012 to 1 million in 2017, highlighting the exponential growth characteristics of the EV market.

Figure 6.1 illustrates EV sales and market share under the Net Zero Scenario from 2015 to 2030. The growth in EV sales has been particularly robust in China, Europe and the United States, but it has yet to become a truly global phenomenon. In developing and emerging market countries, EV sales have been relatively slow due to higher purchase costs and a lack of charging infrastructure. This status quo underscores the challenges in promoting the global adoption of EVs while also pointing to future growth potential, particularly given the efforts to optimise the cost-effectiveness of EVs and expand charging infrastructure.

The surge in demand for EVs has correspondingly fuelled the demand for batteries and associated critical minerals (Wang et al. 2023; World Economic Forum 2021). The demand for lithium-ion (Li-ion) batteries for automotive applications grew from approximately 330 gigawatt-hours (GWh) in 2021 to 550 GWh in 2022, marking an increase of around 65%, primarily driven by the rise in electric passenger vehicle sales. By 2022, approximately 60% of lithium, 30% of cobalt and 10% of nickel demand originated from EV batteries. In contrast, these proportions were only 15%, 10% and 2%, respectively, five years before. Given the recent surge in battery raw material prices, reducing reliance on these critical minerals is crucial for ensuring the sustainability, resilience and security of supply chains.

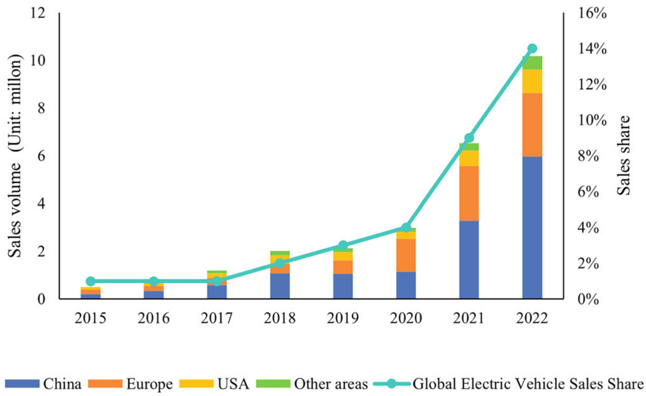

Fig. 6.1 Sales volume and market share of electric vehicles under the net-zero scenario from 2015 to 2030. (*Source* IEA)

In terms of infrastructure, the number of public charging points is on the rise. While the majority of charging needs are currently met through home charging, the demand for publicly accessible charging facilities to provide the same convenience and accessibility as traditional gasoline stations is growing. By the end of 2022, there were 2.7 million public charging points globally, with over 900,000 installed in 2022 alone, representing an increase of approximately 55% from 2021. By the end of 2022, China accounted for roughly two-thirds of the world's public charging stations, while Europe ranked second, with approximately 540,000 public charging points, a 50% increase from the previous year.

Alternative battery chemistries are increasingly gaining attention, helping alleviate the pressure on critical mineral supplies (Nature Energy 2022). Severe fluctuations in mineral prices and supply chain constraints could pose obstacles to the development of the EV industry. Currently, lithium-ion batteries dominate the EV battery market, with most common chemistries relying on critical minerals such as lithium, cobalt and nickel. In 2022, NMC continued to dominate the battery chemistry landscape with a 60% market share, followed by lithium iron phosphate (LFP) with slightly less than 30%, and NCA oxide accounting for approximately 8%. Notably, LFP batteries make up the only lithium-ion battery chemistry that does not use nickel or cobalt, achieving its highest market share since 2012. This is partly due to fluctuations in battery metal prices, making LFP batteries more attractive despite their lower energy density.

In recent years, alternatives to lithium-ion batteries have emerged, notably sodium-ion batteries. These batteries offer a dual advantage: they rely on materials that are cheaper than those used in lithium-ion batteries, making them more affordable, and they completely forgo the need for critical minerals. Currently, sodium-ion batteries are the only viable alternative to lithium-ion batteries that do not contain lithium. It is estimated that the sodium-ion batteries developed by China's CATL company are 30% cheaper than LFP batteries. However, sodium-ion batteries have a lower energy density than lithium-ion batteries, which may make them more suitable for city vehicles with shorter driving ranges or stationary storage applications. Deploying sodium-ion batteries in scenarios where consumers prioritize maximum driving-range autonomy or where charging facilities are less accessible could pose challenges. There are currently nearly 30 sodium-ion battery production facilities in operation, planning or construction, with a total capacity exceeding 100 GWh, almost entirely located in China. In comparison, the capacity for lithium-ion batteries stands at approximately 1500 GWh. Several automakers have already unveiled sodium-ion EVs, such as BYD's "Seagull" with a driving range of 300 kms and a price tag of US$11,600 and the Sehol EX10 produced by the VW-JAC joint venture, offering a range of 250 kms.

According to the IEA, based on current policies and automotive industry targets, the global outlook for EV sales in 2030 has increased to 35% of total vehicle sales. In China, the European Union and the United States, the average share of EVs in total car sales is projected to rise to around 60% by 2030.

6.1.2 Development of China's Electric Vehicle Industry

In recent years, China has significantly intensified its investment in the EV sector, resulting in a continually expanding market size that has positioned the country as a global leader in the EV industry. According to the report, "Global EV Outlook 2023" (IEA 2023b), China's EV exports accounted for 35% of the global total in 2022, marking an increase from 25% in 2021. Europe stands as one of China's largest trading partners in the EV and battery sectors, with the proportion of EVs produced in China and sold in the European market reaching 16% in 2022, up from 11% in 2021. Within China, despite a 3% decline in overall vehicle sales in 2022 compared with 2021, EV sales maintained a growth trajectory. In 2022, EVs accounted for 29% of total domestic vehicle sales, surpassing the 16% share in 2021 and significantly exceeding the levels below 6% observed from 2018 to 2020. Specifically, sales of BEVs in China grew by 60% year-on-year in 2022, reaching 4.4 million units, while sales of PHEVs surged by nearly 200%, totalling 1.5 million units. This signifies that China has already surpassed its national target of achieving a 20% share of new energy vehicle sales by 2025, ahead of schedule.

The Chinese government has reiterated its commitment to strengthening the electrification of road transportation in strategic documents such as the "Collaborative Implementation Plan for Pollution Reduction, Carbon Reduction, and Efficiency Enhancement" and the "Carbon Peaking Action Plan by 2030". It aims to achieve a 50% sales share in key air pollution control areas and a 40% share nationwide by 2030 in support of the national carbon peaking action plan. Additionally, provincial governments in China have vigorously supported the adoption of new energy vehicles, with 18 provinces having established related targets (Zhang and Hanaoka 2021). This local government support has fuelled the development of some of the world's largest EV manufacturers, such as BYD, headquartered in Shenzhen. China currently accounts for nearly 60% of global EV registrations, and in 2022, it surpassed the 50% threshold for all EVs on the road globally for the first time, totalling 13.8 million vehicles. This robust growth is attributed to over a decade of policy support, encompassing purchase incentives, charging infrastructure development and strict enforcement of policies restricting non-EV registrations.

6.2 Global Distribution of Critical Minerals for the Electric Vehicle Industry

6.2.1 Types of Critical Minerals

In addition to ubiquitous minerals, such as silicon, nickel and rare earth elements, which are also crucial for the development of the EV industry, this section focuses on the unique minerals that are specifically vital for EVs. Silicon is used in the production of power electronics equipment, such as inverters, which transfer energy from vehicle batteries to electric motors. Silicon carbide (SiC), another material gaining popularity in the EV sector due to its superior thermal conductivity and high-temperature stability, is utilized in the manufacture of high-power electronic devices for EVs. Nickel serves as the cathode material in lithium-ion batteries, while manganese acts as a stabilizing component in NMC lithium-ion battery cathodes, enhancing energy density and thus driving range while reducing the flammability of EV battery packs. Rare earth elements are indispensable for the production of permanent magnets in EV motors. The following are the critical minerals uniquely required by the EV industry, along with their specific applications:

Graphite

Graphite is a crucial component in the manufacturing of EV batteries and energy storage systems (USITC 2022; Zhang et al. 2021). According to the International Energy Agency (IEA), clean energy technologies, such as EVs, require a diverse range of minerals and metals, including graphite. By weight, graphite comprises almost 50% of the materials needed for batteries.

Lithium

Lithium-ion batteries are the primary energy storage devices in EVs, accounting for a significant portion of the overall cost (Xie and Lu 2020). The cathode materials in lithium-ion batteries are typically oxides, such as lithium cobalt oxide, NMC or lithium iron phosphate (LFP), all of which contain lithium (Manthiram 2020).

Titanium

Titanium dioxide (TiO2) is a vital material in energy storage systems (Wei et al. 2021; Tshimangadzo and Mpfunzeni 2024). TiO2 nanostructures, including nanoparticles, nanorods, nanoneedles, nanowires and nanotubes, are being investigated as active battery materials due to their high safety, low cost, thermal and chemical stability, and moderate capacity (Vardan et al. 2022). Furthermore, titanium is used as a raw material for hydrogen storage alloys in nickel-metal hydride batteries.

6.2.2 Major Importers/Exporters and Producers of Critical Minerals

Major Importers and Exporters

Table 6.1 summarizes the primary import and export countries for critical minerals essential to the EV industry, along with their respective import and export volumes. Major importers of graphite are China, the United States, Germany, Japan and Canada, and major exporters of graphite are China, Mozambique, Madagascar, the United States and Germany. China is a significant player in the graphite market, both as an importer and an exporter. Its graphite resources are widely distributed but relatively concentrated, with a higher concentration in the east. Large crystalline graphite deposits are found primarily in Heilongjiang, Inner Mongolia, Shandong, Henan and Sichuan provinces. Heilongjiang and Shandong are the most concentrated regions, accounting for 47% and 19% of China's total crystalline graphite ore reserves, respectively, representing 66% of the country's total reserves.

Major importers of lithium are South Korea, Japan, China, France and Canada, and major exporters are China, Chile, the United States, Russia and Netherlands. Global

Table 6.1 Major importing and exporting countries and volumes of critical minerals for electric vehicles (*Unit* Tons)

Importing country	Import volume	Exporting country	Export volume
Graphite			
China	170,439	China	225,301
USA	89,409	Mozambique	159,462
Germany	66,957	Madagascar	120,091
Japan	59,141	USA	52,637
Canada	52,860	Germany	17,679
Lithium			
South Korea	70,907	China	91,429
Japan	35,543	Chile	13,903
China	2041	USA	8420
France	1983	Russia	5970
Canada	1597	Netherlands	2617
Titanium			
China	3,466,688	Mozambique	2,250,898
United States	882,695	South Africa	766,180
Germany	479,932	Norway	666,978
Japan	465,796	Australia	544,550
Norway	269,914	Madagascar	530,229

Source UN Comtrade and research team calculations lithium resources are abundant but unevenly distributed, with significant concentrations in the South American Lithium Triangle (Bolivia, Argentina and Chile), the United States, Australia and China. According to the US Geological Survey (USGS), the global lithium resource reserve was 26 million tons in 2022 (equivalent to approximately 138 million tons of lithium carbonate). Chile leads with a 35.78% share, followed by China with less than 10% and ranking fourth. China's lithium mine reserves increased by 57% in 2022, with Jiangxi Province topping the list with 40% of the country's total reserves. China primarily exports natural graphite, with exports far exceeding imports. Specifically, during the period from 2017 to 2019, China's import and export volumes of natural graphite showed an overall upward trend. However, in 2020, due to the impact of the COVID-19 pandemic, both import and export volumes declined. By 2022, China's import volume of natural graphite had reached 170,000 tons, with an import value of US$120 million, while the export volume was 285,500 tons, with an export value of US$470 million. In terms of export distribution, Korea, Japan and the United States are the primary export destinations for China's natural graphite. Specifically, Korea accounts for 34.48%, Japan for 32.08% and the United States for 9.53% of China's total natural graphite exports.

Regarding titanium, the primary importing countries include China, the United States, Germany, Japan and Norway, while the major exporting countries are Mozambique, South Africa, Norway, Australia and Madagascar. According to the USGS, global titanium ore reserves are estimated to be 817 million tons, with ilmenite resources accounting for 770 million tons, or approximately 94.2%, and rutile resources for 47 million tons, or approximately 5.8%. Except for Antarctica, all other continents are rich in titanium ore resources distributed across more than 30 countries. Australia ranks first in the world in terms of titanium resources, followed by China, India, South Africa, Kenya, Brazil, Madagascar, Norway, Canada, Mozambique, Ukraine, the United States, Vietnam and Sierra Leone. The titanium reserves of these 14 countries account for approximately 97% of the world's total reserves. From 2018 to 2020, the import volume of processed titanium materials in China showed a downward trend. In 2019, China's import volume of titanium processed materials was 8117 tons, a year-on-year decrease of 6.49%. In 2020, due to the impact of the COVID-19 pandemic, foreign operating rates declined, and China's import volume of titanium processed materials reached 6139 tons, a year-on-year decrease of 24.37%.

Major Producers

Based on USGS data, this section compiles information on the major producing countries and production volumes of graphite, lithium and titanium, as shown in Table 6.2. The primary graphite-producing countries include China, Madagascar and Mozambique, with China currently being the world's largest producer of graphite. In terms of global production, there have been no significant fluctuations in the production of natural graphite worldwide in recent years. This stability is partly attributed to the lack of explosive growth in graphite-related industries, which have remained stable within a certain range. Additionally, due to graphite's specialized uses in cutting-edge industries and national defence technologies, various countries have imposed restrictions on the exploitation of graphite resources. According to USGS data, global natural graphite production reached 1.6 million tons in 2023, representing a year-on-year increase of 3.5%. From 2011 to 2022, China's natural graphite production grew slowly, fluctuating between 600,000 and 1.21 million tons. By 2022, China's natural graphite production had reached 1.21 million tons. Within the production mix, flake graphite accounted for a relatively high proportion, while amorphous graphite had a lower share. China's natural graphite resources are primarily distributed in Henan, Shandong, Sichuan, Hunan, Inner Mongolia, and Heilongjiang. Among these regions, Hunan contributes the highest output, accounting for approximately 28% of the total production. Heilongjiang follows, contributing 25% of the total, and Inner Mongolia ranks third with a 21% share. Hunan, Heilongjiang and Inner Mongolia are China's primary natural graphite–producing regions, collectively accounting for 74% of the country's total production.

Lithium production is primarily concentrated in countries such as Australia, Chile and China. Global lithium resources are abundant but unevenly distributed. In 2022, global lithium production (metal equivalent) was approximately 130,000 tons, representing a year-on-year increase of 21.5%, with Australia being the world's largest

Table 6.2 Major producing countries and production of critical minerals for the electric vehicle industry in 2022 (*Unit* Tons)

Major producing country	Production volume
Graphite	
China	1,210,000
Mozambique	166,000
Madagascar	130,000
Brazil	72,000
South Korea	23,800
Lithium	
Australia	74,700
Chile	38,000
China	22,600
Argentina	6590
Brazil	2630
Titanium	
China	180,000
Japan	47,000
Russia	20,000
Kazakhstan	15,000
Saudi Arabia	9700

Source USGS

producer. In terms of supply types, global lithium resources are diverse, with salt lakes and mine exploitation continuing to dominate in the short term.

As for titanium iron ore, the primary producing countries globally include China, Australia, Canada, Mozambique, South Africa and India. These eight countries contribute an annual production of 5.56 million tons, accounting for approximately 79.2% of the global total. The remaining countries, including Kenya, Senegal, Ukraine, Norway, Vietnam, the United States, Madagascar and Brazil, produce an annual output of 1.46 million tons, representing approximately 20.8% of the total. China is relatively rich in titanium resources, characterized by abundant reserves, wide distribution, and a predominance of primary ore over placer deposits. Additionally, China has more titanium iron ore than rutile ore, with a majority of low-grade ores and a few high-grade ones, all of which are multimetal-associated ores. The major high-volume ores exist in the form of vanadium–titanium magnetite, a rock-type ore, while rutile-type titanium ores that are easy to mine and utilize are very scarce. China's titanium ore purification technology is not highly developed, and its beneficiation technology is limited, resulting in relatively low-grade titanium concentrate output. Consequently, China relies heavily on imports for high-quality titanium concentrate. From 2009 to 2019, China's titanium ore production experienced significant fluctuations, starting with an annual output of 2.6282 million tons in 2009 and peaking at 12.963 million tons in 2011. Following this, production declined consecutively, reaching its lowest point in recent years of 345,400 tons in 2015. However, starting in 2016, titanium ore production gradually increased, reaching 1.4698 million tons in 2019, which is only 11% of the peak output.

Policies

Drawing from the IEA policy database, this section summarizes the policies pertaining to critical minerals for EV, as presented in Table 6.3. Countries such as Canada, China, the United States and Germany have formulated policies focused on the critical minerals required for EVs. Among them, China and the United States place significant emphasis on rare earth elements, followed by critical minerals, such as lithium and platinum group metals. In contrast, Germany and Finland have a relatively stronger focus on cobalt, nickel, lithium, copper and graphite.

Table 6.3 Policies on critical minerals for the electric vehicle industry by country or region

Country/ region	Year	Policy
Canada	2022	To fully unlock the potential of Canada's minerals and metals, the government has adopted a "Mine to Mobility" approach, leveraging Canada's resource richness and mining expertise to establish battery and critical minerals supply chains that meet the demands of the EV market and support a broader clean energy transition
China*	2011	The government issued the "Suggestions on Promoting the Sustainable and Healthy Development of the Rare Earth Industry" policy document aimed at further raising awareness of the importance of effectively protecting and rationally utilizing rare earth resources and promoting the sustainable development of the rare earth industry. The document also established national policies for the rare earth industry, including measures to establish and strengthen regulatory systems with strict controls on illegal mining and exports, pollution, and new rare earth smelting and separation projects
China*	2021	To realize the complementary advantages of rare earth resources and the coordinated development of the rare earth industry, the State-owned Assets Supervision and Administration Commission of the State Council announced the establishment of China Rare Earth Group, creating the world's largest strategic rare earth element producer and strengthening direct control by the central government
China*	2021	The State Council published the "New Energy Vehicle Industry Development Plan (2021–2035)" in 2020, which encourages enterprises to increase production capacity for critical resources such as lithium, nickel, cobalt and platinum
United States	2015	The National Energy Technology Laboratory (NETL) provided funding for the development of innovative midstream processing technologies to purify, separate and reduce high-purity rare earth elements and other critical minerals from coal, coal byproducts or alternative non-coal feedstocks. In 2017, NETL provided over $20 million in funding for this research direction
United States	2021	The Department of Energy's Office of Science awarded a total of $30 million to 13 national laboratory and university-led research projects to develop new technologies to ensure the security and diversification of domestic critical materials supply chains and improve the reuse and recycling of critical components for clean energy and high-tech applications (such as rare earths and platinum group metals)
United States	2022	The Inflation Reduction Act of 2022 grants a 10% tax credit on production costs to producers of critical minerals applicable to manufacturing, including aluminium, antimony, barite, beryllium, cerium, caesium, chromium, cobalt, dysprosium, erbium, fluorspar, gadolinium, germanium, graphite, indium, lithium, manganese, neodymium, nickel, niobium, tellurium, tin, tungsten, vanadium and ytterbium. Eligible minerals must be produced in the United States. The tax credit for critical mineral production began in 2023 and is exempt from phaseouts applicable to other eligible components that started in 2023
United States	2023	Japan and the United States announced an agreement to strengthen the critical mineral supply chain for EV batteries

(continued)

Table 6.3 (continued)

Country/ region	Year	Policy
Japan	2023	Japan and the United States announced an agreement to strengthen the critical mineral supply chain for EV batteries
Germany	2019	Raw materials strategy measures indicate that the German government will support the European Commission's initiative to increase the primary mining of metals needed for EVs and the energy transition (such as copper, lithium and nickel) within EU member states
Finland	2021	In 2020, the Ministry of Economic Affairs and Employment began developing a National Battery Strategy to encourage projects in the battery sector, helping Finland become a significant player in batteries and electrification, with a focus on the responsible sourcing of raw materials processing and research activities related to battery materials and recycling. According to the strategy, the Finnish government is "committed to becoming the world's leading expert in battery minerals", with a particular focus on cobalt, nickel, lithium, copper and graphite
Peru	2021	In 2021, Peru's Congress, exercising the powers granted by Article 6 of Supreme Decree No. 014–92-EM, passed Law No. 31.283, declaring the exploration, extraction, and industrialization of lithium and its derivatives on national territory as activities of public necessity and national interest. Additionally, the law stipulates that the commercialization of lithium and its derivatives is a strategic resource for national development. Finally, under the law, the executive branch must issue a regulation on the commercialization of lithium. This regulation will also ensure the development of the national battery industry and recycling procedures for lithium batteries

Note * denotes countries rich in critical minerals required for electric vehicles

6.3 Global Trade Network Security of Critical Minerals in the Electric Vehicle Industry

6.3.1 Overall Characteristics of the Trade Network

Figure 6.2 illustrates the evolution of the degree distribution within the trade networks for various critical minerals required by the EV industry across the years 2000, 2005, 2010, 2015 and 2020. This analysis examines the heterogeneity among different nodes within trade networks. The power-law characteristics of the trade networks for lithium and titanium have become increasingly pronounced, indicating a growing concentration of resources in a few select countries and regions, signifying a trend towards monopolization. In contrast, the power-law feature of the graphite trade network is relatively weaker than those of lithium and titanium, although it did exhibit a stronger power-law characteristic in 2015.

Figure 6.3 presents the evolution of the relationship between the clustering coefficient and degree within the trade networks for various critical minerals required

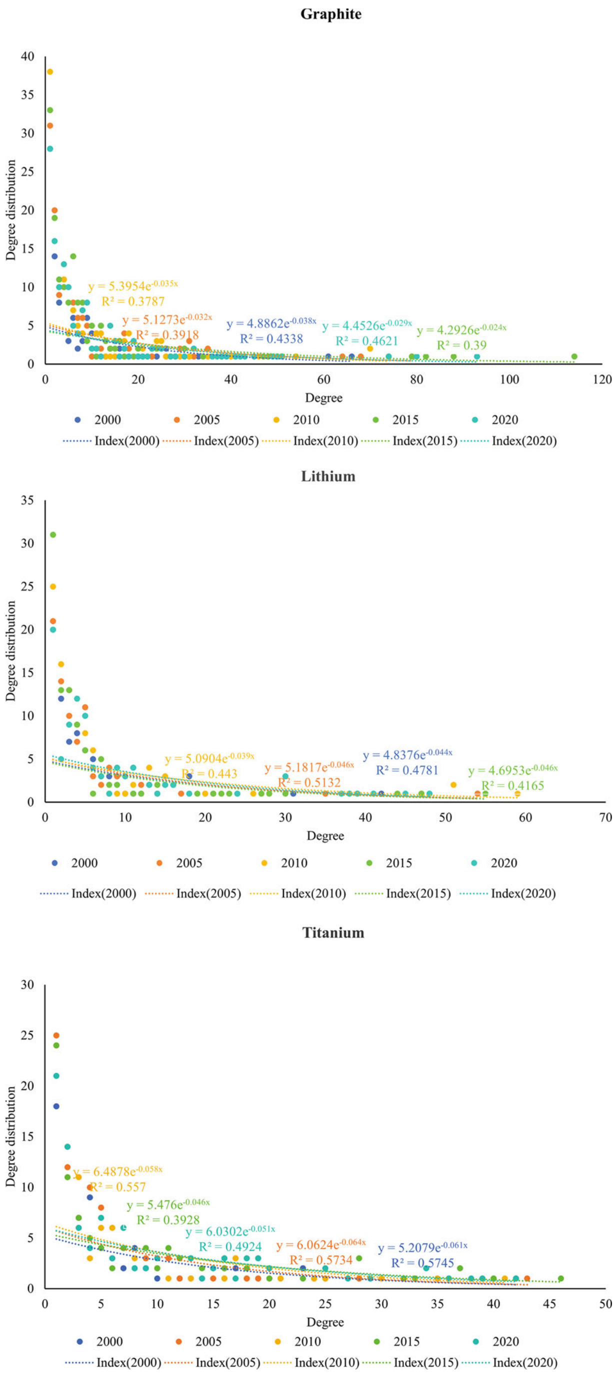

Fig. 6.2 Evolution of degree distribution in the trade network of critical minerals for the electric vehicle industry

by the EV industry across the years 2000, 2005, 2010, 2015 and 2020. All the trade networks for graphite, lithium and titanium exhibit power-law characteristics, with the clustering coefficient decreasing as the degree increases. This indicates the presence of a distinct hierarchical structure. As time progresses, the power-law characteristics become more pronounced, suggesting that within the trade networks of graphite, lithium and titanium, there is a trend in which countries with high degrees have less frequent trade interactions, while those with low degrees exhibit a higher degree of closeness, and this characteristic is becoming increasingly evident.

6.3.2 Trade Network Security

Figure 6.4 shows the evolution of trade risks associated with critical minerals required by the EV industry from 2000 to 2020. On the whole, lithium possesses the highest trade risk among the essential minerals for the EV industry, followed by graphite, while titanium exhibits the lowest trade risk. The trade risk associated with lithium has been on a steady rise annually, whereas the trade risk of titanium experienced a downward trend from 2005 to 2020.

6.3.3 Major Trade Countries

This section measures the status of critical mineral-exporting countries within the networks essential to the EV industry (Table 6.4). It can be observed that the stability of graphite trade is primarily influenced by major exporting countries, such as China, and countries like the United Arab Emirates (UAE) and Iran that control the transit of mineral resources. In the lithium trade network, the most significant export countries include the UAE, the Netherlands, China, the United States and Russia. For titanium, the vital nations in the trade network are China, the UAE, Norway and the United States. Notably, both China and the UAE have emerged as essential exporters of the critical minerals required by the EV industry. While the UAE's import volumes may not be substantial, they play a crucial role in the trade of these minerals critical for the EV sector.

6.4 Conclusion

This chapter delves into the development trends of the EV industry and examines the trade patterns, trade security and key countries involved in the trade of critical minerals necessary for this industry. The study reveals that the distribution of lithium and titanium resources is becoming increasingly uneven. Among the critical minerals required by the EV industry, lithium poses the highest trade risk, followed by graphite,

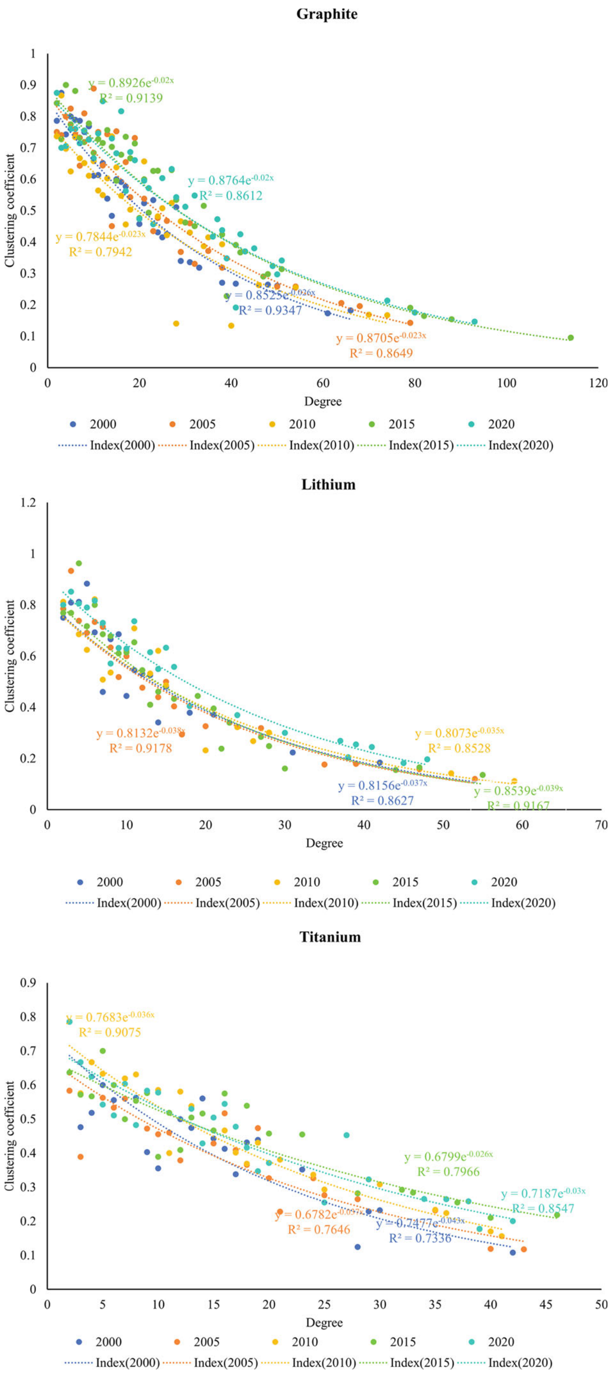

Fig. 6.3 Evolution of clustering coefficient versus degree in the trade network of critical minerals for the electric vehicle industry

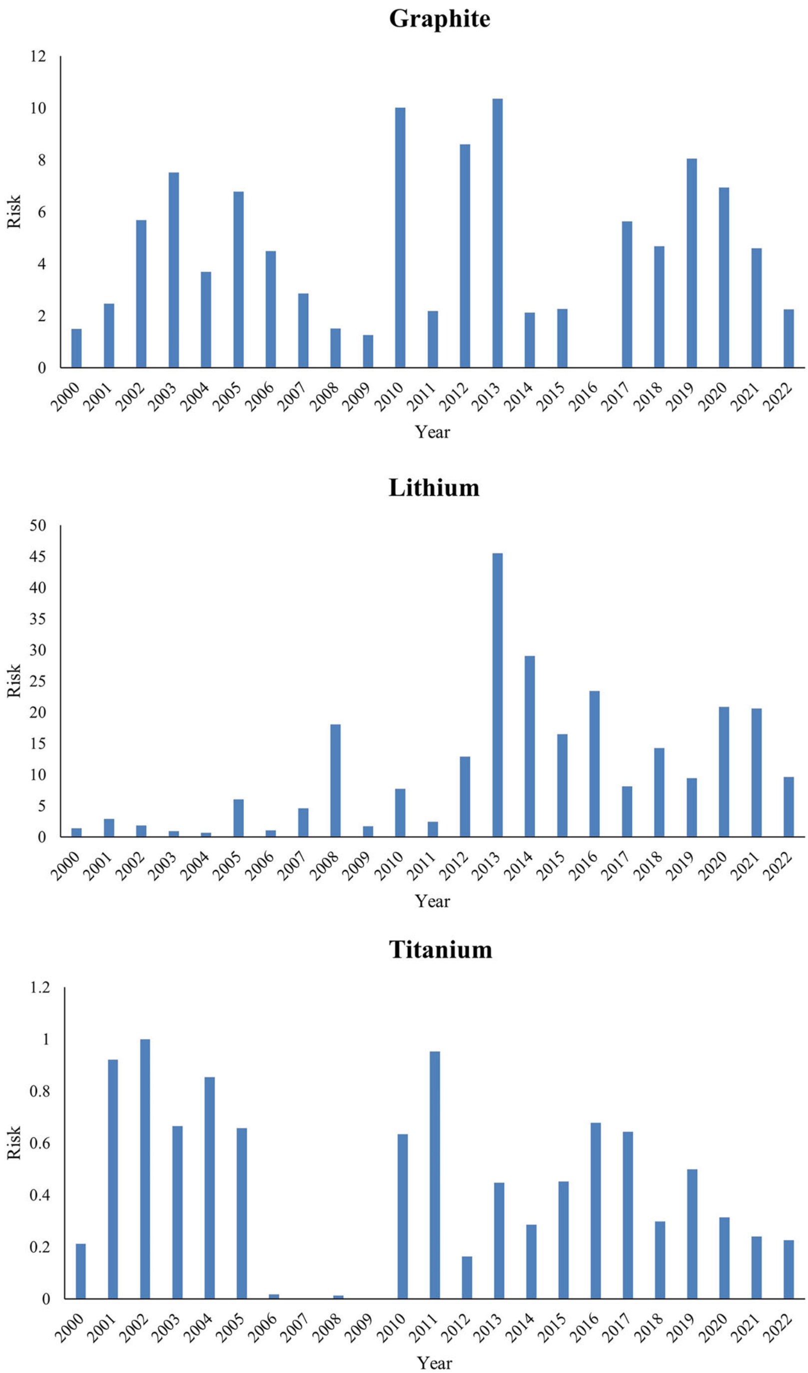

Fig. 6.4 Evolution of trade risks in the trade network of critical minerals for the electric vehicle industry

Table 6.4 Evolution of the ranking of importance of exporting countries for critical minerals required by the electric vehicle industry

2000	2005	2010	2015	2020
Graphite				
France	Iran	North Korea	Iran	USA
China	China	UAE	North Korea	Iran
Iran	Germany	India	Burundi	China
Spain	UAE	China	Tanzania	UAE
UAE	Netherlands	Iran	Germany	Madagascar
Lithium				
Germany	UAE	Iran	Chile	Netherlands
China	Germany	Chile	UAE	France
Switzerland	Russia	USA	Belgium	UAE
USA	China	Belgium	Russia	Russia
Russia	Belgium	Japan	China	USA
Titanium				
South Africa	Iran	UAE	UAE	UAE
Australia	UAE	China	China	China
Norway	Norway	Vietnam	Kenya	Mozambique
Germany	India	Norway	Germany	USA
Japan	Vietnam	Germany	USA	Ukraine

Source UN Comtrade and calculations by the research team

while titanium exhibits the lowest trade risk. The stability of the graphite trade is primarily influenced by major exporting countries, such as China, and countries like the UAE and Iran that control the transit of mineral resources. On the policy front, nations like Canada, China, the United States and Germany have formulated policies related to critical minerals for EVs. China and the United States prioritize rare earth elements, followed by critical minerals like lithium and platinum group metals. In contrast, Germany and Finland place relatively more emphasis on cobalt, nickel, lithium, copper and graphite.

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Chapter 7
Risk-Return Analysis of China's Traditional Energy and New Energy Industries

Yiran Shen and Longfei Li

Abstract Amid the deep integration of energy and finance, the stock price linkage of energy companies exhibits complex network characteristics. From the perspective of risk and return, this study constructs minimum spanning tree networks of returns, volatility, and investor sentiment for Chinese new energy and traditional energy companies, identifying the impact of COVID-19 and the dual-carbon policy on these networks. The empirical results show: (1) The sentiment network has the highest transmission efficiency and easily transmits between the two types of companies, while the return network has the lowest transmission efficiency and primarily transmits within the same type of companies. (2) During the COVID-19 pandemic, the transmission efficiency of all networks increased. (3) After the dual-carbon policy, the correlation between the two types of companies weakened, and the similarity between the return, volatility, and sentiment networks increased. This study helps regulators monitor systemically important companies and guides investors in risk management based on multidimensional network characteristics.

Keywords Energy listed companies · Minimum spanning tree network · Graph similarity · COVID-19 pandemic · Dual-carbon policy

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7.1 Background

7.1.1 Listed Companies in China's New and Traditional Energy Industry

With global climate change posing unprecedented challenges to socio-economic structures and human lifestyles, low-carbon transformation has become a consensus of the international community. China's energy consumption and production are among the highest in the world, and its practice in the process of low-carbon transition is of great significance and leadership for the world. At present, fossil energy still dominates China's energy structure, with fossil energy consumption accounting for 81% in 2023. However, under the dual-carbon policy, the energy structure is accelerating the adjustment, and the new energy industry is gradually becoming a strategic emerging industry that focuses on cultivation and development. In the face of the impact of the COVID-19 and the pressure of energy transformation brought about by the dual-carbon policy, it is of great significance to accurately grasp the development trend of the energy industry, especially the dynamic correlation between traditional energy and new energy companies, to promote the high-quality development of the energy industry and to serve the dual-carbon policy.

As an important part of the capital market, the development of listed companies in the energy industry has attracted wide attention. With the deepening of energy and financial integration, the stock prices of energy companies have become increasingly linked, showing complex network characteristics. On the one hand, the stock prices of energy companies are affected by common factors such as energy commodity prices, industrial policies, and macroeconomics, and the convergence of stock prices among different companies has increased; on the other hand, in the context of the rapid development of new energy sources, the stock price linkages show dynamic changes due to the rotation of different energy subsectors, and the competition game between traditional energy sources and new energy sources. Accurately portraying energy companies' stock price correlation network and identifying its dynamic evolution pattern are significant for government regulation and investment decision-making. Especially in the face of the impact of major events such as the COVID-19 and the dual-carbon policy, the changes in energy stock price correlation networks are more worthy of in-depth study.

In addition, investor sentiment plays an important role in the stock market. First, major events affect investor sentiment, which in turn change their trading behavior and asset prices. For example, the outbreak of COVID-19 triggered panic in the market, which may induce irrational selling and form a negative feedback effect. Second, compared with traditional energy, new energy companies are more susceptible to the influence of policy guidance and market sentiment. Positive signals from carbon–neutral policies affect investors' expectations of new energy companies, which in turn drive up stock prices. As a result, when studying the correlation network of energy stock markets, it is necessary to incorporate multiple dimensions, such as returns, volatility, and investor sentiment, into the analytical framework to obtain a more comprehensive and detailed understanding.

Scholars have conducted some fruitful studies on the correlation between traditional and new energy listed companies. For example, Sadorsky (2012) used a four-variable multivariate GARCH model to study the volatility spillovers among oil prices, tech stocks, and clean energy stocks. Wen et al. (2014) used an asymmetric BEKK model to study the volatility spillovers between the stock prices of new energy and fossil fuel firms in China. Zhang and Du (2017) built and estimated a three-variable TVP-SV-VAR model to investigate the dynamic correlation between the stock prices of new energy companies, high-tech companies, and fossil fuel companies. Zeng (2018) discusses the long-term and short-term effects of carbon emission rights price on the stock prices of traditional energy companies and new energy companies by building a VECM model. These studies reveal the stock price correlations between traditional energy listed companies and new energy listed companies at different historical stages. Most studies used econometric models such as VAR, VECM, and ARCH to portray the pri ce linkage characteristics, and these studies also mentioned that the application of econometric models requires the data to satisfy prior assumptions such as stationarity and specific distributions, which leads to many limitations of econometric models in the application of actual multi-subject complex linkages.

The existence of multiple linear or nonlinear dynamic correlations among stock prices is essentially a complex socio-economic network with market linkages as its kernel (Tabak et al. 2010). Huang et al. (2021) address the modeling difficulty of accurately characterizing network linkages and extracting systematically important firms that play critical roles in the system. It has become a new research consensus to utilize complex network technology to study the complex correlation structure of socioeconomic networks (Diebold et al. 2015; Sun et al. 2020a; Ji et al. 2019; Feng et al. 2021). Among these, the minimal spanning tree (MST) has been widely used to identify and characterize the network structure of financial markets since its proposal (Mantegna 1999). For example, Onnela (2003) used complex network theory for the first time to construct the return network of 116 stocks in the S&P 500 index during the period of 1982–2000 by using the MST algorithm to analyze the impact of the 1987 "Black Monday" on the U.S. stock market. Majapa and Gossel (2016) analyzed the evolution of the network topology in the three periods before, during, and after the 2008 financial crisis by constructing a MST network of stock market closing prices of the top 100 companies in South Africa. In the field of energy finance, Kazemilari et al. (2019) computed the MST network among listed renewable energy companies in the US based on price similarity, carved out its topological features, and identified the core subsectors and dominant companies in the renewable energy industry in different periods. In short, utilizing complex network technology to construct price linkage networks in different time periods can more comprehensively identify the dynamic features of price linkage networks and clearly capture systematically important nodes, so as to grasp the overall market situation. This is of great significance for risk management by market regulators and portfolio optimization by investors.

This chapter takes listed companies in China's energy industry as the research object, focusing on two subsectors: traditional energy and new energy. By constructing a minimum spanning tree (MST) network of the stock prices of listed companies in the energy industry, the chapter analyzes their linkage characteristics from three dimensions: return, volatility, and investor sentiment. In particular, the outbreak of the COVID-19 and the proposal of the dual-carbon policy provide a unique analytical perspective for this chapter. The intensification of energy transition expectations has significantly changed the stock price linkages between traditional and new energy sectors. This change reflects, on the one hand, the difference in the investment value of different energy sectors in the market game and, on the other hand, the higher demand for stable supply of mineral resources. The results in this chapter help academics and the industry to deeply understand the security of mineral resources in the context of low-carbon transition.

7.1.2 Impact of Major Events on Chinese Energy Companies

In identifying dynamic network characteristics of price correlations, many scholars have focused on the impact of major events on network structure and characteristics. Major events demonstrate that the mutual coupling structure of stock markets plays an important role in risk diffusion. For example, Li and Pi (2018) analyzed the structural characteristics and changes in stock indices in major countries in the world before, during, and after the 2008 financial crisis. Liu et al. (2018) analyzed the linkages of China's financial markets, such as stocks, bonds, real estate, and foreign exchange, during the financial crisis and proved that the degree of linkages among the sub-markets was significantly strengthened during the financial crisis. Sun et al. (2020b) focused on the analysis of risk transfer characteristics from the international commodity market to the shipping market, as well as the interaction characteristics of the sub-sector of the shipping market, before and after the financial crisis. When a crisis event occurs, stock market linkages intensify, propagating rises rapidly and exerting substantial pressure on monetary policy and market sentiment (Yang et al. 2003, 2014; Choudhry et al. 2007; Wang et al. 2018). Accurately measure and portraying the impact of such major events has become an important issue of utmost concern to scholars in various fields at present.

In recent years, COVID-19 pandemic and the dual carbon policy have been key events that have significantly impacted energy markets. COVID-19 pandemic, as a public health emergency of international concern, has had a significant impact and disruption on the financial markets as a whole, as well as on all areas of the global socio-economic spectrum. Before and after the epidemic outbreak, the financial market structure showed significantly different patterns (So et al. 2021). For example, Zhang et al. (2020) calculated a minimum spanning tree network of stock market return similarities in 12 countries around the world to explore changes in the global financial market structure in the context of COVID-19. Unlike the epidemic, which had a great impact on the whole market, the release of the dual-carbon policy also greatly impacted the structure of the energy market. The green signal conveyed by the dual-carbon policy and the environmental regulations it brings change the competitive relationship between traditional energy companies and new energy companies in the market (Zhu et al. 2020), change the industrial structure (Anand and Giraud 2020), and affect the value of companies (Yan and Chen 2017).

The COVID-19 pandemic and the dual-carbon policy, as important events affecting the energy market, not only have a direct impact on the economy and industrial structure but also a strong influence on investor sentiment (Gormsen and Koijen 2020; Baig et al. 2021). Investor sentiment during epidemics can spread rapidly through the market (Zhao et al. 2014), affacting trading behavior and leading to extreme price volatility (Broadstock and Zhang 2019; Tian and Liu 2021). In particular, the development of new energy companies is particularly sensitive to policy (Song et al. 2019; Henriques and Sadorsky 2008; Sadorsky 2012), and companies associated with carbon neutrality are more likely to attract investor attention (Bansal and Roth 2000), which in turn affects their stock market performance (Geng et al. 2021; De Long et al. 1990; Lee et al. 2002; Gao and Liu 2020; Ho et al. 2020). Therefore, investor sentiment plays a particularly important role in the energy stock market, and return, volatility, and sentiment need to be considered together. Most existing studies using complex networks to portray risk contagion in financial markets construct a single network for volatility or return contagion (Zeng et al. 2015), with less research on the contagion of sentiment and the structural differences among these three networks. Therefore, when discussing the impact of the COVID-19 pandemic and the dual-carbon policy on the structure of complex networks and their changing patterns, this chapter also includes investor sentiment factors in the research framework.

To summarize, this chapter tries to incorporate investor sentiment, construct three-dimensional networks of returns, volatility, and sentiment, explore the linkage structure of new energy companies and traditional energy companies, identify systemically important companies, and analyze how the COVID-19 pandemic and the dual-carbon policy influence the network structure and the changes in systemically important companies.

7.2 Modeling Approach

It is difficult to provide a comprehensive picture of financial markets with a single-dimensional network. Therefore, in this section, we construct return, volatility, and investor sentiment networks to systematically characterize the structure of the stock markets of new energy and traditional energy companies by comparing the different features of these networks and their structural differences in before and after the COVID-19 pandemic and the dual-carbon policy. In this section, the return, volatility, and investor sentiment indices are first constructed, then the minimum spanning tree network is constructed from these three dimensions, and three indicators, namely, network agglomeration, node degree, and network similarity are designed to characterize the network features.

7.2.1 Return, Volatility, and Investor Sentiment Indices

Return and Volatility

The return is calculated using the logarithmic difference of the closing price, and the intraday return for the stock *i* on the first *t* day is defined as Eq. (7.1):

$$Ret_{it} = \ln P_{it}^{Close} - \ln P_{i,t-1}^{Close} \tag{7.1}$$

where $P_{it}^{Close}, P_{i,t-1}^{Close}$ are the closing prices of stock *i* on day *t* and day *t − 1*, respectively.

Volatility is extracted using the GJR-GARCH model proposed by Glosten et al. (1993). Since most index return series are characterized by skewed distribution (Gao and Li 2021), this study adopts a skewed t-distribution setting for the error term. Generally speaking, ARMA(p,q)-GJR-GARCH(1,1) is widely used in volatility measurement due to its ability to effectively fit return series. Based on this, the ARMA(p,q)-GJR-GARCH(1,1) model for the return series in this section is shown below:

$$R_{i,t} = \varphi_0 + \sum_{j=1}^{p} \varphi_j R_{i,t-j} + \varepsilon_{i,t} + \sum_{j=1}^{q} \Psi_j \varepsilon_{i,t-j} \tag{7.2}$$

$$\varepsilon_{i,t} = \sigma_{i,t} z_{i,t} z_{i,t} \sim i.i.d.skst \tag{7.3}$$

$$\sigma_{i,t}^2 = \alpha_0 + (\alpha_1 + \gamma_1 d_{t-1})\varepsilon_{i,t-1}^2 + \beta_1 \sigma_{i,t-1}^2 \tag{7.4}$$

$$d_{t-1} = \begin{cases} 1, & \varepsilon_{i,t-1} < 0 \\ 0, & \varepsilon_{i,t-1} \geq 0 \end{cases} \tag{7.5}$$

where Eq. (7.2) is the return series extracted using the GARCH(1,1) model, Eq. (7.3) shows the distributional characteristics of the error term, and Eq. (7.4) is the conditional variance equation that *i* represents the sample of stocks, and $\sigma_{i,t}^2 = Var\left(R_{i,t}|I_{t-1}\right)$ is the volatility series, and I_{t-1} is the conditional information set at moment $t - 1$, and d_{t-1} is a dummy variable, and Eq. (7.5) defines the values of the dummy variables that reflect the leverage effect of good and bad news on different stock shocks, respectively.

Investor Sentiment Index

This section constructs an investor sentiment index based on stock bar text data and the FinBERT deep learning method. In recent years, deep learning models such as LSTM and CNN have gained popularity in sentiment computing and can achieve high classification accuracy (Kraus and Feuerriegel 2017). However, as supervised learning models, it is difficult for these deep learning models to fully utilize the potential of sentiment analysis due to the lack of large labeled financial datasets. FinBERT, as a pre-trained model in the financial domain, overcomes the lack of large financial labeled datasets by leveraging pre-trained parameter values and fine-tuning them according to the classification task. Using FinBERT's pre-training parameters, the matrix composed of word vectors is transformed into low-dimensional sentence vectors, and the sigmoid function is used to determine the sentiment tendency of the text data, achieving the model classification accuracy of 94%. In this section, positive sentiment is labeled as 1 and negative sentiment is labeled as − 1. Positive sentiment is mostly comments such as "buy" and "hold", which indicates that investors are bullish about the stock price outlook; negative sentiment is mostly comments such as "sell" and "stop loss", which indicate that investors are worried about stock prices and bearish on stocks (Wang et al. 2020).

After obtaining the sentiment propensity of each stock review, an investor sentiment index is constructed based on the methodology of Antweiler and Frank (2004), who first investigated the relationship between investor sentiment contained in texts such as Internet posts and market variables. This methodology has been widely used in the construction of sentiment indices (Huang et al. 2020). Building on this index, it is considered that high-quality investment opinions are considered to be disseminated and recognized through the readership of stock bar posts, enhancing their influence (Xiong et al. 2017). In this study, stock sentiment propensity is weighted based on post readership. The specific calculation formula is:

$$w_{kt} = \frac{read_{kt}}{\overline{read}_{it}} \tag{7.6}$$

$$Sen_{it} = \frac{\sum_{k=1}^{n} w_{kt} I\left(y^{(k)} = 1\right) - \sum_{k=1}^{n} w_{kt} I\left(y^{(k)} = -1\right)}{\sum_{k=1}^{n} w_{kt} I\left(y^{(k)} = 1\right) + \sum_{k=1}^{n} w_{kt} I\left(y^{(k)} = -1\right)} \ln(1 + M_{it}) \tag{7.7}$$

where in Eq. (7.6) w_{kt} are the weights, and $read_{kt}$ is the number of readings of stock review k on day t, and $\overline{read}_{it}$ is the average reading of all stock reviews of stock i on day t, and in Eq. (7.7) Sen_{it} is the investor sentiment index, the $y^{(k)} = 1$, $y^{(k)} = -1$ represent stock comment k sentiment as positive and negative on day t, respectively. M_{it} is the total number of posts for stock i on day t.

7.2.2 Minimal Spanning Tree Networks

Risk in the stock market is transmitted from one company to other companies through the correlation between companies (Chen et al. 2022). In this study, based on the correlation between companies, the Prim algorithm is used to construct a minimum spanning tree network of energy companies, which is used to identify the linkages among them.

In order to construct a MST network among energy companies, inter-company correlations are first calculated. The correlation between individuals in a complex network of financial markets can generally be quantified by quantified using the correlation between time series of asset prices. The Pearson Correlation Coefficient (PCC) is the most commonly used method to calculate correlation coefficients between asset prices. The PCC is converted into Euclidean distance, which are then the correlation algorithm are used to obtain a complex network of financial markets.

This study uses the method proposed by Mantegna (1999) to convert the correlation coefficient to distance. The distance between two variables is defined as Eq. (7.8):

$$e_{ij} = \sqrt{2(1 - C(i,j))} \tag{7.8}$$

where $C(i,j)$ is the Pearson correlation coefficient between the two variables. Using this method, the MST network of new energy and traditional energy system is constructed from a three-dimensional perspective of return, volatility and sentiment. Network characteristic indices are then designed to analyze the network structure and identify core nodes.

7.2.3 Network Characterization Indicators

Network Agglomeration Indicators

In order to quantitatively characterize the degree of agglomeration of these three networks, this section calculates the network diameter and average path length of the three networks. The distance between two nodes in a network d_{ij} is defined as the distance from node i to node j. The minimum number of edges to be traversed and its reciprocal $\varepsilon_{ij} = 1/d_{ij}$ is called the node i to node j efficiency between nodes, which is used to measure the speed of information transfer between them. Network diameter $D = \max_{i \le 1, j \le N} d_{ij}$ is the maximum value of the distance between any two nodes, which measures the distance between the farthest nodes. The network diameter metric is used to assess the minimum number of edges traversed in the network. The average path length measures the average separation of nodes in the network, indicating its compactness. In a network of N number of nodes, the average path length L is calculated as Eq. (7.9):

$$L = \frac{1}{\frac{1}{2}N(N-1)} \sum_{i \neq j} d_{ij} \tag{7.9}$$

Node Degree Indicator

Barabási and Albert (1999) proposed the scale-free network model to describe many real networks with a power-law degree distribution, where the degree k of node i is defined as the number of nodes connected to it. In scale-free networks, a few nodes have high degrees, while most have low degrees. Therefore, the importance of nodes and their roles in the network vary. A higher node degree indicates greater importance and a stronger potential for risk contagion within the system. In this study, the degrees of network nodes are calculated to characterize the variability of companies' roles in the network of new energy and traditional energy.

Network Similarity Indicator

In order to quantitatively assess the magnitude of changes in the network structure and core nodes before and after the COVID-19 pandemic, the graph embedding method is used to vectorize the representation of the network, and then the similarity between the three networks before and after the epidemic is calculated.

The shortest path length between nodes in the network is determined using Floyd's algorithm. For any node $i \in G$, the average shortest path length to other nodes in the network a_i and convert a_i as the vector X, i.e. $X = (a_1, a_2, a_3, \ldots, a_n)$ a_i is calculated as:

$$a_i = \sum_{i,j \in G} \frac{d(i,j) - 1}{n-1} \tag{7.10}$$

where i, j are the nodes in the network, and n is the total number of nodes. According to Eq. (7.10), the average shortest path vector X for the pre-epidemic network and the average shortest path vector Y for the nodes during the epidemic are derived respectively. Subsequently, the Pearson correlation coefficients between the vectors are computed according to Eq. (7.11), which is used to measure the similarity between the two networks before and during the epidemic. $S_{X,Y}$ is a number between [− 1,1], the closer it is to 1, the more similar the network structures represented.

$$S_{X,Y} = \frac{E\left[(X - \mu x)(Y - \mu y)\right]}{\sigma_X \sigma_Y} \tag{7.11}$$

7.3 Sample and Data

In this study, 38 constituent stocks of China Standard Industrial Mainland New Energy Thematic Index and 76 constituents of the China Standard Industrial Classification (CSIC) energy category are selected as samples. The sample data range span the period from January 2, 2019 to December 31, 2021, covering 730 trading days.

The text data used for constructing investor sentiment index are sourced from the Eastmoney stock bar, using Python to crawl the content, release time, and readership volume of stock reviews for 114 sample stocks. After data cleaning, 6, 187, 191 valid text data points were obtained, with 3,134,373 stock reviews for new energy companies and 3,052,818 for traditional energy companies. Table 7.1 shows the descriptive statistics of return, volatility, and sentiment series. From this table, it can be seen that the average return of new energy companies during the sample period is higher than that of traditional energy companies. Correspondingly, the variance of their stock price volatility and sentiment is also larger, reflecting the higher investment risk and stronger speculative attributes of the new energy market compared to the traditional energy market. In addition, the mean and median of the sentiment indices are both negative, indicating predominantly pessimistic market sentiment, mainly due to the limited expertise and asymmetric information among small and medium-sized investors in the market, consistent with findings in related studies (Cai et al. 2021).

To visualize the relationship between returns, volatility, and sentiment, Fig. 7.1 presents time series plots of the three indices of return, volatility, and sentiment averaged over the full sample, where the data are processed through a 7-day moving average. The line-shaded period in Fig. 7.1 shows a higher synchronization between sentiment and return, indicating that the sentiment index constructed

Table 7.1 Descriptive statistics

	Mean	Std. Dev.	Min	Q1	Median	Q3	Max
Panel A: full sample							
Ret_{it}	0.0905	2.9117	− 22.4090	− 1.3400	0.0000	1.3903	18.2496
$Volatility_{it}$	2.8084	1.1938	0.6415	1.9457	2.5617	3.4527	13.3036
Sen_{it}	− 1.6947	1.7029	− 7.7824	− 2.9555	− 1.7415	− 0.4774	4.9381
Panel B: new energy companies							
Ret_{it}	0.1648	3.1599	− 22.2773	− 1.4647	0.0000	1.6295	18.2496
$Volatility_{it}$	3.0964	1.1230	0.8105	2.2534	3.0075	3.8120	11.0692
Sen_{it}	− 2.1390	1.7933	− 7.7824	− 3.5264	− 2.3338	− 0.8326	3.8921
Panel C: traditional energy companies							
Ret_{it}	0.0517	2.7680	− 22.4091	− 1.2778	0.0000	1.2899	18.2408
$Volatility_{it}$	2.6546	1.1984	0.6415	1.8464	2.3674	3.1369	13.3036
Sen_{it}	− 1.4725	1.6106	− 7.1736	− 2.6567	− 1.4748	− 0.3479	4.9381

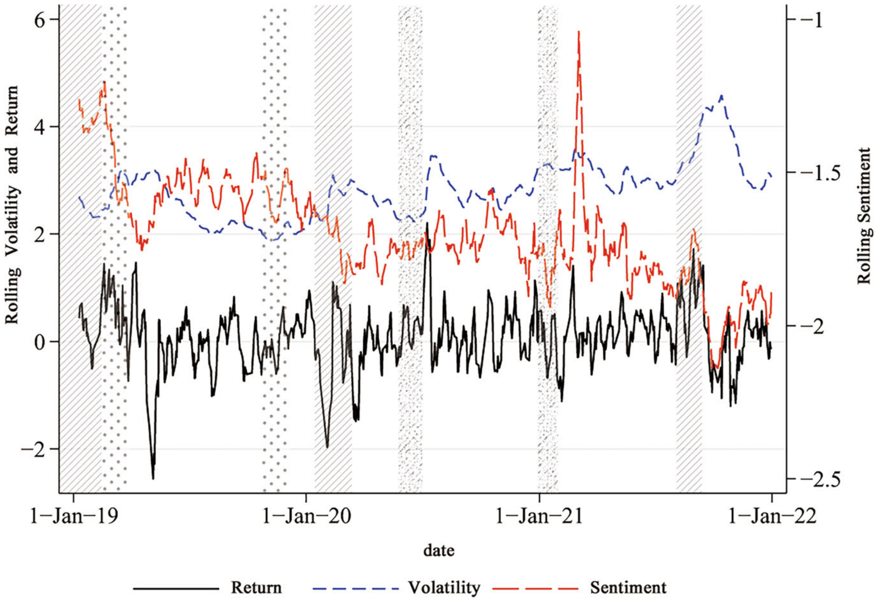

Fig. 7.1 Time series of returns, volatility and sentiment

in this study possesses rationality. In addition, observing periods of maximum return and maximum decline during the sample period reveals a consistent pattern in the relationship between sentiment and return indicators. During the down period, sentiment leads the decline in return, as shown in the dot-shaded in the figure, indicating that sentiment plays a certain early warning signal in the system. During uptrends, sentiment lags behind the rise in return, as observed in the overlay-shaded period of the chart.

7.4 Empirical Results

Firstly, we construct a three-dimensional network of return, volatility and sentiment for the whole entire sample period and analyze the network characteristics from the perspective of network agglomeration and node degree to describe the overall characteristics of the system of new energy and traditional energy companies. Detailed information on the companies is provided in Appendix Table 7.6. Considering that the COVID-19 and the dual carbon policy have significant impacts on the stock market structure of energy companies, this study selects the two key dates, January 30, 2020, when the World Health Organization announced that the COVID-19 as a public health emergency of international concern, and September 22, 2020, when China announced its dual-carbon policy for 2030 and 2060 to divide the sample into three time periods. Based on the characterization of the whole sample, the similarity of nodes among the networks in each time period is characterized, and the influence of the COVID-19 pandemic and the dual-carbon policy on the network structure is analyzed.

7.4.1 Full Sample Network Characterization

The degree of node aggregation in the new energy and traditional energy complex network system can reflect the strength of the links between new energy and traditional energy companies. In order to gain an overall understanding of these nodes and their relationships, this study constructs MST network graphs of 114 new energy and traditional energy listed companies based on stock price correlation, as shown in Fig. 7.2 In this graph, the node color represents the industry to which the listed company belongs, where green nodes are new energy listed companies and pink nodes are traditional energy listed companies. A cross-connected edge between new energy and traditional energy companies, (i.e., an edge connecting two different colors of nodes) indicates information transmission between two different companies. From the figure, it can be visualized that at the node level, higher degree nodes in the return and volatility networks are relatively uniform, whereas higher degree key nodes in the investor sentiment MST network are the most aggregated.

The average path lengths of the return, volatility, and sentiment networks are 10.92, 8.13, and 7.49, respectively. The sentiment network has the shortest average path length, indicating that sentiment changes are more likely to be rapidly transmitted to neighboring companies along the network relative to return and volatility. This is consistent with the finding that the nodes of the sentiment network are most densely distributed in Fig. 7.2. The return network has the longest diameter and average path length, suggesting that information transmission is least efficiently in this network. Although the number of edges in all three MST networks is 113, the number of connecting edges across categories is different in three networks. For the return network, the number of edges connecting new and traditional energy companies is 5, while the number of connecting edges across categories in the volatility and sentiment networks is 18 and 27, respectively, which is much more than in the return network. This indicates that return is more likely to be transmitted within the same type of companies, while there are more interactions between new and traditional energy companies in the volatility and sentiment networks. The tendency of return to be transmitted within the same type of companies is not conducive to satisfying investors' need for investment diversification, making investors concentrated in similar more vulnerable to asset losses. Therefore, identifying central companies in the network and assessing the position and role of investment targets is crucial for better portfolio management.

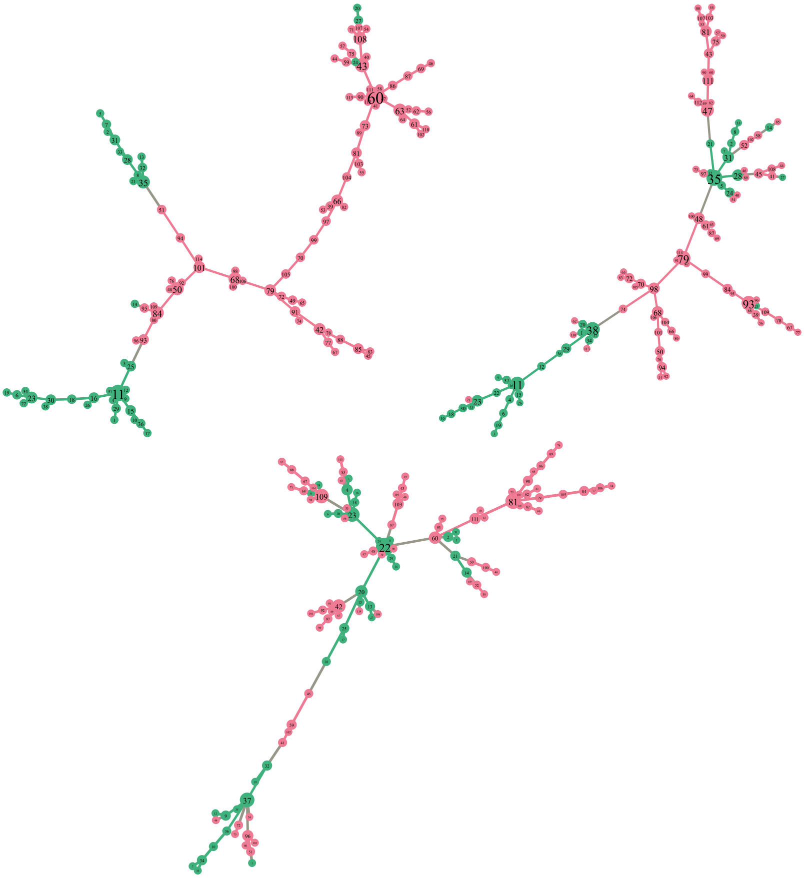

Fig. 7.2 Three minimal spanning tree networks for new energy-conventional energy company systems

7.4.2 Evolution of Network Characteristics Before and After Major Events

As events with important impacts on energy companies, the COVID-19 and the dual-carbon policy may cause changes in the structure and core nodes of the complex networks of energy companies. The sample is divided into three time periods using these two important events as nodes, where T1 is the period before the outbreak (2019.1.1–2020.1.30), which serves as a benchmark to explore the changes in the network structure; T2 is the period of the outbreak (2020.1.31–2020.9.22), which is used to characterize the impact of the COVID-19 on the energy market; T3 is the period after the enactment of the dual-carbon policy (2020.9.22–2021.12.31), which portrays the impact of the dual-carbon policy on the energy market. We calculate network agglomeration and core node changes for the three types of MST networks across these periods, and discuss the changes in the MST network structure caused by the COVID-19 and the dual-carbon policy by calculating the network similarity.

Network Transmission Efficiency

By calculating the network diameter and the average path length, we quantitatively analyze changes in network transmission efficiency in the three time periods. The network diameter and average path length in each time period are shown in Table 7.2. After dividing the network into different time periods, the diameters of the return, volatility and sentiment networks are shorter in T2, which indicates that the COVID-19 has significantly increased the transmission efficiency of the overall energy company network, which is consistent with the findings in the literature (Yang et al. 2003). This study further analyze the changes in network transmission efficiency after the release of the dual-carbon policy and find that the diameters of all three types of networks increase in T3 compared to T2. On the one hand, the COVID-19 has entered a stable period in T3, which reduces the degree of risk transmission in the networks. On the other hand, the release of the dual-carbon policy has weakened the degree of interaction between new energy and traditional energy sources. With the release of the dual-carbon policy, the energy industry is facing structural adjustment, and the traditional energy with high energy consumption and high emissions is gradually replaced by clean energy like wind power. The degree of differentiation of risk factors between the traditional energy industry and the new energy industry has increased, which reduces the degree of interaction between them.

From the perspective of inter-company interactions, firstly, comparing the number of cross-collinear edges of networks in different periods, sentiment is the most likely

Table 7.2 Network diameter and average path length by time period

Type	Phase	Network diameter	Average path length	Number of cross-linked edges
Return network	Full sample	26	10.922	5
	T1	18	6.467	16
	T2	16	6.233	14
	T3	18	8.125	3
Volatility network	Full sample	20	8.132	18
	T1	24	8.980	22
	T2	21	9.071	26
	T3	25	10.188	18
Sentiment network	Full sample	20	7.492	27
	T1	20	7.465	44
	T2	19	7.939	41
	T3	25	10.012	23

network to generate cross-collinear edges in all periods, and return is the most easily transmitted within similar companies, which are consistent with the pattern obtained in the full sample. Second, the number of cross-collinear edges between new energy and traditional energy companies decreases significantly after the release of the dual-carbon policy, which confirm the conclusion that the degree of interaction between new energy and traditional energy decreases after the release of the dual-carbon policy.

Changes in Core Nodes

The MST network degree distribution of return, volatility and sentiment for new and traditional energy companies follows a power law distribution. A few companies have very large node degrees, exerting significant influence on information transmission within the network (Li et al. 2021), while most have small node degrees with few neighboring nodes. This indicates that only number of nodes are central to the network. The power law relationship of energy companies' affiliation concentrates market risks among these key companies, whose return, volatility and sentiment changes are likely to trigger localized crises, potentially causing turbulence across the entire energy company system. Therefore, this section examines the evolution patterns of high-degree core nodes in the new and traditional energy companies system over time.

As shown in Fig. 7.3, in addition to changes in the network structure, the core nodes of the new and traditional energy companies system underwent significant changes during the COVID-19 epidemic. Table 7.3 shows the compares the top 5 core nodes in each time period across the three networks. Table 7.3 reveals that, among the nine of most important nodes in each time period for three networks, five of them are new energy companies. Furthermore, new energy companies have gained prominence in the return and volatility networks. Specifically, in the volatility network, four of the five nodes with the highest weighted degree are new energy companies. In the return network, not only has the number of new energy companies among the core nodes increased, but also the most influential nodes in the network have shifted from traditional energy companies to new energy companies. This indicates that new energy companies have become central the network. However, traditional energy companies continue to dominate the sentiment network. Due to high information asymmetry and the pessimistic sentiment of small and medium-sized investors, which positions traditional energy companies as key conduits for transmitting pessimism in the network.

Network Similarity

This section calculates the similarity of network structures across time periods to assess the impact of events on network structures. The results, shown in Table 7.4, indicate that both the COVID-19 and the dual-carbon policy have

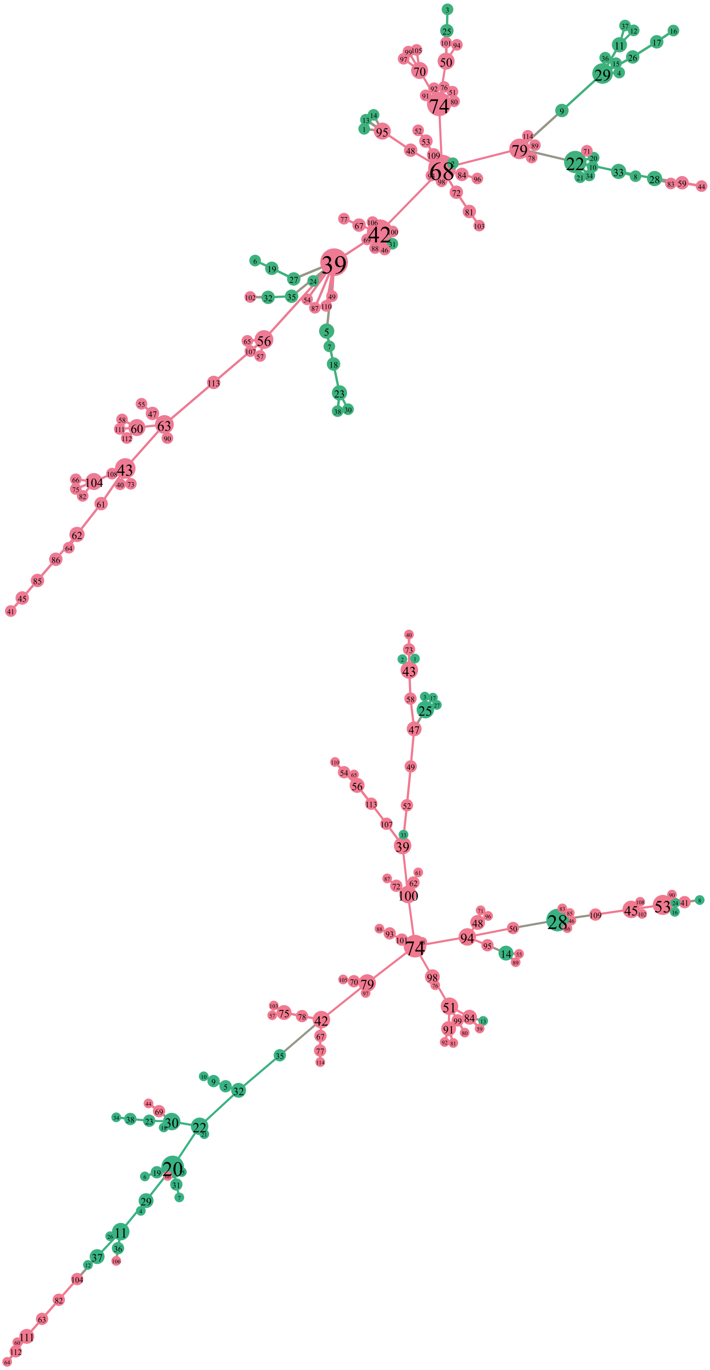

Fig. 7.3 Minimum spanning tree network by time period

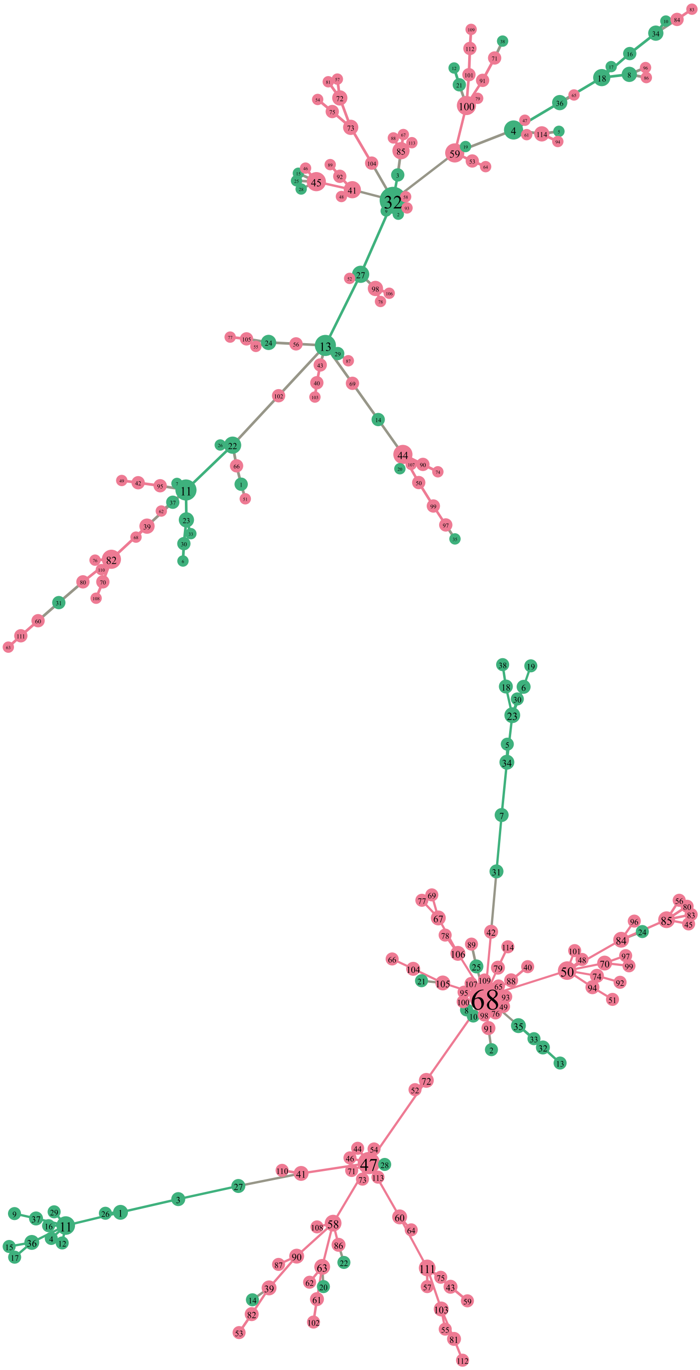

Fig. 7.3 (continued)

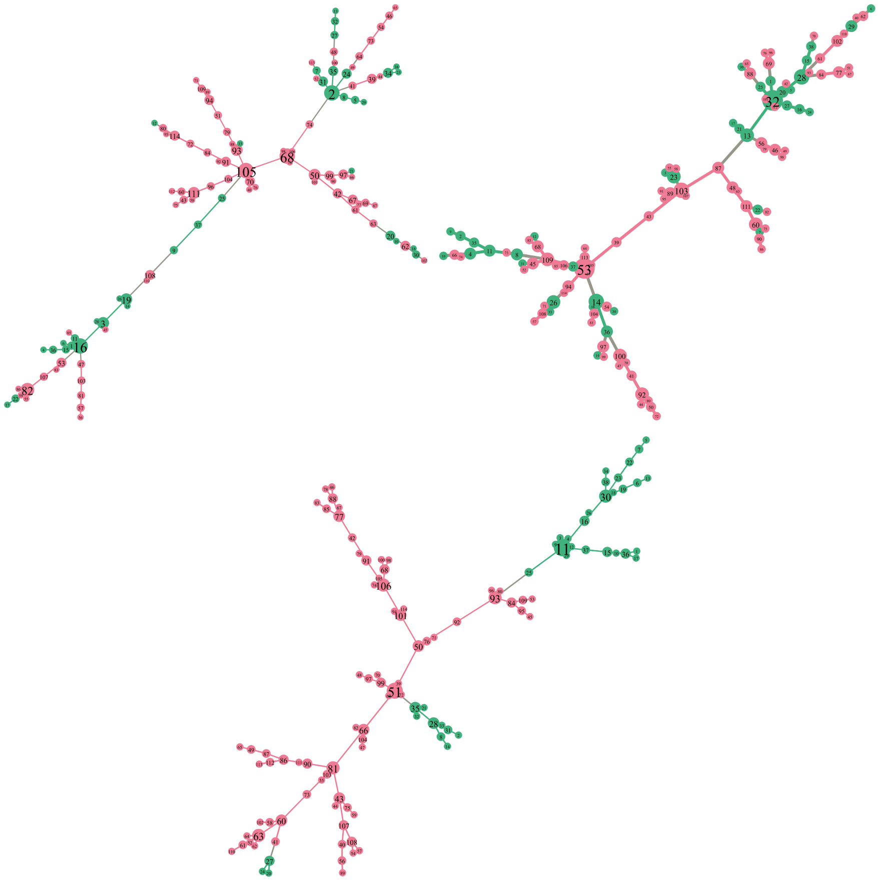

Fig. 7.3 (continued)

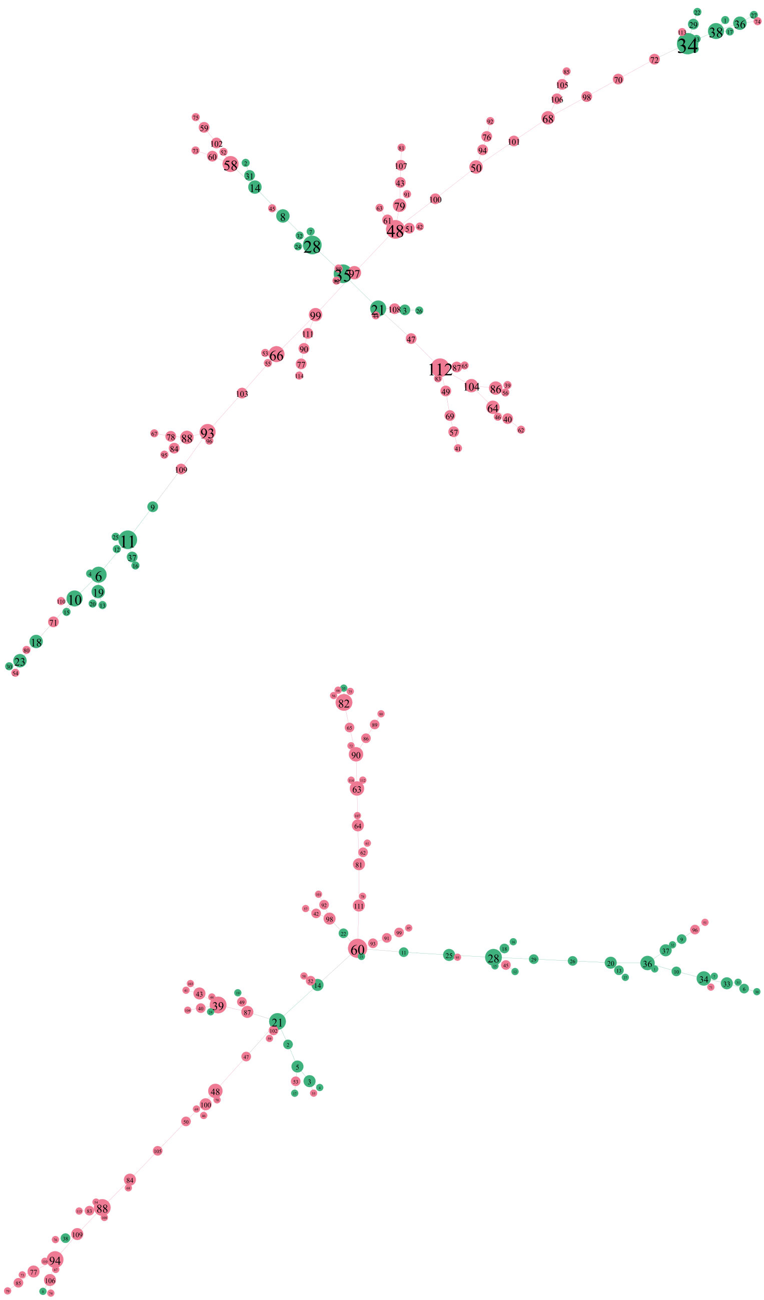

Fig. 7.3 (continued)

Table 7.3 Changes in core nodes by time period

	Time period	The five most important nodes with the highest weighted degree				
Volatility network	T1	28	20	74	53	43
	T2	16	2	105	68	82
	T3	34	35	28	112	11
Sentiment network	T1	32	11	13	82	4
	T2	53	32	28	14	103
	T3	60	82	94	88	39
Return network	T1	39	68	42	74	22
	T2	68	47	11	50	85
	T3	11	51	93	63	30

minimal impact on the structure of return and sentiment networks but significantly affect the volatility network. Combined with the changes in core nodes across time in Table 7.3, it can be seen that the systemically important companies in the sentiment and returns networks overlap in all three time periods, while the systemically important companies in the volatility network change radically. Although the systemically important companies in the volatility network differ across the three time periods, newly prominent companies in the volatility network in the T2 and T3 time periods overlap with those in the sentiment and return networks. For example, Shanghai Petrochemical is a key company in the T1 and T3 time periods of the sentiment network, while Ganfeng Lithium is significant in the T1 time period of the sentiment network, as well as the T2 and T3 time periods of the return network. Therefore, integrating information from the return, sentiment and volatility networks is essential for identifying systemically important companies, and their combined analysis supports informed decision-making (Table 7.4).

In addition to comparing the similarity of the same type of networks across time periods, this section further examines the evolution of similarity between the return, volatility, and sentiment networks over time. Table 7.5 presents these similarities, where greater consistency among the three values in a row indicates a more stable relationship between the networks across different periods, and greater consistency among the three values in a column suggests more similar structure and importance among the three network types in that period. The results show that the similarity between the sentiment and return networks increases gradually with the occurrence of two significant events: the COVID-19 and the dual carbon policy. Especially

Table 7.4 Similarity of network structure by time period

	Return network	Volatility network	Sentiment network
T1 vs. T2	0.64	0.23	0.54
T2 vs T3	0.45	– 0.11	0.45

Table 7.5 Similarities in the structure of inter-category networks across time periods

	T1	T2	T3
Similarity of return and volatility networks	0.63	0.59	0.53
Similarity of sentiment and return networks	0.14	0.20	0.30
Similarity of sentiment and volatility networks	0.30	− 0.18	0.45

in T3, stronger network similarity emerges between sentiment-return network and sentiment-volatility network. Therefore, the role of sentiment should be emphasized during such events, and the public opinion early warning mechanisms should be improved to effectively mitigate systemic risks.

7.5 Conclusion

This chapter investigates the effects of the COVID-19 pandemic and the dual carbon policy on the stock market system of Chinese new energy and traditional energy listed companies. A minimum spanning tree complex network is constructed from the three dimensional composite perspective of return, volatility and sentiment, and then the characteristics and differences in network structure among the three time periods are analyzed and compared. In addition, the chapter identifies systemically important companies in the three systems and analyzes their evolutionary trends.

The empirical results reveal two key findings. First, the sentiment network is the most efficient, with rapid transmission between new and traditional energy companies, while the return network is the least efficient, with transmission primarily occurring within the same type of companies. This tendency of return to propagate within similar energy companies hinders investment diversification, increasing the vulnerability of investors concentrated in on company type to asset losses. Therefore, investment decisions should involve assessing the position and role of the investment target in the network and adequately diversifying risk for effective portfolio management. Analysis of systemically important companies in the return, volatility and sentiment networks across different time periods shows that in the return and volatility networks, new energy companies have played an increasingly important role, while the systemically important companies in the sentiment network are still dominated by traditional energy companies. Consequently, when investor sentiment fluctuates significantly, regulators should pay particular attention to traditional energy companies, which play a central role in the network, to mitigate systemic risks arising from the rapid transmission of negative sentiment.

Second, changes in network structure over time indicate that transmission efficiencies of all networks increased during the COVID-19, suggesting rapid intercompany risk transfer and heightened systemic risk of energy companies. After the dual carbon policy, the role of new energy and traditional energy companies weakened. This is attributed to the release of the dual carbon policy. The energy industry is facing structural adjustment as the competitive landscape undergoes significant changes. High energy consumption, high emission traditional energy is being gradually replaced by clean energy sources like wind power. Consequently, the risk factor differentiation between the traditional and new energy industries has intensified.

By comparing the similarity between the return, sentiment and volatility networks reveals that the similarity between the sentiment and return networks gradually increases with the COVID-19 and the dual carbon policy. The similarity between the sentiment and return networks reaches the highest after the dual carbon policy. In addition, although the systemically important companies in the volatility network have changed fundamentally after the dual carbon policy, newly emerged important companies in the volatility network overlap with those in the return and sentiment networks across different periods. Therefore, regulators and investors need to fully integrate the information from the return, sentiment and volatility networks, leveraging their combined analysis to support informed decision-making.

Appendix

(See Table 7.6).

Table 7.6 Name of sample companies

ID	Code	Name	Type
1	000009	China Baoan Group Co., Ltd	New1
2	000690	Guangdong Baolihua New Energy Stock Co., Ltd	New2
3	002056	Hengdian Group DMEGC Magnetics Co	New3
4	002074	Gotion High-tech Co., Ltd	New4
5	002080	Sinoma Science & Technology Co., Ltd	New5
6	002129	Tianjin Zhonghuan Semiconductor Co	New6
7	002202	Xinjiang Goldwind Science & Technology Co	New7
8	002266	Zhefu Holding Group Co., Ltd	New8
9	002340	GEM Co., Ltd	New9
10	002407	Do-Fluoride New Materials Co	New10
11	002460	Ganfeng Lithium Co., Ltd	New11
12	002466	Tianqi Lithium Corporation	New12
13	002506	GCL System Integration Technology Co., Ltd	New13
14	002665	Shouhang High-Tech Energy Co., Ltd	New14
15	002709	Guangzhou Tinci Materials Technology Co	New15
16	300014	Eve Energy Co., Ltd	New16
17	300207	Sunwoda Electronic Co	New17
18	300274	Sungrow Power Supply Co., Ltd	New18
19	300316	Zhejiang Jingsheng Mechanical & Electrical Co	New19
20	300376	East Group Co., Ltd	New20
21	600021.SH	Shanghai Electric Power Co., Ltd	New21
22	600089.SH	TBEA Co., Ltd	New22
23	600438.SH	Tongwei Co., Ltd	New23
24	600482.SH	China Shipbuilding Industry Group Power Co., Ltd	New24
25	600549.SH	Xiamen Tungsten Co., Ltd	New25
26	600563.SH	Xiamen Faratronic Co., Ltd	New26
27	600770.SH	Jiangsu Zongyi Co., Ltd	New27
28	600875.SH	Dongfang Electric Co., Ltd	New28
29	600884.SH	Ningbo Shanshan Co	New29
30	601012.SH	LONGi Green Energy Technology Co	New30
31	601016.SH	CECEP Wind-Power Corporation	New31
32	601611.SH	China Nuclear Engineering Co., Ltd	New32
33	601727.SH	Shanghai Electric Group Co	New33
34	601877.SH	Zhejiang Chint Electrics Co	New34
35	601985.SH	China National Nuclear Power Co., Ltd	New35
36	603659.SH	Shanghai Putailai New Energy Technology Co	New36
37	603799.SH	Zhejiang Huayou Cobalt Co., Ltd	New37

(continued)

Table 7.6 (continued)

ID	Code	Name	Type
38	603806.SH	Hangzhou First Applied Material Co	New38
39	000059.SH	North Huajin Chemical Industries Co., Ltd	Traditional1
40	000096.SH	Shenzhen Guangju Energy Co	Traditional2
41	000159.SH	Xinjiang International Industry Co	Traditional3
42	000552.SH	Gansu Jingyuan Coal Industry And Electricity Power Co	Traditional4
43	000554.SH	Sinopec Shandong Taishan Petroleum Co., Ltd	Traditional5
44	000571.SH	Sundiro Holding Co., Ltd	Traditional6
45	000723.SH	Shanxi Meijin Energy Co., Ltd	Traditional7
46	000780.SH	Inner Mongolia Pingzhuang Energy Resources Co	Traditional8
47	000852.SH	Sinopec Oilfield Equipment Corporation	Traditional9
48	000937.SH	Jizhong Energy Resources Co., Ltd	Traditional10
49	000968.SH	Shanxi Blue Flame Holding Co., Ltd	Traditional11
50	000983.SH	Shanxi Coking Coal Energy Group Co., Ltd	Traditional12
51	002128.SH	Huolinhe Opencut Coal Industry Corporation Limited of Inner Mongolia	Traditional13
52	002207.SH	Xinjiang Zhundong Petroleum Technology Co., Ltd	Traditional14
53	002221.SH	Oriental Energy Co., Ltd	Traditional15
54	002278.SH	Shanghai SK Petroleum & Chemical Equipment Co	Traditional16
55	002353.SH	Yantai Jereh Oilfield Services Group Co., Ltd	Traditional17
56	002490.SH	Shandong Monlong Petroleum Machinery Co	Traditional18
57	002492.SH	Zhuhai Winbase International Chemical Tank Terminal Co., Ltd	Traditional19
58	002554.SH	China Oil Hbp Science & Technology Co., Ltd	Traditional20
59	002629.SH	Zhejiang Renzhi Co	Traditional21
60	002828.SH	Xinjiang Beiken Energy Engineering Co	Traditional22
61	300084.SH	Haimo Technologies Group Corporation	Traditional23
62	300157.SH	LandOcean Energy Services Co., Ltd	Traditional24
63	300164.SH	Tong Petrotech Corporation	Traditional25
64	300191.SH	Sino Geophysical Co., Ltd	Traditional26
65	300483.SH	Sino Prima Gas Technology Co., Ltd	Traditional27
66	600028.SH	China Petroleum & Chemical Corporation	Traditional28
67	600121.SH	Zhengzhou Coal Industry & Electric Power Co., Ltd	Traditional29
68	600123.SH	Shanxi Lanhua Sci-Tech Venture Co	Traditional30
69	600157.SH	Wintime Energy Co	Traditional31
70	600188.SH	Yanzhou Coal Mining Co., Ltd	Traditional32
71	600207.SH	Henan Ancai Hi-Tech Co., Ltd	Traditional33
72	600256.SH	Guanghui Energy Co., Ltd	Traditional34

(continued)

Table 7.6 (continued)

ID	Code	Name	Type
73	600339.SH	China Petroleum Engineering Corporation	Traditional35
74	600348.SH	Shan Xi Hua Yang Group New Energy Co., Ltd	Traditional36
75	600387.SH	HY Energy Group Co., Ltd	Traditional37
76	600395.SH	Guizhou Panjiang Refined Coal Co., Ltd	Traditional38
77	600397.SH	Anyuan Coal Industry Group Co., Ltd	Traditional39
78	600403.SH	Henan Dayou Energy Co	Traditional40
79	600508.SH	Shanghai Datun Energy Resources Co., Ltd	Traditional41
80	600532.SH	Shanghai Topcare Medical Service Co., Ltd	Traditional42
81	600583.SH	Offshore Oil Engineering Co., Ltd	Traditional43
82	600688.SH	Sinopec Shanghai Petrochemical Co., Ltd	Traditional44
83	600725.SH	Yunnan Yunwei Co	Traditional45
84	600740.SH	Shanxi Coking Co., Ltd	Traditional46
85	600758.SH	Liaoning Energy Industry Co	Traditional47
86	600759.SH	Geo-Jade Petroleum Corporation	Traditional48
87	600777.SH	Shandong Xinchao Energy Co., Ltd	Traditional49
88	600792.SH	Yunnan Coal & Energy Co., Ltd	Traditional50
89	600856.SH	Zhongxing Tianheng Energy Technology (Beijing) Co., Ltd	Traditional51
90	600871.SH	Sinopec Oilfield Service Corporation	Traditional52
91	600971.SH	Anhui Hengyuan Coal Industry and Electricity Power Co	Traditional53
92	600985.SH	Huaibei Ming Holdings Co., Ltd	Traditional54
93	600997.SH	Kailuan Energy Chemical Co., Ltd	Traditional55
94	601001.SH	Jinneng Holding Shanxi Coal Industry Co., Ltd	Traditional56
95	601011.SH	Baotailong New Materials Co	Traditional57
96	601015.SH	Shanxi Heimao Coking Co., Ltd	Traditional58
97	601088.SH	China Shenhua Energy Co., Ltd	Traditional59
98	601101.SH	Beijing Haohua Energy Resource Co., Ltd	Traditional60
99	601225.SH	Shanxi Coal Industry Co., Ltd	Traditional61
100	601666.SH	Pingdingshan Tianan Coal Mining Co., Ltd	Traditional62
101	601699.SH	Shanxi Lu'an Environmental Energy Dev. Co., Ltd	Traditional63
102	601798.SH	Lanpec Technoligies Limited	Traditional64
103	601808.SH	China Oilfield Services Limited	Traditional65
104	601857.SH	Petrochina Co., Ltd	Traditional66
105	601898.SH	China Coal Energy Co., Ltd	Traditional67
106	601918.SH	China Coal Xinji Energy Co., Ltd	Traditional68
107	603003.SH	Shanghai Lonyer Fuels Co., Ltd	Traditional69
108	603036.SH	Jiangsu Rutong Petro-Machinery Co., Ltd	Traditional70

(continued)

Table 7.6 (continued)

ID	Code	Name	Type
109	603113.SH	Jinneng Science & Technology Co., Ltd	Traditional71
110	603223.SH	Hengtong Logistics Co., Ltd	Traditional72
111	603619.SH	Zhongman Petroleum And Natural Gas Group Co., Ltd	Traditional73
112	603727.SH	BOMESC Offshore Engineering Co., Ltd	Traditional74
113	603800.SH	Suzhou Douson Drilling & Production Equipment Co	Traditional75
114	900948.SH	Inner Mongolia Yitai Coal Co., Ltd	Traditional76

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Chapter 8
Price Formation Mechanisms of Energy and Critical Minerals

Yiming Chen and Jingyu Li

Abstract Natural resources are the cornerstone of industrial development and energy supply, and their pricing mechanisms are directly related to the stability of the global economy and the industrial competitiveness of various countries. With the increasing integration of the global economy and the constant changes in market demand, the pricing mechanisms for minerals have become increasingly complex. This chapter delves into the pricing mechanisms of 25 different types of minerals, categorizing them into four groups: common industrial metals, non-metallic minerals, rare minerals, and energy minerals. The common industrial metals include nine types of minerals, such as manganese, iron, and copper; non-metallic minerals include four types, such as phosphorus and fluorite; rare minerals include nine types, such as chromium, gallium, and beryllium; energy minerals include petroleum, natural gas, and steam coal. Through this classification, we can better analyze the market dynamics of each category of minerals and gain a deeper understanding of their market behavior and pricing mechanisms. In the analysis, this paper also introduces the challenges and issues faced by China's mineral pricing power, aiming to provide decision support for policymakers and industry participants to cope with the uncertainties and challenges in the global mineral market.

Keywords Mineral pricing mechanisms · Mineral pricing power

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8.1 Common Industrial Metals

8.1.1 Manganese Ore

As a key industrial raw material, manganese plays a pivotal role in the global mining and steel industry chain. The evolution of its pricing power not only reflects the changes in the market supply-and-demand relationship but also epitomises the adjustment of the global mining and steel industry pattern. The manganese ore trade pricing model is changing from the traditional long-term negotiated price to a spot and index pricing model. According to data released by the United States Geological Survey (USGS), as of 2023, global manganese ore reserves contain about 1.9 billion tons, and the spot price of manganese ore is frequently higher than the long-term agreement price. Taking South Africa, Brazil and other large manganese ore sources as an example, these countries spot market is active, and the participation of a large number of speculative traders has pushed up the spot trading price of manganese ore. This shift in the pricing model allows manganese ore suppliers to respond more flexibly to market changes, but it also increases market uncertaint.

At present, the global manganese mineral market shows characteristics of high resource concentration and high production capacity. According to the USGS, more than 95% of the world's manganese mineral sources are concentrated in South Africa, Australia, Gabon, Ghana, Brazil, Cote d 'Ivoire, India and China. In terms of production, the global manganese ore production in 2023 was about 60.3 million tons, with Australia, South Africa and Gabon as the main producing areas. Mining giants in these regions, such as BHP Billiton and Vale, have a strong influence on the price of manganese minerals by virtue of their control of high-quality resources.

The competition for the pricing power of manganese minerals is essentially a data game. USGS data show that in 2023, South Africa accounted for about 36% of the global manganese ore supply, Gabon accounted for about 23% and Australia accounted for about 15%. The production and price policies of these major suppliers directly affect the global manganese ore market. On the demand side, the steel industry is the main consumer of manganese ore, and its output and import and export policies also have a significant impact on the price of manganese ore. In the battle for pricing power, mines and large steel companies compete for pricing dominance by participating in annual price negotiations. Numerous major suppliers and customers participate in the annual negotiations, among which mining giants, such as Vale, Rio Tinto and BHP Billiton, and large steel companies, such as ThyssenKrupp of Germany and Nippon Steel of Japan, are the main participants. These enterprises determine the long-term agreement price of manganese ore through negotiations, while the spot and index prices are more affected by market supply and demand and speculative trade.

Looking ahead, multiple challenges and opportunities pertaining to global manganese mineral pricing power will be encountered. With the recovery of the global economy and the upgrading of the steel industry, the demand for manganese ore will continue to grow, and market competition will be more intense.

8.1.2 Iron Ore

Iron ore is the core raw material of the steel industry, and its pricing mechanism has always been a topic of concern. From spot pricing to long-term agreement price—and now index pricing—the global iron ore pricing power has undergone many changes, showing a diversified trend. In this process, international iron ore production giants, international financial institutions and steel consumers in various regions have made the ownership of iron ore pricing power complicated and variable.

Before 1950, iron ore pricing was mainly done through spot trading. The market size was relatively small, and buyers and sellers reached deals through direct negotiations. However, with the rapid development of the iron and steel industry, the demand for iron ore rapidly increased, and the limitations of spot pricing gradually emerged. From the 1960s to the 1980s, long-term contract pricing gradually became mainstream. Japanese steel mills, led by Nippon Steel, signed long-term supply contracts with iron ore suppliers, such as Australia and Brazil, ensuring a stable source of raw materials by locking in prices and supplies. During this period, the iron ore market showed a relatively stable pattern of supply and demand.

As the iron ore market continues to mature and the contradiction between supply and demand intensifies, the drawbacks of the long-term agreement price mechanism have been gradually exposed. The long-term agreement price is inflexible, and real-time changes in the market are difficult to reflect. At the same time, suppliers occupy a dominant position in the pricing process, while the demand side has a weak voice. In 2010, the collapse of long-term negotiations between China and the "Big Three" iron ore producers (Vale, Rio Tinto and BHP Billiton) marked the end of the long-term pricing mechanism. Prior to this, China started the reform of the short-term agreed pricing mechanism for iron ore. Zhe et al. (2020) found that the introduction of the short-term agreed pricing mechanism was closely related to price fluctuations of domestic imported iron ore and that it could effectively restrain the sharp rise in price in the short term but could not restrain the international iron ore price. Since then, index pricing has gradually become mainstream, and international authoritative iron ore price indexes, including the Platts Index and MB Iron Ore Index (MBIO), have been widely used around the world.

At present, global iron ore pricing power shows a diversified and decentralised trend. On the one hand, international iron ore production giants, such as Vale, Rio Tinto, BHP Billiton and others with rich resources and capacity advantages, have a greater say in the pricing process. On the other hand, international financial institutions, such as the Vanguard Group and Blackstone Group, have a profound impact on iron ore pricing through holding industries and releasing pricing indexes. In addition, the bargaining power of regional steel-consuming countries in the pricing process cannot be ignored.

However, global iron ore pricing power faces a number of challenges. First, the changing relationship between supply and demand has increased the volatility of iron ore prices. In recent years, global economic growth has slowed. Affected by the continued high interest rate policy of the US dollar, overseas iron ore demand continues to decline, while the Chinese economy has maintained a stable operation, and the domestic demand for iron ore has grown strongly. The supply side is affected by factors such as capacity constraints and environmental constraints, and it is difficult to respond quickly to demand growth. At the same time, in terms of supply and demand, in the first three quarters of 2023, the US dollar's high interest rate policy continued. Additionally, the world economic recovery was weak, overseas iron ore demand continued to be low, and the global mining market struggled to recover. This contradiction between supply and demand has led to frequent fluctuations in iron ore prices, bringing great risks to steel companies and investors. Second, the monopoly position of international iron ore production giants has an important impact on pricing power. These enterprises affect the balance of supply and demand in the market by controlling output and adjusting the pace of delivery, with the aim of mastering the pricing initiative. At the same time, they can further consolidate their dominance in the pricing process by, for example, cooperating with financial institutions to publish pricing indices. In addition, the influence of international financial institutions on the pricing power of iron ore cannot be ignored. These institutions carry out deep intervention and manipulation of the iron ore market by mastering a large amount of financial capital and information resources. Not only do they affect the market price trend by releasing pricing indexes, but they also obtain excess returns by participating in iron ore futures trading. This trend in financialisation makes the ownership of iron ore pricing power more complex and variable.

8.1.3 Copper Concentrate

The pricing mechanism for copper concentrates has gone through three stages. Before the 1930s, the market was mainly controlled by a few manufacturers, and pricing power was in the hands of these manufacturers. However, with the impact of the turbulent international environment on the market economy, the government began to intervene in copper prices from the 1930s to 1950s, implementing measures such as rationing systems and directly affecting copper prices. At the beginning of the 1950s, the futures market emerged and futures pricing dominated. The London Metal Exchange (LME) and the New York Mercantile Exchange (COMEX) are increasingly influential.

In recent years, global copper concentrate production has stabilised at around 20 million tonnes of metal, with major producers including Chile, Peru, China, the Democratic Republic of the Congo, the United States and Australia. Together, these countries account for 65.4% of global production, showing a high concentration of production. However, unlike the highly monopolised iron ore market, there are many producers in the copper concentrate market, and competition is relatively fierce. Although copper giants have an advantage in terms of output, the maturity of the futures market makes it difficult for a single producer or an international copper cartel to form a price monopoly. At the consumption end, copper consumption in developed countries in Europe and in the United States has shown a shrinking trend, while emerging economies in Asia have gradually become the main force of copper consumption. China, in particular, accounts for nearly half of the world's copper smelting capacity and has a growing influence on global copper prices. This change in consumption patterns has gradually increased the influence of the Asian copper consumption market on copper prices.

Global copper concentrate pricing power is influenced by a number of factors, including the dominance of the LME, the participation of financial institutions, the movement of the US dollar index, refined copper prices and copper processing fees, international inventories and copper scrap recycling. Su et al. (2023) studied the nonlinear characteristics of international copper futures prices and their driving factors, and found that the price fluctuations showed a dynamic mechanism conversion pattern of "expansion", "plateau" and "contraction". The long-term stability of international copper futures prices is mainly affected by demand-related factors, especially the demand for strategic metals. LME copper stocks and their futures have a significant impact on prices, while in some regimes the impact of global refined copper consumption on prices is not significant. During the contraction, the increase in volume is the main driver; During expansions, the increase in global refined copper production capacity pushes up prices, while crashes usually occur during plateaus or contractions.

At present, the new energy industry is developing rapidly, but the volatility and uncertainty of the global economy require us to be cautious about changes in copper demand. At the same time, with the continuous progress of technology and the improvement of environmental protection requirements, the supply of copper is also facing new challenges. As a result, the global copper market presents a more complex and volatile pattern.

8.1.4 Nickel Ore

The global supply of nickel is highly concentrated. According to the China Geological Survey, Indonesia, Australia and Russia are the main owners of global nickel resources, of which Indonesia's nickel resources account for more than one-third of the world's reserves. This geographical distribution gives these countries a pivotal position in the global nickel market. Nickel is seen as a key strategic metal for national economies and the development of new technologies, so the drivers of its price movements are attracting increasing attention (Zheng et al. 2022). Indonesia is the world's largest source and supplier of nickel, and changes in its nickel mining policy have had a profound impact on global nickel prices. Since 2014, Indonesia has banned the export of raw ore to promote the formation of a nickel processing industry chain. This policy not only made the Indonesian nickel price rise several times, but also prompted the global nickel industry chain restructuring. Relevant studies have shown that nickel prices are affected by the principle of supply and demand, and supply fluctuations significantly affect prices (Cummins et al. 2015). In the future, as Indonesia tilts toward the production of new energy battery raw materials and plans to extend the downstream industrial layout, global nickel prices are expected to continue to rise.

Similar to supply, global consumption of nickel resources is highly concentrated. China is the world's largest consumer of nickel, accounting for more than half of global consumption. This consumption pattern gives China a huge voice in the global nickel market. From the perspective of consumption structure, stainless steel and new energy vehicle batteries are the two main consumption areas of global nickel resources. Stainless steel accounts for more than 70% of nickel consumption, while the battery sector accounts for only 5% of nickel consumption. However, with the rapid development of the global new energy vehicle industry, the demand for battery nickel is also growing rapidly. According to the International Energy Agency, by 2030, the global nickel consumption of new energy batteries will reach 928,000 tons. This trend will make the battery industry the main driver of nickel consumption growth in the future. The new energy vehicle (NEV) industry has played a key role in the rise in nickel prices (Yao et al. 2021), and nickel's high energy density and low cost have increased its proportion in ternary batteries, effectively reducing costs and extending battery life (Nguyen et al. 2021).

In terms of nickel market trading, the LME is the core pricing reference for global nickel market trading. About 50% of global nickel trading involves the LME nickel price, making the LME the pricing center for global nickel market trading. The LME's pricing influence is mainly due to its well-established trading system, broad group of participants and flexible trading rules. These factors enable the LME to compile the world's most comprehensive supply and demand information on the nickel market, resulting in a credible nickel price. The Shanghai Futures Exchange (SHFE) has also become more influential in nickel trading in recent years. As the largest metals exchange in China, the Shanghai Futures Exchange has become a regional nickel trading and pricing center. Nickel price fluctuations not only affect China's domestic nickel market; They also affect global nickel prices. Especially after the LME incident, the market crisis in March 2022, as a short squeeze and price spike led to billions of dollars of trade suspension and cancellation, the LME was plunged into a crisis of confidence, and a large number of investors began to shift their trades from the LME to the SHFE, further enhancing SHFE's position in the global nickel market.

Although the current global nickel pricing power situation is relatively clear, there are still many challenges. First of all, the geographical distribution of nickel resources is uneven, so that the pricing power on the supply side is mainly concentrated in the hands of a few countries, increasing the uncertainty and volatility of nickel prices. The geographic concentration of nickel resources has led to global supply disruptions caused by natural disruption, mining conflicts, and policy restrictions, thus limiting production growth (Su et al. 2020). Secondly, the rapid development of the new energy battery field has made the demand for nickel grow rapidly, but it will also lead to excessive volatility and speculation in nickel prices. Due to the low price elasticity of nickel supply, production constraints can drive up prices (Ma and Xiong 2021). In addition, the market position of traditional pricing centers such as the LME, while solid, is also facing challenges and competition from emerging markets.

Global nickel reserves are mainly concentrated in Indonesia, Australia, Brazil and Russia, which poses a high supply risk (Elshkaki et al. 2017). In the case of scarcity, if demand increases, limited supply will lead to excessive price increases and even bubbles (Geman and Smith 2013). Furthermore, research by Tiwari et al. (2021) suggests that geopolitical instability increases volatility in nickel markets, increasing the risk of supply disruptions. Nickel has gradually become the focus of strategic competition, and major economies have further strengthened their control over nickel resources (Su et al. 2019; Gong and Xu 2022).

8.1.5 Cobalt Ore

Unlike other commodities, the global pricing power of cobalt is concentrated in the quotation system centered on Fastmarkets, formerly known as Metal Bulletin, while futures markets, such as LME cobalt contracts. are relatively marginal. The formation of this pricing mechanism is related to the scarcity and uneven distribution of cobalt resources as well as changes in international political and economic patterns. With the Fastmarkets MB quotation at the core of the global cobalt price, its formation relies on real-time surveys of major producers and traders in Europe and the United States. As the main participants in the market, the transaction prices of these enterprises often reflect the real supply and demand situation of the market. By collecting these data, MB is weighted to form the daily cobalt price, which provides an important price reference for the global market. Due to the authority and transparency of MB pricing, it has become the core pricing mechanism for cobalt prices and has a significant impact on the global cobalt market.

Although the LME, one of the world's largest metal futures exchanges, has launched cobalt futures contracts that provide the market with more investment options, due to the particularity of the cobalt market and liquidity restrictions, LME cobalt futures have relatively little influence on pricing. Nevertheless, the LME cobalt price is still one of the important references for the global cobalt price, especially when the market is volatile and its futures price has a certain guiding role for the spot price.

The global distribution of cobalt resources is extremely uneven, concentrated in a few countries such as the Democratic Republic of the Congo (DRC), Indonesia and Australia. This uneven distribution of resources gives these countries high pricing power in the global cobalt market. In particular, in the DRC, the stability of its political and economic environment is directly related to the volatility of global cobalt prices. In recent years, due to the unstable political situation and backward infrastructure in the DRC, the mining and export of cobalt ore in the country has faced many challenges that have further exacerbated the volatility of global cobalt prices.

Historically, cobalt price fluctuations have been mainly influenced by supply and demand. The mining and refining technology of cobalt is relatively complex, and the distribution of resources is uneven, which makes the supply has a certain rigidity.

With the rapid development of new energy and electronics industries, the demand for cobalt has increased significantly. In turbine production, cobalt in permanent magnets is critical to improving the efficiency and reliability of renewable wind energy systems (Jian et al. 2023). Demand for electric vehicles and wind turbines continues to drive cobalt consumption, but price volatility, gas emissions, fragile supply chains, and labor costs pose challenges (Cerruti et al. 2023; Lee and Manthiram 2022). Bahini et al. (2024) show that cobalt plays a key role in renewable power generation through storage and enhancement technology and innovation.

The existence of contradiction between supply and demand has caused the price of cobalt to fluctuate sharply many times in history. For example, the ban on cobalt ore exports in the DRC in 2007 and the explosive growth of the global new energy vehicle market in 2016–2017 led to sharp rises in cobalt prices. However, with increasing supply and slowing demand, cobalt prices experienced a series of fluctuations from 2018 to 2023. After reaching a peak in 2018, cobalt prices began a decline that persisted into 2023, but with the decline slowing compared to the previous year's sharp drop. According to the data from the business community, the cobalt price in 2023 repeatedly bottomed out, and the domestic cobalt price fell 31.69% throughout the year. The cobalt price at the end of the year was 220,900 yuan/ton, which was significantly lower than the 323,400 yuan/ton at the beginning of the year. In addition to supply and demand, geopolitical factors, such as Sino–US trade frictions and unrest in Africa, also significantly impact cobalt prices. Therefore, when investors participate in cobalt market trading, they need to pay close attention to changes in the international political and economic landscape to deal with possible risks.

With the rapid development of the new energy and electronics industries, the demand for cobalt is expected to continue to grow. However, due to the scarcity and uneven distribution of cobalt resources and the interference of geopolitical factors, the volatility of cobalt prices will continue to exist.

8.1.6 Bauxite

In the global resource market, bauxite is a key raw material in the aluminium industry chain. At present, global bauxite pricing is mainly based on the spot market. Under this pricing mechanism, the price of bauxite is affected by multiple factors, such as origin, ore quality, transportation distance and tariffs. In addition, long association pricing and spot market prices coexist. Long association pricing helps to avoid risks, but in recent years, problems, including its transparency, restraint ability and price adjustment mechanism, have gradually emerged, leading some traders to turn to spot market pricing. The relationship between supply and demand is the decisive factor in the price of bauxite. Bauxite price changes in recent years have also been affected by a variety of factors. In 2023, the supply situation of domestic bauxite was still not ideal, and the supply was tightened, thus supporting the price of domestic aluminium ore. In terms of the imported ore market, due to the influence of domestic mining over many years, the grade of domestic bauxite has declined year by year, making the supply of high-grade ore difficult to sustain. This has led to a low operating rate of domestic mines, procurement difficulties for many aluminium oxide plants, and an overall market shortage. Consequently, the dependence of aluminium oxide plants on imported mines has increased year by year.

Bauxite resources are abundant in the world but concentrated in specific areas. Guinea, Australia and Vietnam are the main producers of bauxite in the world, with their combined output accounting for more than 60%. The bauxite resources in these regions are of good quality and easy to exploit, so they occupy an important position in the global bauxite market. In addition, the geopolitical situation and policy changes in important bauxite-producing areas may also have an impact on global bauxite prices. Global demand for bauxite continues to grow, mainly in China, Australia and Brazil. As the world's largest consumer and importer of bauxite, China has a pivotal position on the demand side. This provides favourable conditions for China to fight for pricing power in the global bauxite market.

As the upstream raw material of aluminium industry chain, bauxite's price is affected by the overall operation of the aluminium industry chain. From alumina to electrolytic aluminium to aluminium production, raw material costs are high. Therefore, the fluctuation of aluminium prices directly affects the price of bauxite. At the same time, the demand for aluminium products downstream of the aluminium industry chain continues to grow, which has also led to a rise in bauxite demand and prices. Especially in the fields of automotive lightweight and rail aluminium, the demand for aluminium is growing, providing a broad space for the bauxite market.

In the global bauxite market, the battle for pricing power involves resources, politics and economy, among many other aspects. As the world's largest consumer and importer of bauxite, China has certain advantages in terms of pricing power, but it also faces many challenges. First, the global concentration of bauxite resources is limited to select areas, and the major producing countries have a greater influence on trade. This could limit China's bargaining power in the global bauxite market. Second, geopolitical factors may have an impact on the global bauxite supply, which in turn affects bauxite prices. In addition, the competitive landscape of the international bauxite market, trade policies and other factors may also have an impact on China's position in the global bauxite pricing power.

8.1.7 Tin Ore

Before the 1990s, global tin pricing was mainly influenced by intergovernmental agreement pricing and LME trading prices. The UK was once a global tin trading centre, and its Royal Exchange provided a platform for trading tin and other metals. With the advent of the Industrial Revolution, Britain's demand for raw materials, including tin, soared, making London a global centre for tin trade and pricing. The establishment of the LME in 1877 marked a new stage in the pricing mechanism of tin ore. The trading price published by the LME has gradually become the benchmark for international trade in tin. At the same time, the International Tin Council also played an important role in stabilising market prices. However, during most of the twentieth century, the intergovernmental agreement pricing model was affected by multiple factors, such as the international situation and the domestic political environment of the producing countries, and the price of tin fluctuated greatly. In 1989, the LME introduced a major reform of the tin futures market, which marked a fundamental change in the pricing power of tin mines worldwide. With the dissolution of the International Tin Council due to insufficient control over tin production and consumption, the LME tin futures market gradually became the dominant force in global tin pricing. The success of the LME tin futures market is due to its international membership system and extensive warehouse network. These advantages allow the LME to attract producers, consumers and traders from all over the world to participate in transactions, thus setting the tin price with global influence. At this stage, although the tin trading markets of China, Malaysia, Indonesia and other countries also have a certain influence, their tin price trends basically follow LME price curve fluctuations.

Global tin pricing is influenced by a variety of factors, including supply and demand, global economic developments and unexpected events. From the perspective of supply and demand, the consumption structure of tin is relatively stable, mainly concentrated in solder, tinplate and chemical industries. However, in recent years, the overall consumption of tin has stagnated, which limits the price of tin to a certain extent. At the same time, the global supply of tin resources is relatively concentrated. The main production areas include China, Southeast Asia and South America. Production in these regions has a significant impact on the global tin market.

China plays an important role in the storage, import, production and consumption of tin ore and is an exporter of refined tin. Since 2002, China has implemented export quota management of tin and tin products until the official abolition of related quotas and tariffs in January 2017. Zhu et al. (2018) pointed out that the Chinese market has a comparative advantage in tin trade, and changes in export policy will not affect tin prices on the Shanghai Futures Exchange (SHFE). The cancellation of the export policy led to an increase in supply in the international tin market, which led to a long-term downward trend in the LME tin price. In addition, this policy change has increased investor uncertainty about the tin market, resulting in short-term volatility in LME tin prices.

The impact of global economic trends on tin ore pricing cannot be ignored. For example, tin prices fell sharply during the 2008 global financial crisis. When the economy recovered and demand increased, tin prices rose. In addition, geopolitical events, such as the Ukraine crisis, may have an impact on tin prices. In the future, global tin ore pricing power will continue to be affected by multiple factors. With the rapid development of new energy, new materials and other fields, the consumption structure of tin may change, which will bring new challenges and opportunities for tin ore pricing. Changes in the global political and economic landscape may also have a profound impact on tin ore pricing. For example, policy adjustments in major producing areas or changes in trade relations may trigger fluctuations in tin prices.

At the same time, global tin ore pricing power is also facing challenges concerning environmental protection and resource depletion, among other issues. With the increasing global attention on sustainable development, environmental protection in tin mining and smelting processes will be put under more scrutiny. In addition, the limited nature of tin resources also makes the problem of resource depletion increasingly prominent, which will have a long-term impact on global tin pricing.

8.1.8 Zinc Ore

The pricing of global zinc resources is mainly dependent on the futures market. The official price published by the LME, the global zinc futures pricing centre, reflects the change in zinc supply and demand in the world and provides an important price reference for the international trade of zinc. At the same time, the SHFE, as the only zinc futures market in China, has gradually become an important part of the global zinc pricing system. Since its inception, the LME's zinc futures market has been the global benchmark for zinc pricing. Its active trading and strong price influence provide an effective risk management tool for the international trade of zinc. In contrast, the COMEX briefly launched zinc futures trading, but it was not successful, further highlighting the LME's dominance in global zinc pricing.

Zinc price fluctuations are affected by a variety of factors, of which supply and demand relations and the global economic situation are the most important. Since the 1960s, zinc prices have gone through several cycles of ups and downs, reflecting fluctuations in the global economy and changes in supply and demand in the zinc market. For example, in the early 2000s, zinc prices experienced a rapid rise, largely due to the recovery of the global economy and the growth of zinc demand. After the 2008 financial crisis, zinc prices fell sharply, reflecting the impact of the global recession on zinc demand. The distribution of global zinc resources is highly concentrated, with Australia and China holding the largest zinc reserves in the world, accounting for more than 40%. This resource distribution pattern has an important impact on global zinc pricing. The production of zinc mines in Australia and China directly affects the global zinc supply, and the performance of the two countries in the zinc consumption market also directly affects the demand for zinc. In terms of production, since 2015, China's zinc metal production has basically remained stable. According to data organised by the China Economic Industry Research Institute, China's zinc metal production in 2020 was 6.425 million tons, an increase of 3.03%. Global zinc concentrate production stabilised at around 12.5 million tons starting in 2017 but dropped to 12.252 million tons in 2020 due to the impact of the COVID-19 pandemic, a decrease of 4.27%. In 2022, global zinc concentrate production declined by 2.5% to 12.476 million tonnes. The main producers are China, Peru and Australia, whose miners have some influence on global zinc prices. In particular, large zinc producers, such as Glencore, the world's largest zinc trader, control a large part of the global refined zinc circulation with their fast and efficient sourcing, strong allocation of zinc resources and keen insight into the zinc market. This gives these producers a pivotal position in global zinc pricing, and their trading strategies directly affect the trend of global zinc prices.

The global consumption of zinc is mainly concentrated in the Asia–Pacific, Europe and the United States. China's zinc consumption accounts for the highest proportion. The formation of this consumption pattern is closely related to China's industrialisation process and infrastructure construction. In terms of zinc demand, domestic apparent consumption of refined zinc in 2023 maintained high growth, with a total annual growth rate of 6.93 million tons, exceeding 15% year-on-year. Domestic sectors such as automobiles, wind power and infrastructure are the main sources of growth, while the real estate sector continues to be weak. The overall supply and demand pattern of the future zinc market is expected to narrow; the supply side is expected to continue to grow, and the tightening of the global zinc mine supply and demand will become a key variable in determining whether the new capacity of refined zinc can be fulfilled. The consumption structure of zinc can be divided into two categories: initial end and terminal. Initial consumption mainly concerns galvanisation, which accounts for 64% of initial consumption, while terminal consumption mainly concerns infrastructure, which accounts for nearly 60% of terminal consumption. This consumption structure makes the consumption demand for zinc closely related to the global economic situation and infrastructure construction. When the global economic situation is improving and infrastructure construction is accelerating, the consumption demand for zinc increases, which promotes a rise in zinc prices. On the contrary, when the global economic situation is not good and infrastructure construction slows down, zinc consumer demand declines, and zinc prices are suppressed.

The evolution and current situation of global zinc ore pricing power reflect the leading role of the futures market, the influence of major producers and the changes in consumption patterns. In the future, considering the challenges and uncertainties faced by the global economy between 2020 and 2023, as well as supply and demand changes in the zinc market and the influence of major producing countries, global zinc mining pricing power is likely to undergo more complex and diversified changes.

8.1.9 Lithium Ore

With the vigorous development of the global new energy industry with lithium as the key raw material, the pricing power of lithium ore has become increasingly important. Lithium, as the main component of rechargeable lithium-ion batteries (LiBs), plays an integral role in the clean energy industry (Heredia et al. 2020). From long-term agreement prices to futures trading, the evolution of lithium pricing power not only reflects market power, but also reflects the strategies and wisdom of participants.

For a long time, the trade of lithium resources was mainly based on the long-term agreement price model. This pricing model takes into account the cost of production and the price of lithium salt and uses formula pricing, which is usually adjusted on a quarterly or annual basis according to market conditions. However, the long association pricing mechanism has many problems, such as a lack of transparency, weak smelter restraint ability and an inflexible price adjustment mechanism. In the context of soaring global lithium prices, the number of companies buying lithium resources is increasing rapidly, and lithium resource companies are also seeking to change their pricing models. In 2021, the emergence of futures pricing and auction pricing models marked the beginning of a new stage in lithium resource pricing.

Global lithium resources are rich, but their distribution is concentrated. South America's "lithium triangle" region, Australia, China and the US are the main global suppliers of lithium. In recent years, due to the high demand for new energy vehicle batteries, the price of lithium resources has continued to rise, and the premium to the resource side has increased. This phenomenon shows that the pricing of lithium resources is affected not only by supply and demand but also by factors such as global politics and economics. International lithium giants, such as the United States's Arbel and Chile's Sociedad Química y Minera de Chile S.A. (SQM), affect the international lithium resource price through long association trade. These enterprises have the world's best-quality lithium brine salt lakes and the highest-grade lithium mines, forming a monopoly pattern. They supply global demand for lithium resources through a long-term pricing model, which affects international prices. In addition, lithium resource enterprises have been further integrated into resource leaders, and their bargaining power has been further strengthened. This trend adds to the complexity of pricing lithium resources, making pricing power even more elusive.

The emergence of the auction model of lithium bulk ore has impacted the current long order pricing mechanism. The multiple Pilbara auctions, which were priced at a premium to the day's long orders, acted as a clear guide for market price expectations, driving the short-term price upward. The successful implementation of this model and the high premium space relative to the long order may trigger subsequent new mines to follow suit, driving the proportion of the long association to decline or the pricing formula to adjust. This change shows that the pricing mechanism of lithium resources is gradually moving toward diversification and flexibility.

The US and other Western countries took the lead in launching lithium futures, which had a gradual impact on the price of lithium resources. The Chicago Mercantile Exchange (CME) and the LME trade lithium carbonate and lithium hydroxide futures, providing the market with more authoritative market quotations. Despite the short trading time and small delivery scale of lithium futures, their price formation mechanisms have begun to work. The launch of lithium futures not only provides the market with more pricing tools but also gives participants more means of risk management.

8.2 Non-Metallic Minerals

8.2.1 Phosphate Rock

Phosphorus plays an important role in agriculture and industry, and its pricing power is particularly critical to the global market. The pricing of phosphate rock resources is affected by the cost, the supply and demand relationship and global political and economic patterns.

The distribution of phosphate resources in the world is extremely uneven and is mainly concentrated in Africa and the Middle East. Morocco holds the world's largest phosphate resource reserves, which account for more than 70%, reaching an astonishing 50 billion tons. China and Algeria also have relatively rich phosphate resources. However, the exploitation and utilisation of these resources is not entirely determined by reserves; they are also affected by political, economic and technological factors.

From the perspective of supply, China is the world's largest phosphate rock producer, accounting for nearly half of the world's total output. However, China's share of the export market is relatively small, at 1.1%. Morocco and Jordan are major phosphate exporters, with Morocco's OCP serving as the world's largest phosphate exporter. The demand side of phosphate rock is mainly concentrated in Asia and Europe, with Asia being the largest phosphate rock import region. This imbalance of supply and demand distribution leads to fluctuations in phosphate rock prices and the dispersion of pricing power. The scarcity and irreplaceability of phosphate rock resources make its price directly affected by the market supply-and-demand relationship, and changes in the international political and economic environment also have a profound impact on the price of phosphate rock.

The pricing mechanism of phosphate rock has gradually changed from cost based to market based. Historically, phosphate rock pricing has mainly adopted cost-plus pricing or target pricing. However, with the increasing scarcity of phosphate rock resources and the growing market demand, it has been difficult to adapt this pricing method to changes in the market. At present, phosphate ore pricing is more affected by market supply and demand, phosphate fertiliser prices and transportation costs. The strong demand for lithium iron phosphate in the field of new energy has promoted the high operation of phosphate rock prices. At the same time, the continuous growth of the demand for agricultural products and a rise in food prices have also led to a rise in the price of phosphate fertiliser, which has boosted the price of phosphate ores. In addition, due to the uneven distribution of phosphate rock resources and the difference in transportation costs, international phosphate rock prices show regional characteristics, and the price of imported phosphate rock is much higher than that of domestic phosphate rock.

The distribution of global phosphate pricing power is affected by many factors, including resource reserves, production scale, technical level, market demand and international political and economic patterns. With their rich resources and huge production scales, Morocco, the United States Maison Company, China Yuntianhua

Co., Ltd. and other key enterprises in the global production of phosphate rock have a greater say in phosphate rock pricing. These enterprises adopt different pricing strategies, such as the principle of lower cost and market price, long-term negotiated price or demand-oriented pricing, to cope with market changes and safeguard their own interests. At the same time, they also integrate upstream and downstream resources of mineral development and phosphorus chemical industry to form integrated enterprises to withstand market risks and expand market share. In the international market, the influence of these key enterprises is reflected not only in the supply and price of phosphate rock but also in its shaping of the global market pattern and leading of the development trend of the industry. For example, as the world's largest phosphate exporter, Morocco OCP's pricing strategy and market behaviour have a significant impact on global phosphate prices.

Looking ahead, global phosphate pricing power will continue to be affected and challenged by a variety of factors. With the rapid development of the new energy field and the continuous growth of the demand for agricultural products, the scarcity and importance of phosphate rock resources will become more prominent. Changes in international political and economic patterns and the rise of trade protectionism may also have a profound impact on phosphate rock pricing power. In this context, global phosphate ore production enterprises need to continuously improve their resource utilisation efficiency, technical level and market competitiveness to cope with market changes and challenges. At the same time, governments also need to strengthen cooperation and coordination, promote the rational development and utilisation of global phosphate rock resources and promote the stability and sustainable development of the global phosphate rock market.

8.2.2 Graphite

The global graphite market has experienced price fluctuations over the past few decades, which are related to graphite production, market demand and producer strategies. From a global perspective, the distribution of graphite resources is mainly concentrated in Turkey, Brazil and China. This distribution of resources has a certain impact on the production and price of graphite. Global graphite production generally shows a trend of continuous growth, especially in recent years, given the emergence of the field of new energy. The demand for graphite has increased sharply, and graphite prices have also risen. However, the production area of graphite is relatively concentrated, with China, Mozambique, Madagascar and Brazil accounting for more than 90% of the production. This phenomenon of production concentration may lead to instability of graphite prices in some regions, as changes in the production of one region can impact the global graphite market price. Large graphite producers influence graphite prices by controlling production capacity, which is also an important factor in graphite pricing. These producers balance market demand and supply by adjusting production, thus keeping prices stable. However, the emergence of new graphite-producing regions, such as Africa, may have new consequences for global graphite prices. The global graphite consumption area is mainly concentrated in the Asia–Pacific region, making it the world's largest graphite consumption market. With the continuous development of new energy, new materials and other emerging industries, the demand for graphite is also increasing, which will further promote a rise in graphite prices.

8.2.3 Fluorite

The global price of fluorite is mainly determined by the market supply-and-demand relationship, and no long-term or short-term agreement price negotiation mechanisms have been formed. Similar to phosphate rock pricing, the price of fluorite moves with the market, mainly referring to the public price published by international media. such as the British "Metal Guide." These prices include both FOB (Free on Board) and CIF (Cost, Insurance, and Freight) fluorite of different qualities and from different regions, providing a reference for international transactions. In addition, quotation platforms, such as Shanghai Steel Union and Business Society, also provide benchmark prices, but market participants pay more attention to actual trading conditions and changes in supply and demand. Under this pricing mechanism, acid grade fluorite is usually more expensive than metallurgical fluorite, and the price increase is also larger. This is because acid grade fluorite has a higher CaF_2 content requirement and a tighter supply. From the data disclosed by the British "Metal Guide" in 2022, the international price of fluorite, especially acid grade fluorite, has generally risen. In 2023, the price continued to rise, with a price of 3300 yuan/ton at the beginning of the year and a price of 3544 yuan/ton at the end of the year, an annual increase of 7.39%. In 2023, the price fluctuated significantly, with the highest point in mid-October, at 3781.25 yuan/ton, and the lowest point in mid-March, at 2950 yuan/ton. The price increase was mainly due to tight supply, although prices fell slightly in the fourth quarter as demand weakened. In the first half of 2024, the demand for fluorite powder weakened, and the price fluctuated slightly. The mainstream market price was 3700–3850 yuan/ton. The strengthening of mining regulations has led to a tight supply, but weak demand has led to a decline in prices. In June 2024, the import volume and the average price of fluorite in China increased from the previous month, while the export volume decreased. Although the price of fluorite fluctuated in the first half of 2024, the overall level remained high, with tight supply and changes in demand being the main factors affecting the price (Zhu et al. 2023).

Fluorite resources are abundant across the world but are mainly distributed in the metallogenic belt around the Pacific Ocean, accounting for more than 50%. Mexico, China, South Africa and Mongolia are the main suppliers of fluorite resources. However, despite abundant resources, the global supply of fluorite is limited by a number of factors. First, environmental protection requirements are increasingly strict, and the development of new mines is limited. In developing countries, such as China, environmental protection policies have had a greater impact on mining, limiting the production and supply of fluorite. Some major supplier countries, such as Canada and Mexico, shut down mines, further exacerbating the tight supply situation. On the demand side, the demand for fluorite is increasing rapidly, especially for lithium hexafluorophosphate and semiconductor applications. The demand for fluorite in these areas continues to grow, driving up the price of fluorite.

There are obvious regional differences and structural scarcity in the distribution of global fluorite resources. Compared with Mexico, China and other countries, developed countries and regions such as the United States, the European Union, Japan and South Korea have relatively scant fluorite reserves, forming a structural scarcity. This imbalance in resource distribution leads to a certain separation between global fluorite consumption and resource supply. Economies such as the United States, Japan and Western Europe consume large amounts of fluorite but have limited domestic fluorite resources and are therefore extremely dependent on imports. This dependence has increased competition and price volatility in the international fluorite market.

The global fluorite import and export market shows an obvious trend in concentration. As the world's largest producer and supplier of fluorite, China's export volume occupies an important position in the global market share. However, with the implementation of environmental protection policies and the restriction of mine development, China's fluorite exports gradually decreased. At the same time, the demand for acid grade fluorite in developed regions, such as Europe and the United States, began to shift to the Chinese market. This shift in the import and export market reflects the changes and trends in the global fluorite market. Because of the influence of environmental protection policies in China and other developing countries, the production of fluorite is restricted, and supply is reduced. However, the demand for high-quality fluorite in developed countries continues to grow, promoting a market shift. This shift provides new opportunities and challenges for the international fluorite trade.

The future trend of global fluorite pricing power will be influenced by a number of factors. First, environmental policies and resource availability will continue to have an impact on fluorite prices. As environmental requirements increase and mine development is limited, fluorite supply may be further tightened, pushing prices higher. Second, new demand and technological progress will change the supply and demand patterns of the fluorite market. Developments in areas such as lithium hexafluorophosphate and semiconductors will increase the demand for high-quality fluorite and drive market upgrades. Finally, the international trade environment and geopolitical factors also have an impact on the pricing power of fluorite. Rising global trade protectionism and geopolitical tensions could exacerbate market volatility and uncertainty. Therefore, global fluorite production enterprises need to continuously improve the efficiency of resource utilisation, technical level and market competitiveness to cope with market changes and challenges. At the same time, governments also need to strengthen cooperation and coordination, promote the rational development and utilisation of global fluorite resources and promote the stability and sustainable development of the global fluorite market.

8.2.4 Boron Ore

Unlike the pricing mechanism of fluorite, the pricing of boron resources mainly depends on agreement pricing. This is mainly because the supply side of boron resources is relatively concentrated and mainly controlled by a few international boron resource head enterprises. These enterprises determine the transaction price by conducting one-on-one negotiations with downstream buyers to determine volume, variety, delivery time and other details of the transaction. This pricing gives strong pricing power to the supply side, which makes the price of boron resources closely related to supply and demand. At the same time, online platforms also play a role in the pricing of boron resources. These platforms, such as ECHEMI and Business Society, collate and display seller information to provide buyers with a certain price reference. Although the quotes from these platforms do not directly determine the transaction price, they are of great significance for the transparency of market prices and the efficiency of information transmission.

Boron mineral resources are abundant across the world, but their distribution is extremely uneven. Turkey is the world's largest boron mineral resource holder, and its reserves account for nearly 90% of the world's total reserves. This highly concentrated resource distribution pattern places Turkey in a pivotal position in the global boron resource market. Countries such as the United States, Russia and Chile also have a certain amount of boron mineral resources, but these are comparatively small compared to Turkey's reserves. As the world's fifth-largest boron mineral resource holder, China's reserves only account for about 1.6% of the global total reserves.

In addition, the global supply side of boron resources is highly concentrated. Several international boron resource leaders, such as Etimaden, Rio Tinto and US Borax, account for the majority of the market share. These companies have a strong pricing influence on global boron resource prices, as they control the exploitation and sale of resources. In particular, Etymar, the world's largest boron mine producer, has most of its boron mines exported, which has an important impact on the global boron resource market. Corresponding to the highly concentrated distribution of resources, global boron ore consumption shows characteristics of diversification. Asia and North America are the main regions of global boron ore consumption, with countries such as China, the US, Japan and South Korea having particularly high consumption. In recent years, with the rapid development of new energy batteries, rare earth permanent magnet materials and medicinal glass, the global demand for boron ores has increased significantly (Cheramin et al. 2021). The study of Zhu et al. (2023) shows that the international demand and trade of boron ores are increasing year by year, and the production and trade of certain mineral resources are becoming more and more closely related, and the level of economic development significantly affects the import competition, especially the dominant position of China and the United States in the mineral consumption market. There is a high demand for boron resources in the construction, glass and ceramics industries in these countries. Due to the relatively concentrated supply of boron resources, there is an obvious separation between global boron ore consumption and supply. This separation adds complexity and uncertainty to the global boron resource market.

The global boron ore import and export market is also characterised by concentration. As the world's largest supplier of boron mineral resources, Turkey's exports occupy an important position in the global market. At the same time, the import and export market of China, the world's fifth-largest boron mineral supplier and one of the main boron consumer countries, also has a certain influence in the world. However, due to the high concentration on the boron resource supply side, the global boron ore import and export market faces the challenge of diversified cooperation. The future trend of global boron pricing power will be influenced by a number of factors. The concentration of resource supply is the key factor affecting pricing power. The supply structure of the market may undergo changes as the resources of the dominant supplier countries gradually decrease and other new resources are developed. In addition, changes and technological innovations on the demand side will also affect pricing power, especially growth in emerging applications that may drive up the price of boron resources and expand the market size. The international trade environment is as critical as geopolitics, with protectionism and political tensions likely to increase market instability.

To address these challenges, leading players in the boron mining industry need to cooperate to stabilise market supply, demand and prices. At the same time, governments and enterprises should strengthen cooperation to promote the sustainable development and utilisation of boron resources. Such cooperation is not only conducive to market stability but also important to achieving healthy development.

8.3 Rare Minerals

8.3.1 Chromium Ore

The pricing mechanism of chromium ore is relatively flexible and is mainly determined by market supply and demand conditions. However, this flexibility does not result in a fixed annual or monthly price negotiation mechanism. Instead, pricing power tends to be concentrated in the hands of a few of the world's leading chromium ore producers, such as Glencore and Samarco. These two companies set the base price of international chromium ore through consultation with the trading party. This price has not only become the reference standard for manufacturers to supply and users to purchase but also affects the price trend of the global chrome ore market to a large extent.

The global supply and demand pattern of chromium ore is highly concentrated, mainly in South Africa, Kazakhstan, India, and other countries. The reserves and production of chromium ore in these regions account for the vast majority of the world's total, giving chromium ore producers in these countries an important position regarding global pricing power. The world's largest chromium ore producers, such as

Glencore, Samarco, and Eurasia Resources, have further consolidated their positions in the global chromium ore market through mergers and acquisitions, forming an oligopoly market pattern.

In recent years, the supply and demand relationship of the global chromium ore market has changed significantly. On the one hand, the growth rate of the chromium ore supply has continuously exceeded that of stainless steel production, resulting in the easing of chromium element supply and demand. On the other hand, having been affected by the COVID-19, the global stainless steel market as a whole is weak, as is the demand for chromium ore. These factors have combined to keep chromium ore prices low since 2017. Owing to the combination of supply and demand mismatches, high costs, and declining inventories, chromium ore prices began to rise rapidly in early 2022. However, after June, with the substantial production reduction of stainless steel plants and the weakening demand for ferrochrome, the price of chromium ore fell rapidly. Entering 2023, the chromium ore market as a whole showed a high and volatile trend, and the fundamentals from January to October showed a cumulative gap. However, the sharp increase in imports and port inventories from November to December addressed the supply gap, and the market closed to a tight balance. South Africa's export growth eased supply pressures, but port inventories surged toward the end of the year. On the demand side, the downstream ferrochrome plant continued to increase production, and the actual annual production of ferrochrome increased 13% to about 7.9 million tons. Chromium ore prices remained strong for most of 2023, with the price top essentially flat at a 22-year high, and the overall volatility range narrowed from 2022. In the first half of 2024, although chromium ore imports increased significantly year-on-year, the investment in new downstream ferrochrome capacity was large, resulting in chromium ore supply growth that could not keep pace with the rigid demands of iron mills. As a major exporter of chromium ore, South Africa significantly increased its exports, especially to China, in the first half of 2024. At the same time, domestic high-carbon ferrochrome production remained high in the first half of 2024, further boosting the demand for chromium ore. Chromium ore prices remained firm in the first half of 2024, with a further upward trend.

8.3.2 Gallium Ore

Owing to its relatively small market size, gallium, as a kind of dispersed metal, has not yet formed a mature global gallium trade market and futures market, and its pricing is affected by various factors.

The global gallium pricing mechanism is relatively special and is based primarily on spot and zero-order trading. Because there is no unified futures market, the price of gallium is mainly quoted publicly by the manufacturer every day, and the quotation agency carries out inquiries, calculations, and announcements. China's domestic gallium prices have played a leading role in this process, becoming the benchmark price for global trade. Many well-known quotation institutions, such as the Shanghai Nonferrous Metal Network (SMM) and Metal News (Fastmarkets MB), have released the price information for gallium made in China, and the price of gallium in the Port of Rotterdam in the Netherlands also has a certain influence in some areas. The formation of this pricing mechanism is inseparable from China's position in the global gallium market. As the world's main owner and producer of gallium resources, China has a pivotal position on the supply side. In the past five years, with the depletion of overseas inventories, the impact of domestic supply and prices on the global market has become increasingly obvious. Especially in the two rounds of price increases in 2017 and 2021, the leading role of China's price changes has become increasingly prominent, and the market generally uses China's domestic gallium as a price reference benchmark.

The main products in the global gallium trade can be divided into crude and refined gallium, whose prices are positively correlated with purity. Owing to the increasing requirements of purification technology, the price gap is also rising in a step-like pattern. Based on the average annual prices of the past five years, the price of 6N gallium is about 172 yuan/kg higher than that of 4N gallium, while the price of 7N gallium is about 230 yuan/kg higher than that of 6N gallium. Examining the historical price trend reveals that the global gallium price has experienced three rounds of sharp rises and falls and is currently at a high of nearly 10 years. Since 2005, the price of gallium produced in China has experienced significant fluctuations, but the overall trend is rising. From 2015 to 2024, gallium prices experienced several major fluctuations. In recent years, the price of gallium has experienced significant ups and downs, but on the whole, it has maintained stable growth. In particular, the price of gallium showed a significant rise in 2023; the highest price was 9700 yuan/kg that year, refreshing the high point in several years, with an annual increase of 18.24%. The global gallium trade is mainly spot and zero-order trading, China's domestic gallium prices dominate the global price trend, and China is the world's largest gallium producer and exporter. Its output accounts for more than 97% of the supply side and has a certain pricing influence. Considering the rapid development of global new energy and semiconductor technology, gallium prices may enter an upward period again.

Global gallium resources are relatively scarce and are mainly concentrated in bauxite deposits in China. China has an absolute advantage regarding reserves of gallium resources, accounting for about 68% of the world's total reserves. This resource distribution pattern determines China's dominant position vis-à-vis the global gallium supply. Although the United States, South America, Africa, and Europe also have gallium resources, the recoverable amount is relatively low. Global crude gallium production is growing overall, and China's share in this field is the largest and continues to increase. Over the years, China's crude gallium production has accounted for more than 90% of the world's total, showing the country's strength in global gallium production. While countries such as Germany, Kazakhstan, Hungary, and Ukraine have stopped or restarted gallium production, China's production position remains solid. In terms of refined gallium production, global production has increased overall, and China is also one of the major producers. With the continuous progress of technology and the expansion of production capacity, China's position in the global fine gallium market is also increasing.

The global consumption of gallium is growing rapidly. Gallium also has great potential for future growth. With the rapid development of new energy and semiconductor technologies, the demand for gallium's downstream compound products continues to grow. Especially in the Asia–Pacific region, which is dominated by China, the center of gravity of gallium consumption is shifting to this region. This change in consumption trends has had a significant impact on global gallium pricing. In addition, the concentration of major gallium producers in the world is high, and Chinese enterprises occupy an important position in this regard. Consequently, China's influence on the global gallium market is not only reflected on the supply side but also extended to the consumer side.

China is the world's most important exporter of gallium. Japan, Germany, South Korea, and other major importers are highly dependent on China, and this pattern of trade gives China some pricing influence on the supply side. By controlling export volumes and prices, China can influence the price trend of the global gallium market to a certain extent. However, despite China's significant position in the global gallium market, it faces some challenges. For example, in the production of high-purity and recycled gallium, China has room for improvement. In addition, with the rapid development of global new energy and semiconductor technologies, the demand for gallium's downstream compound products will continue to grow, which may push the price into the upward period again. Therefore, to consolidate its position in the global gallium market, China needs to continue to strengthen its technology research and development and industrial upgrading to improve the quality and added value of gallium products.

8.3.3 Beryllium Ore

Beryllium products trading has not established a unified platform; its pricing model is mainly based on the manufacturer's quotation. Because of beryllium's strategic significance, there is less disclosure of its related information. The quotation of beryllium ore and products mainly depends on the pricing strategy of the manufacturer. Owing to the nature of beryllium, its market applications are mainly concentrated in high-end fields, such as the aerospace and electronics industries; the supply and demand sides are closely combined; and the supply and demand fluctuations are relatively small. Therefore, the price of beryllium ore and beryllium metal is relatively stable, while that of beryllium copper alloy mainly changes with the fluctuation of copper price.

Over the past few years, beryllium prices have experienced certain fluctuations. From 2006 to 2010, affected by the growth of demand in the consumer sector, the price of beryllium in the United States continued to rise. In 2013, beryllium prices fell. In 2014, the price of beryllium metal was about $370/kg. In the Chinese market, the price of Yunnan beryllium ore (Be: 10%) is relatively stable, with an average of about 970 yuan/ton. The price of Shanghai beryllium beads (Be: $\geq$ 99%) varies between 6000 and 7500 yuan/kg. Before 2018, the price of beryllium copper alloy mostly fluctuated between 120,000 and 140,000 yuan/ton. However, in 2012–2013, stimulated by demand, the price rose to 165,000 yuan/ton and then dropped to normal levels. After 2018, beryllium prices showed an upward trend, rising to an all-time high of 175,000 yuan/ton in May 2021, an increase of 20.3% compared with 145,500 yuan/ton in 2018.

In terms of global beryllium resource pricing and market conditions, first, global beryllium resources are relatively concentrated, with Brazil, Russia, and India accounting for more than 60% of the reserves and the United States ranking fourth. Owing to this resource distribution pattern, these countries occupy an important position in the global beryllium market. Of the proven beryllium reserves, 60% of deposits are located in the United States, followed by Brazil, Russia, Kazakhstan, India, China, and Africa. According to the United States Geological Survey (USGS), the global beryllium resource (the amount of metal) is 481,000 tons, with the top six countries accounting for 81.08%. This concentration of resources gives these countries a greater say in global beryllium pricing power. Second, fluctuations in global beryllium production also affect the allocation of pricing power. Affected by the market supply and demand in the application field, beryllium production shows a fluctuating trend. From 1994 to 1998, global beryllium production showed a steady upward trend, but from 1998 to 2002, production declined rapidly. Since 2003, global beryllium production has been stimulated by the increasing demand in the application field, and output has increased year by year. However, since 2015, production has declined owing to lower demand in the energy, medical, and consumer electronics markets. This fluctuation in production makes the pricing of beryllium more complex and uncertain. The world's largest consumers of beryllium are the United States and China. According to the USGS, the United States consumed 202 tons of beryllium products in 2018. The largest segment of beryllium consumption is beryllium copper alloy, which accounts for more than 80% of the market share. Metal beryllium and other beryllium products also occupy a certain market share. Owing to this consumption pattern, the United States has a greater influence on the global beryllium market. The United States controls the main flow of the global beryllium trade. Materion, an American company and one of the largest beryllium manufacturers in the world, has an absolute advantage in production technology and a greater right to speak. Japan's NGK Corporation, the world's largest importer of beryllium oxide, also has advantages in secondary processing technology. This difference in production and processing technology complicates the global beryllium trade pattern.

Faced with the challenge of global beryllium pricing power, governments and enterprises need to adopt active strategies to deal with it. First, strengthening the protection and rational development and utilization of resources is key. By improving the efficiency of resource utilization, promoting technological innovation, and reducing production costs, enterprises can enhance their competitiveness in the global beryllium market. Second, international cooperation should be extended to the sustainable management of beryllium resources, including environmental protection and social responsibility, to enhance the international image and public trust of the entire industry. Corporate cooperation can jointly address global challenges such as climate change and resource depletion, build a more stable global beryllium market, and promote the long-term development of the beryllium industry.

8.3.4 Hafnium Ore

Similar to that of boron resources, the pricing mechanism of hafnium is based primarily on enterprise quotation and negotiation. This is because hafnium is a small metal mineral and its market is mainly spot trading. The spot market for hafnium is based on the European, American, and Asian markets, and price information is regularly published by the London Metal Herald (MB). Hafnium enterprises in China set their prices based on production costs and supply and demand in the international market, with quotation platforms such as Baichuan Yingfu and CBC providing pricing information. This pricing method makes the hafnium price subject to the downstream material supply and demand relationship. Owing to low demand for hafnium in the aerospace industry, the spot supply activity of hafnium has slowed and prices have been relatively stable. However, with the rapid growth in demand for hafnium in the aerospace and semiconductor industries in the past two years, the price of hafnium has shown a rapid upward trend. In particular, the semiconductor industry, one of the main application areas of hafnium, has experienced a surge in demand for it, resulting in an extreme imbalance between supply and demand for hafnium and rising prices.

Global supply and demand for hafnium ore are also relatively concentrated. First, hafnium and zirconium are associated, and the global resources of both are mainly distributed in Australia and South Africa, accounting for 70% of the global total resources. This gives these countries an important position in the global hafnium market. At the same time, the supply side of hafnium is affected by extraction costs and technical limitations; consequently, enterprises with rich zirconium resources and mature zirconium and hafnium separation technology have strong bargaining power. On the supply side, the global production of hafnium is concentrated in France, the United States, China, and Russia. Europe is the largest producing region, accounting for 55% of the share. France's Famatone is the world's largest producer of hafnium, with a 40% market share. This highly concentrated supply pattern gives these countries an important position in regard to global hafnium pricing power. On the demand side, superalloy applications dominate the hafnium market, while the development of artificial intelligence has driven the continued increase in the demand for hafnium from large global memory chip producers. This has led to rapid growth in the demand for hafnium, especially in the semiconductor industry. However, because of the relatively limited supply of hafnium, the imbalance between supply and demand has caused its price to continue to climb.

The global trade pattern of hafnium resources has certain characteristics. Germany, China, and the United States are the main global exporters of hafnium resources, while the United States, Germany, and the United Kingdom are major importers. This trade pattern reflects supply and demand and the geopolitical factors in the global hafnium market. However, with the rapid development of the global hafnium market and the growing demand for hafnium, the challenge of pricing power has become increasingly prominent. First, the imbalance between supply and demand has led to increased price volatility for hafnium. The fact that the supply of hafnium is relatively limited while the demand for it is growing makes its price vulnerable to the market supply and demand relationship. Second, geopolitical factors may also have an impact on hafnium pricing power. For example, certain countries may protect their own interests by controlling the exports of hafnium, thus affecting prices in the global hafnium market. In addition, technological advances and market changes may have an impact on hafnium pricing power. As technology continues to evolve, new application areas may have an impact on the demand for hafnium. At the same time, increased market competition may also lead to fluctuations in hafnium prices.

Looking ahead, the hafnium market will continue to grow, driven by the high-tech industry. In particular, the rapid development of the semiconductor industry will increase the demand for hafnium. Environmental policies and sustainability trends will drive the hafnium industry to improve its production efficiency and environmental standards. Market participants need to address potential risks through supply chain diversification, technological innovation, and sensitive market strategies to ensure the stability and cost-effectiveness of raw material supply.

8.3.5 Antimony Ore

In the global mineral resources market, antimony plays an irreplaceable role in many fields, such as the fire prevention and semiconductor industries, owing to its unique physical and chemical properties. However, the pricing power of antimony ore has experienced a complex evolution from the monopoly of single-head enterprises to multipolarization and market-oriented pricing.

In the early days, the global antimony market was dominated by a few large enterprises in the United States, the United Kingdom, Germany, and other countries, and they negotiated the price of antimony ore and its products through long-term cooperation or spot transactions. However, with the expansion of market size and the development of global trade, this situation has been gradually changing. In the 1980s, major exchanges began to launch spot and futures contracts for antimony ore to stabilize its price through futures trading. However, owing to market size restrictions and inactive trading, antimony futures trading was difficult to maintain for a long time and was eventually canceled. Since then, the spot market and exchange quotation have become the main references for antimony prices, and the Yangtze River nonferrous antimony quotation and the European strategic small metal antimony quotation have become important global reference indicators.

China is rich in antimony deposits and has favorable metallogenic conditions, which are concentrated in Hunan, Guangxi, Guizhou, and other places. Among them, the tin mine in Xinhua County, Hunan Province, has the largest antimony deposit, known as the "world antimony capital." However, with the extension of China's antimony mining history and the increased production year by year, China's antimony reserves have declined year by year, from 950,000 tons in 2010 to 480,000 tons in 2020, a decrease of 49%. In 2023, China's antimony ore reserves rebounded, reaching 640,000 tons, accounting for 29.48% of the global antimony ore reserves, an increase of 16.60%. At the same time, China's antimony mine production has also decreased year by year, from a high of 180,000 tons in 2008 to 59,100 tons in 2022, representing a huge decline. In 2023, it rebounded to 60,100 tons, and the domestic supply of antimony concentrate is currently basically maintained at about 60,000 metal tons. It is expected that against the backdrop of the decline of domestic major mine reserves and the reduction of ore grade, domestic antimony mine production will show a steady downward trend. Despite this, China remains the world's largest producer and supplier of antimony. China's antimony industry chain is perfect; the country has the leading smelting technology; and antimony concentrate imports are increasing year by year, rendering China as the world's largest antimony ore importer. In addition, China's antimony industry head enterprises continue to improve the antimony industry chain, enhance industry influence, and have a strong influence on global antimony product prices.

Today, global antimony mining pricing power continues to face a series of challenges. First, global antimony resources are unevenly distributed, and the reserves are low but are consumed year by year, resulting in the limited pricing advantages of resource countries. Second, global antimony resource production is increasingly multipolar, and the proportion of production in emerging antimony resource countries, such as Russia and Kyrgyzstan, is rising year by year, gradually increasing the influence on the price of antimony ore. In addition, international trade policies, exchange rate fluctuations, and international competition will also have an impact on the international pricing of antimony ore.

As far as China is concerned, the bargaining basis in the global antimony ore market is gradually weakening. This may lead to a reduction in China's say in global antimony ore pricing, which will affect the country's economic interests. Second, China's antimony ore production has declined year by year, weakening the country's bargaining power in the global antimony ore market. This may make it difficult for China to effectively safeguard its own interests in the face of global antimony price fluctuations. In addition, China's antimony resources industry is relatively developed, there are many small and medium-sized enterprises, and market competition is fierce. As a result, China's antimony resource export enterprises have a low concentration, bargaining power and export scale do not match, and it is difficult to form a joint force to maintain China's pricing power in the global antimony ore market.

In the future, the global antimony mining pricing power will show the following trends. First, the market-based pricing mechanism will continue to be improved. With the development of global trade and the maturity of market mechanism, the pricing of antimony ore will be more dependent on market supply and demand and exchange quotation, and the government pricing mechanism will gradually withdraw from the historical stage. Second, the multipolar pricing pattern will become more obvious. With the rise of new antimony resource countries and the diversification of global trade, the pricing power of antimony ore will no longer be dominated by a single country but, rather, by a multipolar pattern. This will make the price of antimony more stable and transparent. Third, environmental protection and sustainable development will be important considerations. With the improvement of global environmental awareness and the requirement of sustainable development, the antimony mine pricing mechanism will be more focused on resource protection and sustainable development. This will put forward higher requirements for the mining, processing, and trading of antimony ore.

8.3.6 Tantalum Ore

In the global rare metals market, tantalum ore, with its unique physical properties and wide application fields, has become an indispensable material in electronics, aerospace, and other industries. However, with the constant changes in market supply and demand, the global tantalum ore pricing power also presents a series of complex and interesting patterns.

The formation of tantalum ore price mainly depends on the negotiation between buyers and sellers, showing a trend of periodic fluctuation and rise. This trend is influenced by multiple factors, such as market supply and demand instability, fluctuations in the economic cycle, the rise and fall of the consumer electronics industry, and geopolitical risks. Since 2005, tantalum ore prices have experienced three peak cycles, and by the end of 2023, the price stabilized at $66.99/pound, up 67.5% from 2005. Especially in recent years, with the rapid development of 5G communication, artificial intelligence, commercial aerospace, and other fields, the demand for tantalum ore has continued to grow, further promoting the rise in prices.

The world's tantalum reserves are highly concentrated in Australia, Brazil, China, and a few other countries. According to the USGS, there were more than 319,000 tons of tantalum deposits in the world in 2022, with Australia, Brazil, and China accounting for the main share. The global production distribution of tantalum is relatively concentrated, and the main production area has been transferred from Australia to African countries. In 2022, the global production of tantalum ore was about 2000 tons, of which Democratic Republic of the Congo, Brazil, Rwanda, and Nigeria together accounted for about 85%. This change is mainly due to the bankruptcy of Australia's largest tantalum supplier and the lower mining costs in African countries. Tantalum consumption is mainly concentrated in tantalum capacitors, super alloys, and other fields, accounting for about 52% in total. In terms of geographical distribution, global tantalum consumers are highly concentrated, with the United States and China accounting for 71.65% of the world's total. The formation of this pattern is mainly driven by the strong demands of the two countries in the fields of electronics, aerospace, and so on. China is rich in tantalum mineral resources. According to USGS data for 2022, China's tantalum mineral reserves are as high as 180,000 tons, accounting for 56.4% of the world's statistical reserves. However, despite its abundant reserves, China's tantalum production is relatively small, accounting for only 3.9% of the global total. This is mainly due to the small scale of tantalum deposits in

China, low ore grade, fine distribution particle size and dispersion, and multi-metal associated factors leading to difficult mining and low recovery.

The trade pattern of the tantalum industry chain is relatively concentrated, which is mainly affected by many links, such as upstream raw material supply, midstream smelting and processing, and downstream product manufacturing. In the upstream link, tantalum mines in Africa and Brazil are mainly transported to the United States, Germany, China, and other countries for wet and fire smelting to produce tantalum powder and other primary products. In the middle stream, primary products such as tantalum powder are further processed into downstream products, such as tantalum capacitors, tantalum targets, and medical devices, by the United States and Japan as well as European and other countries. In this process, the United States, with its leading position in the manufacturing of downstream products, has a strong influence on the trade and price of tantalum. Because China is one of the most important tantalum primary product smelting markets in the world, it has a certain influence on the price of tantalum primary products. China's tantalum consumption continues to grow, with an external dependence of more than 80%. Imported tantalum concentrate is mainly used for the production of tantalum powder, tantalum wire, and other primary products. In the field of tantalum primary products, the global market share of tantalum powder and tantalum wire produced in China exceeds 30% and 60%, respectively, showing China's important position in the global tantalum primary product market. However, in the downstream tantalum product market, especially the high-end tantalum capacitor market, China's influence is relatively limited. China accounts for about 12% of the world's tantalum capacitor production. The gap with foreign countries is gradually narrowing, but the self-sufficiency rate still needs to be improved. In addition, the average unit price of China's tantalum capacitor imports far exceeds that of exports, reflecting the shortcomings of China's tantalum capacitors regarding quality, technology, and other aspects.

In the future, the global tantalum ore pricing power will continue to be affected by multiple factors. On the one hand, with the acceleration of new energy transformation and the development of new consumer electronic products, such as electric vehicles, the demand for tantalum ore will continue to grow. On the other hand, geopolitical risks, environmental protection policies, and other factors may also have a greater impact on the supply and price of tantalum ore.

8.3.7 Bismuth Ore

In the global rare metals market, bismuth occupies an indispensable position in several industrial sectors owing to its unique physical and chemical properties. However, compared with bismuth's widespread market application, its pricing mechanism and market dynamics are relatively complex.

The global pricing mechanism of bismuth ore is dominated by the manufacturer's agreement quotation, supplemented by auction bidding. At present, the bismuth market is relatively small, and a mature global bismuth futures market has not yet formed. The daily prices of bismuth ingot and bismuth oxide released by the SMM and Shanghai Steel Union provide an important reference for the industry. Although bismuth futures were listed on the Fanya Nonferrous Metals Exchange in 2013, because of excessive speculation and market volatility, the exchange announced a restructuring in 2015, resulting in the cessation of bismuth futures trading. In recent years, although the bismuth ingot futures contract has been listed and traded in the Wuxi Stainless Steel Electronic Trading Center, the trading volume is small, and a global influence has not yet formed.

The global bismuth ore price has experienced significant fluctuations over the past few decades. From 2000 to 2005, bismuth prices were generally stable. However, between 2006 and 2007, the price of bismuth rose sharply to more than $31,000/ton. This occurred because the restructuring of bismuth production enterprises in China and the elimination of outdated production capacity resulted in a global shortage of bismuth supply. Subsequently, the price entered a high-shock stage, but the rebound peak did not exceed the previous high. In 2014, the global supply of bismuth increased, and in 2016, its price fell from $24,900/ton to $9990/ton, reflecting a return to the 2006 price level. Since then, the price continued to fall in shock, to $6000/ton in 2020, a stage low in more than 20 years. In the past two years, the price of bismuth has bottomed out and rebounded slightly, stabilizing at more than $8000/ton, but overall, it is still at a relatively low historical level. Throughout 2023, the price of bismuth showed an upward trend, with the highest point appearing in late September and early October at $8785/ton and the lowest point appearing in January at $6710/ton. The overall market forecast for the bismuth price trend indicates that bismuth prices are still at historical lows, but they are already high compared to previous years. Because of the shortage of raw materials, in the long term, the price of bismuth may continue to rise, hitting to a new high in 2024; however, in the short term, it will face a challenge because of the sale of profitable resources in the market.

The global reserves of bismuth are mainly concentrated in Asia, which accounts for about 79%. China, Vietnam, Mexico, Bolivia, and Canada are the main countries that distribute bismuth resources. Global bismuth production continues to grow, and the production center is gradually shifting to China. In recent years, China's annual output of bismuth has remained at about 20,000 tons, accounting for the proportion of global total output, which has increased year by year. At the same time, owing to resource, environmental protection, and cost factors, bismuth production in traditional bismuth-producing countries, such as Peru, Mexico, and Bolivia, has been reduced significantly. In addition, because of the low industrial concentration of bismuth production enterprises in China, the bargaining power of bismuth producers is relatively weak. Global bismuth consumption continues to increase slightly, mainly in Europe, the United States, China, and Japan. In terms of use structure, the chemical industry is the main area of global bismuth consumption, but the consumption structure varies from country to country. Downstream consumers have relatively strong bargaining power in the bismuth ore market, especially in high-end applications. Traders, the countries that import and export global bismuth products, are relatively concentrated, and the import and export countries are relatively separated. China is the world's largest exporter of bismuth products, while the United States, Germany, Belgium, and Japan are major importers. In addition, the United States, Europe, and other countries export bismuth chemicals, bismuth alloys, and other high value-added bismuth products. Bismuth concentrate imports are highly dependent on China, but the degree of dependence is gradually being reduced.

China has the largest reserves of bismuth in the world, and the bismuth mineral resources are mainly concentrated in the Hunan and Jiangxi provinces. The bismuth mineral resource endowment in these areas is abundant, which provides a solid foundation for the development of China's bismuth industry. China is the world's largest bismuth producer and exporter. Its bismuth output accounts for about 80% of the world's total output, and exports account for more than 60% of the world's total exports.

Although China has an important position in the global bismuth market and outputs a vast amount of bismuth, because of the large number of production enterprises, generally small scale, and different technical levels, the market concentration is insufficient, which affects the effective influence of China in the pricing power of bismuth mines. In addition, China's bismuth ore is mainly used as a by-product of other metal smelting, and its pricing is often affected by that of the main metal, which is difficult to price independently. In addition, China's bismuth consumption market is dominated by traditional fields, such as the bismuth oxide industry and pharmaceutical industry, and the consumption structure is relatively undiversified. At the same time, the overall growth of China's bismuth consumption is slow, mainly low-end products are consumed, and high-end application field demand support is lacking. These factors limit China's bargaining power in terms of its pricing power for bismuth mines. Second, although China is the world's largest exporter of bismuth products, owing to the export products mainly low-end bismuth ingot, bismuth oxide, low added value, and oversupply in the global market, China is in a passive position vis-à-vis global bismuth ore pricing. In addition, China's high import dependence on high value-added bismuth products has also weakened its bargaining power in regard to global bismuth ore pricing.

8.3.8 Germanium Ore

The pricing power of germanium, a strategic rare metal, has an important impact on the global market. At present, global germanium ore pricing is mainly in the spot market, which reflects the demand–supply relationship of the germanium market, resource distribution, production and consumption pattern, and other factors.

The global germanium ore pricing power is mainly concentrated in China and Europe, two price centers. Because germanium has not yet formed a global futures market, its pricing is based on spot market prices and is regularly published by institutions such as the London Metal Herald (MB), SMM, and Antayke. This pricing mechanism reflects the change of the supply and demand relationship in the germanium market, and it is also affected by global economic situation, policy environment, geopolitics, and other factors. From the perspective of global distribution, countries such as the United States, China, and Russia are the main owners of global germanium resources, and their reserves account for more than 90% of the global total. Among them, China, as the largest germanium producer, accounts for about 68.5% of the global total, which has a significant impact on the global germanium market. However, although China has rich germanium resources and produces vast amounts of the metal, it has had insufficient influence on global germanium ore pricing power.

China's rich germanium resources are mainly concentrated in the Inner Mongolia, Yunnan, and Guangxi provinces. Those in Inner Mongolia are particularly prominent, accounting for 70.5% of the national reserves. Germanium resources in China are mainly associated with coal mines and carbonate lead–zinc deposits, which gives the country a natural resource advantage in the global germanium market. China is not only a big country with germanium resources but also the world's largest germanium producer. Since the industrial integration, the concentration of germanium production in China has gradually increased, forming four major producing areas: Yunnan, Guangdong, Jiangsu, and Hunan. Germanium production enterprises in these regions have improved production efficiency and product quality through asset reorganization and technological transformation, providing a stable supply for the global germanium market. China's germanium consumption is mainly concentrated in the infrared, optic fiber, semiconductor, and photovoltaic fields, and the future growth trend is obvious. With the increase in demand for military information construction, 5G network construction, and aerospace development, China's germanium consumption will continue to grow, further consolidating the country's position in the global germanium market. China is also the world's largest exporter of germanium products, which it mainly exports to Germany, Russia, Belgium, and the United States, among other countries. Of these, the United States is highly dependent on China's germanium products; however, with the growth of the former's domestic processing capacity, its dependence on China's germanium resources may be reduced, which will create certain challenges for China's germanium export market.

The future global germanium ore pricing mechanism will be more diversified. In addition to spot market prices, futures markets and electronic trading platforms, will also become important channels for germanium pricing. This will help better reflect the market supply and demand relationship and improve the transparency and fairness of germanium pricing. With the continuous development of the global economy and the sustained progress of science and technology, the application field of germanium continues to expand, demand is growing steadily, and the price marketization degree of global germanium ore will continue to increase.

Despite the positive trend in global germanium pricing power, some challenges remain. First, the supply and demand relationship of the global germanium market is affected by various factors, such as the policy environment, geopolitics, and economic situation. The uncertainty of these factors may lead to large fluctuations in germanium prices and affect the stability of global germanium pricing power. Second, with the continuous development of the global germanium market, market competition will be more intense. To compete for market share and pricing power, countries and enterprises will strengthen competition in technology research and development, reduce costs, and improve product quality. This will make global germanium ore pricing power more complex and changeable. Third, with the continuous progress of science and technology, some new materials and technologies continue to emerge and may replace the application of germanium in some fields. This will reduce germanium demand and prices, posing a challenge for global germanium ore pricing power.

Although China has significant advantages in the global germanium market, it faces a series of challenges regarding the pricing power of germanium ore. First, China has not carried out a systematic evaluation of its germanium resources, and it has been found that resource reserves may not fully reflect the national resource situation, which has affected China's pricing power in the global germanium market to a certain extent. Second, although the concentration of China's germanium production industry has gradually increased, the market order still needs to be further standardized. Some small enterprises have disorderly competition and waste of resources, which is not conducive to China establishing a positive image in the global germanium market trial chain production from smelting to component products, and the high-end technology and component market is still in the hands of Western countries. This makes China's bargaining power in the global germanium industry chain limited to a certain extent.

8.3.9 Rare Earths

Because of their unique physical and chemical properties, rare earth elements, which are kinds of metal elements with relatively limited distribution in nature, have a wide range of applications in the military, new energy, new materials, and other fields. With the development of the global economy and the progress of science and technology, the demand for rare earth is growing daily, and its price formation mechanism is becoming increasingly complex.

In recent years, the global rare earth market has shown a steady growth trend. With the development of high-tech industries, such as new energy and new materials, the demand for rare earths is increasing. At the same time, governments have begun to attach importance to the strategic value of rare earths and to strengthen the protection and development of rare earth resources. These factors have contributed to the boom in the global rare earth market. As the world's largest rare earth producer and exporter, China's rare earth market occupies an important position in the global market. In recent years, the Chinese government has strengthened the regulation and management of the rare earth industry and promoted the transformation and upgrading of the rare earth industry. At the same time, Chinese rare earth enterprises have also strengthened their technological research and development and innovation capabilities and have improved the quality and added value of rare earth products. All these factors have provided strong support for the development of China's rare earth market.

Supply and demand are the core factors affecting global rare earth prices. Demand for rare earths mainly comes from high-tech industries, such as electronics, magnetic materials, and ceramics. As the global economy grows and technology improves, demand for rare earths increases, prices rise, and vice versa.

Second, the production cost of rare earth includes many supply chain links, such as mining, processing, and transportation. Because of the uneven distribution of rare earth minerals and the varying mining conditions, there are vast differences in production costs. Production costs directly affect the supply and price of rare earths, which are global commodities whose prices are influenced by international trade. Political, economic, cultural, and other factors in international trade will have an impact on rare earth prices. For example, trade wars and tariff barriers will affect international trade and the price of rare earths. Guo and Wang (2024) found that the dependence network of rare earth trade is expanding, and trade is becoming more direct. China occupies an important position in the midstream of the industrial chain, while the United States maintains a leading position in the downstream, which shows that there is a clear difference in the degree of dependence between different central countries.

With the rapid growth of the global economy and the rapid development of science and technology between 2000 and 2010, the demand for rare earths gradually increased. In particular, the demand in high-tech fields, such as electronics and new energy, has shown explosive growth. At the same time, because China is the world's largest rare earth producer, its rare earth export policy has had an important impact on global rare earth prices. Against this backdrop, rare earth prices rose steadily and reached an all-time high around 2010. However, after 2011, the global rare earth market began to adjust. On the one hand, the global economic slowdown has inhibited the demand for rare earths to a certain extent. On the other hand, the Chinese government has strengthened the regulation and management of the rare earth industry, restricting the mining and export of rare earth. Combined, these factors caused rare earth prices to fall sharply and reach historic lows around 2015. In 2016, rare earth prices began to gradually recover, mainly benefiting from the gradual recovery of the global economy; the Chinese government's regulation and its transformation and upgrading of the rare earth industry; and the rapid development of high-tech industries, such as new energy and new materials. Since the beginning of 2018, rare earth prices have shown an upward trend, which is mainly driven by the demand side, especially the development of new energy vehicles and the promotion of global carbon–neutral policies, resulting in rapid growth in demand for rare earth. In 2020, the rising trend of rare earth prices became more obvious; in particular, the prices of elements such as praseodymium, neodymium, terbium, and holmium related to permanent magnet materials have risen sharply. In April 2020, the rare earth price index was less than 130 points, but by February 24, 2022, the index had tripled to 430.97 points, hitting a record high. During this period, the rise in rare earth prices reflected not only the tension between supply and demand but also the market's revaluation of rare earth as a strategic resource. In March 2022, rare earth prices retreated after the Ministry of Industry and Information Technology interviewed key enterprises. The prices then entered a technical downward channel. In the second half of 2022, owing to the downward pressure of the macro economy, the end demand for rare earth permanent magnet materials, such as downstream wind power, began weakening. This caused the price of rare earth to continue to fall with no sign of recovery in sight. In 2023, the overall demand of the rare earth industry was poor, and the price reflected a high-opening and low-moving trend. In particular, the market price of light rare earths fell sharply; for example, at the beginning of the year, neodymium oxide was priced at 770,000 yuan/ton, and the price at the end of the year was 447,500 yuan/ton, representing a decline of 41.88% for the year. Similarly, the price of neodymium metal was 952,500 yuan/ton at the beginning of the year and 567,500 yuan/ton at the end of the year, indicating a decline of 40.42%.

A series of problems in the pricing of rare earth prices persists at this stage. First, rare earth prices are affected by a variety of factors and fluctuate significantly. Such price fluctuations bring greater risks to rare earth producers and consumers. To reduce these risks, rare earth producers and consumers need to strengthen their research and analysis of the market and formulate reasonable production and consumption strategies. Second, because of the high price of rare earth, some regions and enterprises excessively exploit and waste rare earth resources; this will not only destroy the ecological environment but also reduce the sustainable use of rare earth resources. Therefore, the government needs to strengthen the protection and management of rare earth resources to promote the sustainable development of the rare earth industry. Third, the current rare earth industry chain is not perfect; there are some weak links. For example, rare earth smelting and processing technology is relatively backward, and the added value of rare earth products is not high. Rare earth recycling and utilization technology is not sufficiently mature, leading to, among other problems, the waste of rare earth resources. To solve these problems, the government and enterprises need to strengthen their technology research and development and innovation capabilities and promote the improvement and development of the rare earth industry chain.

8.4 Energy Minerals

8.4.1 Oil

The history of the oil pricing system dates back to 1859, when industrialization and the invention of the internal combustion engine led to a vast increase in oil demand. Before the 1970s, large multinational companies dominated the pricing of crude oil. However, after the Fourth Middle East War in 1973, OPEC began to set a unified price and took control of the oil market. Since the mid-1980s, with the development of the spot market, international oil pricing has entered a period dominated by exchanges, in which WTI and Brent crude oil prices have become the two most important pricing benchmarks in the global oil market. In the 1990s, oil trade began to use formula settlement, the two parties to the contract based on a variety of crude oil price formula calculations, to determine the final transaction price. This process reflects the historical evolution of the oil pricing system, which is influenced by a variety of factors, such as geopolitics and technological developments. Over time, the participants in the oil market have gradually changed from large oil companies to OPEC to futures markets and formula settlements, which reflects the changes in the market structure and the continuous improvement of the oil pricing system.

The oil pricing mechanism in inland China is different from that in the international market. China's refined oil price adjustment mechanism was adjusted in 2013 and 2016, setting a price adjustment range, changing the price adjustment frequency to 10 working days, and stipulating that no adjustment will be made when the price adjustment range is below 50 yuan/ton, and it will be included in the next price adjustment. However, this mechanism still has problems such as the amplification of market price adjustment expectations, the intensification of speculative hoarding and arbitrage, the lagging price adjustment, and the inability to accurately respond to market supply and demand, resulting in the phenomenon of oil prices rising more and falling less.

Although China's oil pricing mechanism has made progress in market-oriented reform, it still faces several problems. First, there is a lag in the adjustment of domestic oil prices, and the synchronization of international oil prices is insufficient, resulting in prices that cannot immediately reflect changes in market supply and demand. Second, the transparency of the price adjustment mechanism needs to be improved, and the public has limited understanding of the specific calculation methods and operational details of the price adjustment. In addition, the current price adjustment cycle and range limits may cause price fluctuations to be inflexible and unable to respond to market changes in a timely manner. The marketization degree of domestic oil prices is still limited, affected by the benefit pattern of the existing oil industry chain and the competition situation of the downstream market. The setting of the price control range limits the market fluctuation of price to a certain extent. At the same time, tax and subsidy policies may affect the market formation of domestic oil prices when international oil prices fluctuate. To deal with these problems, the reform needs to further shorten the price adjustment cycle, improve the transparency of the mechanism, and gradually open the price of refined oil products to realize the decisive role of the market in the allocation of resources.

8.4.2 Natural Gas

The evolution of the natural gas pricing mechanism is mainly divided into three stages. Initially, gas pricing was based on a regulated "cost plus" model. In the 1970s, as the oil and gas market developed, pricing began to be linked to the price of oil. By the mid-1980s, the North American market gradually developed a market pricing mechanism based on Henry Center/New York Mercantile Exchange spot and futures prices, which had a profound impact on global natural gas pricing.

The global gas market shows a clear trend of resource and production concentration, with Russia becoming the largest resource holder with a 20% share, followed by Iran and Qatar. In 2020, global gas production fell slightly to 3.85 trillion cubic meters, with the United States leading the way at 23.4%, followed by Russia and Iran at 16.6% and 6.5%, respectively. In terms of exports, Australia, Qatar, and the United States, as the top three exporters of Liquefied natural gas (LNG) in the world, have jointly shaped the supply pattern of the international market. At the same time, the United States, Russia, and China are the leaders in global gas consumption, while China, Japan, and South Korea constitute the bulk of global LNG imports, accounting for 24.33%, 20.91%, and 11.33% of global imports, respectively, showing the importance of the Asia–Pacific region in global gas demand. Nevertheless, China, Japan, and South Korea have relatively little influence on international gas pricing, while major producers, such as the United States and Russia, have a larger market say. This market situation highlights the high concentration of natural gas resources and production, as well as the wide distribution on the demand side, and points to the challenges that the major demand countries face in increasing their influence in the international market.

Global gas pricing is affected by extreme weather and geopolitical conflicts. Frequent extreme weather events lead to high volatility in energy demand, which affects natural gas prices. Geopolitical conflicts, such as that between Russia and Ukraine, also have a significant impact on gas prices, resulting in sharp fluctuations in European gas prices.

China's natural gas pricing mechanism differs from that of the international market. The price of natural gas in China is mainly guided and regulated by the government. Historically, China's natural gas price formation mechanism has experienced the evolution from a highly centralized, government pricing, dual-track price system to a government-guided price. At present, China's natural gas pricing mainly adopts the "cost plus" method; the ex-factory production cost plus reasonable profits constitute the cost price. The upstream price is set by the National Development and Reform Commission, and the downstream sales price is set by the Local Development and Reform Commission according to local conditions. Relevant studies have shown that the current natural gas benchmark gate price mechanism is generally in line with the natural gas market structure and actual supply and demand but that it should be improved. These studies have also shown that market-oriented reform—that is, the current natural gas pricing mechanism linked to oil prices—should be the first goal of price mechanism reform and that the formation mechanism of gas competition price should be the ultimate goal model of price mechanism development. At present, China's natural gas electronic trading platforms are the Shanghai Petroleum Exchange and the Chongqing Oil and Gas Trading Center, because their price indexes is not based on the real-time balance of a trading hub, resulting in limited international influence.

8.4.3 Coal

The global coal pricing mechanism is complex and diversified, mainly including long-term agreement price and futures market price benchmarks. The long-term agreement price is the purchase and sale method agreed upon by the supply and demand parties within a certain execution period, with a clear quantity and price. As a benchmark, the futures market price plays an important role in the reference of the spot price index and long-term contract. Coal price indexes, such as the BJ index and general index, provide price references for spot, long-term, and futures contracts. The coal futures contract originated from the price index and has a strong guiding effect on the market price and the future supply and demand relationship.

Global coal prices are diverse, forming multiple price centers around major producing areas and ports. These price centers include ARA in Northwest Europe, Newcastle in Australia, Richard Bay in South Africa, Indonesia, China, and the United States. Since the events in Ukraine, the price gap between the different centers has widened considerably. In Australia, for example, coal prices continued to rise rapidly owing to insufficient coal supply, reaching a record high of $439.43/ton in October 2022, far exceeding coal prices in other regions during the same period. The relationship between supply and demand is the decisive factor in the movement of global coal prices. The supply and demand situation in the global coal market is affected by a variety of factors, including capacity, policy, and weather. For example, China's "overcapacity reduction" policy, coal import controls, and coal price intervention measures have had a significant impact on global coal prices.

The world is rich in coal resources, and the focus of production has gradually shifted to the Asia–Pacific region, which is dominated by China. However, the concentration of global coal producers and projects is not high, and although Chinese enterprises have a certain influence, they are still weak in regard to the pricing rights of the leading enterprises. In 2020, three of the world's top 10 coal producers were Chinese, but the total capacity of the top 10 companies accounted for only 21% of global production. Global coal consumption remains high, with a high degree of concentration, and the focus of consumption has gradually shifted to the Asia–Pacific region, which is dominated by China. This gives China strong bargaining power on the coal consumption end. However, while the overall growth of global coal trade volume, import, and export at both ends of the concentration is also high, trade prices are vulnerable to the geopolitical situation. For example, the Ukraine incident exacerbated the global coal supply and demand tension, resulting in a sharp increase in the price of imported coal. In addition, the global coal supply and demand pattern and elasticity differences also have a significant impact on prices. The uneven distribution of resources and the long-term separation of supply and demand can easily cause energy security and a wide range of price fluctuations. The contraction of global coal production and the inelasticity of supply make the supply and demand pattern tighter and the price rise expectation stronger.

In the context of global "dual carbon," the environmental protection policies introduced by various countries have led to changes in the pattern of coal consumption and the energy consumption structure, which have a greater impact on the supply and demand for coal and on its price. For example, some countries reduce coal consumption to reduce carbon emissions and develop renewable energy sources, which will have a profound impact on the global coal market.

In the future, global coal pricing power will be influenced by many factors. On the one hand, with the transformation of the global energy structure and the implementation of environmental protection policies, coal consumption may gradually decrease, which will affect the supply and demand relationship and price trend of the coal market. On the other hand, changes in the geopolitical and trade landscapes could also have an important impact on coal pricing. For example, regional conflicts and trade frictions can lead to coal supply disruptions or the strengthening of trade barriers, thereby affecting coal prices. At the same time, technological progress and innovation will also have an impact on global coal pricing power. For example, the development and application of clean coal utilization technologies may improve the utilization efficiency and environmental performance of coal, thus enhancing its competitiveness in the energy market. In addition, the emergence of new pricing mechanisms and trading platforms may also change the global coal pricing power landscape.

8.5 Conclusion

In conclusion, this chapter categorizes minerals into four types—common industrial metals, nonmetallic minerals, rare minerals, and energy minerals—and conducts an in-depth analysis of the pricing mechanisms for 25 types of minerals. This classification includes nine common industrial metals, such as manganese, iron, and copper; four nonmetallic minerals, including phosphorus and fluorite; nine rare minerals, such as chromium, gallium, and beryllium; and three energy minerals, including petroleum, natural gas, and coal. The article meticulously discusses and analyzes the pricing mechanisms of various minerals from multiple perspectives, including historical evolution, trading policies, market behaviors, and dynamics. Furthermore, the chapter explores the challenges and issues related to pricing power in the context of China's current situation, emphasizing the need for strategic approaches to ensure sustainable management and competitive positioning in the global mineral market.

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Chapter 9
The Determinants and Volatility of Prices in the Energy and Critical Mineral Markets

Yiming Chen and Jingyu Li

Abstract As a vital material foundation for global economic development, the fluctuation of mineral resource prices has a profound impact on the economies, industrial production, and international relations of various countries. In recent years, with the rapid development of the global economy and the intensification of resource consumption, the instability of mineral prices has become increasingly apparent. Therefore, gaining an in-depth understanding of the complex factors affecting mineral prices is crucial for resource countries, consumer countries, and global market participants alike. This chapter begins by analyzing the factors influencing mineral prices from three aspects: market factors, geopolitical risks, and social impacts. Market factors include supply and demand relationships, competitiveness of market structure, transaction methods, and market dynamics. Social impacts encompass market participants' expectations, financial market trends, investor behavior, and the need for sustainable development. Furthermore, this chapter utilizes historical spot price data for various minerals, combined with significant market events, to provide a detailed descriptive and statistical analysis of the trends and fluctuations in mineral prices, offering a reference for policy-making and market participants' decision-making.

Keywords Mineral prices · Influencing factors · Volatility

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9.1 Factors Affecting Energy and Mineral Prices

Critical minerals such as lithium, cobalt, nickel and rare earth metals are critical to the development of clean energy technologies, electronics, and the defense and space industries, among others (Considine et al. 2023). The price formation mechanism in the global mineral trade is a complex and diversified process, which is affected by many factors, including market supply and demand relationships, market participant expectations, geopolitical risks, market competition, financial market and investor behavior, transaction mode and market structure, and sustainable development requirements (Zhu et al. 2023).

9.1.1 Market Factors

Supply and Demand Relationship

The supply and demand relationship is one of the core factors that determine the price of commodities, and it plays an important role in the global mineral trade. Changes in the supply–demand relationship can directly affect mineral prices and lead to price fluctuations. An increase in supply or a decrease in demand may cause prices to fall. Conversely, a decrease in supply or an increase in demand may cause prices to rise. A variety of factors, including global economic growth, industrial demand, and policy changes, influence the supply and demand relationship.

The impact of global economic growth on mineral trading can be seen in the case of copper, where it has a direct impact on the price of copper. Copper in an important base metal, which is widely used in construction, power transmission, automobile manufacturing, and other fields. When the global economy is growing strongly, demand by various industries for copper increases. On the other hand, if the global economy slows or enters a recession, industrial demand decreases, leading to imbalance in supply and demand, with a resulting fall in the price of copper. During the 2008 global financial crisis, a severe recession caused demand for copper to fall in several industries, and the price of copper plummeted. According to previous research, the relationship between supply and demand ultimately determines long-terms trends in oil prices, including price fluctuations. The latter can be explained by the oil market's dependency on supply from oil-producing countries (Smith 2005; Fattouh 2010; Schmidbauer and Rösch 2012).

Competition

Competition in the global mineral trade market has an important influence on energy prices. Market participants compete for orders and market share, thereby directly or indirectly influencing prices. Competition between countries and companies often revolves around product quality, delivery speed, supply stability, and price competitiveness. Countries, companies, and market participants compete for market share, thereby directly or indirectly influencing prices. Competition often centers on product quality, delivery speed, supply stability, and price competitiveness, as discussed below.

One obvious competitive strategy to attract buyers is to offer higher quality products. Mineral ore purity, content, and chemical composition, as well as other factors, determine mineral ore quality. For example, iron ore produced by different countries and sold by different companies may differ in its ore content and level of impurities.

Higher quality iron ore is preferred by manufacturers because it can be used to make better quality steel products. Thus, buyers favor higher quality iron ore, and suppliers increase their competitiveness by selling higher quality iron ore at higher prices. Timely delivery is crucial to production operations, and suppliers that can provide fast and reliable delivery services may gain a competitive advantage. In terms of supply stability, in the past, China monopolized the supply of rare earth minerals and gained market share due to its fast delivery and reliability of supply. However, in recent years, some countries have begun to increase production and supply of rare earth minerals, thus breaking China's monopoly, providing more options and driving down prices. In terms of price competitiveness, suppliers may cut prices to attract buyers and gain a foothold in the market. However, this strategy can lead to price wars, which in turn erodes profit margins as a whole in the industry. Therefore, suppliers need to find a balance between price advantage and profitability.

South Africa is one of the world's largest gold producers. A decline in its gold production in recent years has allowed other gold-producing countries, such as China, Russia, and Australia, to gradually increase their market share. The resulting competition has led to changes in global gold supply and the gold trading market and has had a significant impact on gold prices. For example, China has increased its gold reserves, which has further pushed up global gold prices. Market competition can also result in cooperation, with some countries and companies choosing to enhance their competitiveness by forming supply chain partnerships. Through collaboration, they can share resources, reduce costs, and provide better delivery and service.

In short, competition in the global mineral trade market has an important impact on price formation. Market players compete for market share by offering high-quality products, fast and reliable delivery, and competitive prices. By employing a range of strategies, market participants directly or indirectly influence mineral trade prices.

Transaction Methods and Market Structure

Trading methods and market structures affect the behavior of market participants and transaction costs and thus directly or indirectly affect mineral trade prices. Trading methods include spot trading, futures trading, and peer-to-peer trading. As a direct way of physical commodity trading between buyers and sellers, spot trading can respond quickly to changes in market demand with its rapidity and flexibility. However, due to the lack of long-term planning and supply stability, spot trading can lead to large price fluctuations. Futures trading takes the form of forward contracts that allow buyers and sellers to deliver a commodity at an agreed price at a predetermined future date. This approach provides market participants with long-term price protection and planning, helping to reduce the risk of market volatility. However, futures trading requires margin payments and fees, and fixed delivery dates limit the flexibility of trading. Peer-to-peer trading is conducted through an online platform, eliminating intermediaries. This type of trading is low cost and highly efficient, with buyers and sellers able to negotiate trading conditions directly, reducing information asymmetry and transaction friction. However, peer-to-peer trading also faces challenges, such as insufficient regulation, transaction security, and legal compliance.

Centralized markets and over-the-counter (OTC) markets are two common market structures. A centralized market is where all buyers and sellers trade centrally on the same exchange or platform. This market structure has the advantages of openness and transparency, price discovery, and transaction regulation. The London Metal Exchange (LME) is one of the world's largest centralized markets for trading minerals, ensuring fairness and transparency through a centralized market trading mechanism. Unlike centralized markets, OTC markets involve private negotiations between buyers and sellers, with no unified exchange or platform. This market structure offers high flexibility and low cost. Some local mineral markets use OTC markets, with traders, dealers, and other intermediaries used to facilitate transactions. However, OTC markets lack unified trading rules and supervision and are prone to problems, such as nonpublic prices, information asymmetry, and fraud.

The influence of different trading methods and market structures on price formation can be seen by looking at the copper market. In spot trading, supply and demand and market competitiveness affect copper prices, with what immediately reflecting market changes. The futures market provides a long-term price protection mechanism, allowing producers and consumers to lock in future prices through futures contracts, reducing the risk of market volatility. At the same time, the futures market also provides speculators with profitable opportunities to trade by predicting market trends. Peer-to-peer trading, which has increased in the mineral ore market, provides small mining companies and investors with a more direct way to trade, reducing intermediate links and transaction costs. In terms of market structure, the copper market shows different characteristics. The LME is one of the most influential copper markets in the world, ensuring fair, open and transparent trading through the trading mechanism of a centralized market. On the LME, buyers and sellers determine the trading price through bidding, achieving price discovery and fair competition among market participants. In addition, the LME uses a standardized contract and settlement procedures to ensure trading smoothly.

9.1.2 Geopolitical Risk

Geopolitical risk refers to a series of potential threats of political and economic events and natural disasters that may affect the international market and global political relations, and is also one of the important factors affecting the formation of global mineral trade prices. This risk covers a variety of factors, such as social instability, war conflicts, terrorist activities, trade frictions, and shortages of natural resources (Caldara and Iacoviello 2022; Su et al. 2021; Wang et al. 2023).

Political instability and war are one of the main factors that lead to the interruption of the supply of mineral resources. The outbreak of the Russia-Ukraine war in 2022 not only limited oil supplies, but also led to a spike in international crude oil prices. Due to a series of unexpected events such as war and political instability, economic and financial slowdowns, terrorist attacks, and natural disasters, crude oil prices have experienced several large fluctuations over the past few decades (Sadorsky 2006; Morales and Andreosso-O 'Callaghan 2014; Kilian 2009), which further amplifies the volatility of oil prices. Pata et al. (2024) used wavelet coherence analysis and time-varying parameter VAR methods to study the impact of geopolitical risk on the prices of aluminum, copper, lead, zinc, cobalt, and nickel between January 1992 and August 2022. The results show that mineral prices fell during COVID-19 and rose after the Russia-Ukraine conflict. Zheng et al. (2023) studied the impact of geopolitical risks on the price volatility of coal, copper, crude oil, gold, and iron ore in the Chinese futures market. The results of GARCH model show that geopolitical risk significantly increases the overall volatility, sustained volatility and temporary volatility of crude oil. Significantly improve the overall volatility and temporary volatility of coal and iron ore futures. Estimates of the TVP-VAR-SV model show that the short-term impact of geopolitical risk shocks on the volatility of futures prices of each commodity is large and long-lasting. When major geopolitical events such as the Paris terrorist attacks occur, Commodity futures volatility responds more and lasts longer to the same level of geopolitical risk shocks.

In addition, trade conflicts will also have an important impact on global mineral trade prices. If trade disputes or trade restrictions are imposed between countries, the cross-border flow of mineral resources may be blocked. In 2018, the United States imposed tariffs on aluminum and steel imports from China, triggering a series of global trade disputes. Such trade barriers could lead not only to a contraction in the supply of mineral resources but also to price volatility. In terms of trade control, for security, human rights or other political reasons, governments or international organizations can restrict the trade of mineral resources by certain countries or companies through regulation or sanctions. In 2019, the U.S. government announced sanctions on Iranian oil exports, limiting the availability of Iranian oil on the international market. Such sectoral controls and sanctions can lead to disruptions in the supply of mineral resources, which can have a significant impact on prices.

On the basis of the impact on mineral use, it will also indirectly affect air pollution, which is not conducive to sustainable development. For example, geopolitical risks will lead to increased use of fossil fuels, which may affect the energy mix and exacerbate CO_2 emissions (Liu et al. 2015; Hanif et al. 2019). Ding et al. (2023) also explored the impact of geopolitical risks on CO_2 emissions in OECD countries from the perspective of mineral resource exploitation.

9.1.3 Social Impacts

Market Participants' Expectations

Market participants' forecasts of future supply and demand conditions affect mineral trade prices. If market participants expect a certain mineral resource to be in tight supply, they may act early, causing prices to rise. Market predictions are often influenced by information analysis, market sentiment, and speculation. Abdelhedi and Boujelbene-Abbes (2020) empirically studied the volatility spillover effect between the Chinese stock market, investor sentiment and the oil market, emphasizing that the sentiment of Chinese investors is the channel of shock transmission between the oil and the Chinese stock market.

Cobalt is a critical mineral resource. With the rapid growth of the electric vehicle and renewable energy industries, the demand for cobalt has increased significantly. Market participants are alert to cobalt supply risks given the high dependence on politically unstable countries such as the Democratic Republic of Congo. As a result, they use strategic purchases and inventory accumulation in anticipation of future supply constraints to mitigate potential supply disruptions. This behavior can push up the price of cobalt, which in turn affects the market trading price of cobalt ore.

Iron ore is a key ingredient in steel production, and as the world's largest consumer of iron ore, China's demand dynamics have a significant impact on the global market. Expectations for China's economic growth and infrastructure construction are a focus for market participants. If the market expects the Chinese economy to maintain its growth momentum and infrastructure investment to continue to expand, demand for iron ore will rise. This causes market participants to buy iron ore in advance or lock in supply contracts, which affects iron ore prices.

Financial Markets and Investor Behavior

Financial market volatility and investor behavior have an impact on global mineral trade prices. The behavior of investors and market psychology factors play crucial roles in the supply and demand relationship of the mineral market, market price formation, and price fluctuations. Investor trading directly affects global mineral trade price volatility. In financial markets, a variety of factors, including economic data, corporate performance, and policy changes, influence investor decisions and behaviors. When investors predict a change in mineral resource demand or supply, they adjust their portfolios accordingly, triggering short-term price fluctuations. Capital flows and currency exchange rate movements also affect global mineral trade prices. Capital flows are influenced by a range of factors, such as interest rate differentials, market risk appetite, and economic expectations. When investors seek higher returns or demand for safe havens increases, they may move funds between mineral markets in different countries, leading to price volatility. When currency exchange rates change, the relative price of import and export commodities also changes, thus affecting mineral trade prices.

Requirements for Sustainable Development

Environmental protection and sustainable development concerns have important impacts on global mineral trade price formation. With greater emphasis today on both global environmental issues and sustainable development, environmental regulations have been strengthened. The mineral industry has had to respond to these regulations, in addition to greater consumer demand for green products. These regulations and consumer sentiment directly affect.

Under new environmental regulations, many countries have placed restrictions on mining of mineral resources. These restrictions, which are aimed at reducing environmental pollution and ecological damage, include strict wastewater discharge standards and air pollutant discharge limits. These regulations have increased environmental protection inputs and the cost of mining enterprises by limiting the use of some traditional mineral mining methods that pollute soil, water and air, making it difficult to meet environmental standards. To comply with these standards, mining companies need to adopt more advanced technology and equipment and improve environmental governance capabilities, which result in increased costs, with potential implications for prices.

Second, increased consumer demand for green products could have an impact on mineral trade. With increasing environmental awareness, consumers are increasingly inclined to buy environmentally friendly and sustainable products. This has driven a transformation of the mineral supply chain, with green, sustainable mineral resources increasingly favored. Some consumers may prefer to buy environmentally certified mineral products, such as oil and copper, rather than products that are not mined environmentally friendly. This change in demand affects the market supply and demand relationship of environmentally friendly mineral resources, and thus affects the price. The supply of environmentally friendly mineral resources is small and the price is relatively high, while the supply of non-environmentally friendly mineral resources is rich and the price is relatively low.

At present, the development of renewable energy is an important issue for environmental protection in various countries. Many scholars have recognized that the development of renewable energy may significantly affect the demand and supply profile of mineral resources. Research by Islam et al. (2022) shows that solar and wind technologies have a positive long-term impact on mineral demand in major mineral importing countries. Bazilia (2018) highlights that regardless of the scale of the transition, the shift to renewable energy will affect supply and trade patterns for critical minerals. Grandell et al. (2016) analyzed the impact of clean energy technologies such as solar energy and wind energy on the demand for critical metals, and highlighted the supply problems that these metals may face in the process of energy transition.

In addition, Beylot et al. (2019) conducted an empirical study of the energy transition in France, exploring the demand for essential minerals such as steel, copper, aluminum, and concrete, as well as the potential impact of these transitions on the climate. According to the empirical analysis by Liu et al. (2024), the consumption of both metal and non-metal minerals is the inhibiting factor in the process of renewable energy transition, especially the impact of metal minerals is more significant. Ding et al. (2024) used the TVP-VAR-SV model to study the dynamic interaction between climate warming, renewable energy consumption and rare earth market, and found that renewable energy consumption has a short-term positive impact on the rare earth market.

9.2 Price Volatility of Energy and Critical Minerals

9.2.1 Measures of Volatility

In this chapter, we consider 18 critical minerals and 3 energy minerals, draw on historical spot data to analyze the factors driving price volatility. Although market volatility itself is not visible, a variety of methods have been developed to measure this key indicator. Among these methods, realized volatility (RV) has become one of the most commonly used volatility indicators due to its practicability, and it is widely used to measure the daily, weekly, and monthly volatility of assets (Gong et al. 2023). Below, we user RV to measure the weekly volatility of each mineral. The expression is as follows:

$$RV_t = \sum_{i=1}^{M} r_{t,i}^2, \tag{9.1}$$

where RV_t represents the realized weekly volatility, and $r_{t,i}$ is the yield on day i in a week.

$$r_{t,i} = 100 * \left(\ln p_{t,i} - \ln p_{t,i-1}\right), \tag{9.2}$$

where $p_{t,i}$ represents the closing price on day i, and M denotes the trading day of week t. On this basis, weekly volatility is converted to annual volatility (%). To reduce the influence of outliers, logarithmic calculations are carried out for the modeling and calculation of the volatility spillover index:

$$\sigma_t = \ln\left(\sqrt{52 \times RV_t}\right) \tag{9.3}$$

9.2.2 Price Volatility of Common Industrial Metals

As shown in Fig. 9.1, the spot price of aluminum exhibited an upward trend between 2002 and 2008. After the global financial crisis in 2008, the spot price of aluminum plummeted. Subsequently, driven by global economic recovery, the spot price of aluminum gradually recovered. Around 2012, the spot price of aluminum declined again. After falling to an all-time low in 2016, the price rose again and peaked around 2022, before declining rapidly. The volatility of aluminum spot fluctuates between 0 and 5, and 2009 is the period after the global financial crisis, the global economy fell into recession, resulting in a sharp decline in aluminum demand and large fluctuations in prices. Similarly, around 2012 and 2015, the slowdown in global economic growth, especially the slowdown in China's economic growth, had a large impact on the aluminum market. Around 2015, global geopolitical tensions increased, especially geopolitical conflicts in the Middle East, which led to disruption of the aluminum supply chain and an increase in price volatility. Around 2020, a global trade war, coronavirus pandemic, and other factors led to increased global economic uncertainty, which led to fluctuations in investor demand for commodities, such as aluminum, which led large fluctuations in aluminum prices. At the beginning of 2022, aluminum prices remained high. However, in the second half of the year, due to global inflationary pressure and interest rate hikes in major economies, aluminum prices showed a certain degree of correction. In 2023, aluminum supply outweighed demand on the global aluminum market, and aluminum prices were tested by cost support.

As shown in Fig. 9.2, with the development of new energy vehicles and renewable energy sectors, demand for cobalt increased significantly, driving increases in the spot price between 2019 and 2022, reaching a peak after 2022, followed by a sharp decline, which has continued to show a downward trend in recent years. In 2024, the cobalt market is characterized by lower prices than in previous years. Although cobalt prices were relatively stable at the beginning of the year, they faced downward pressure as market supply increased and demand fluctuated. The spot price of cobalt

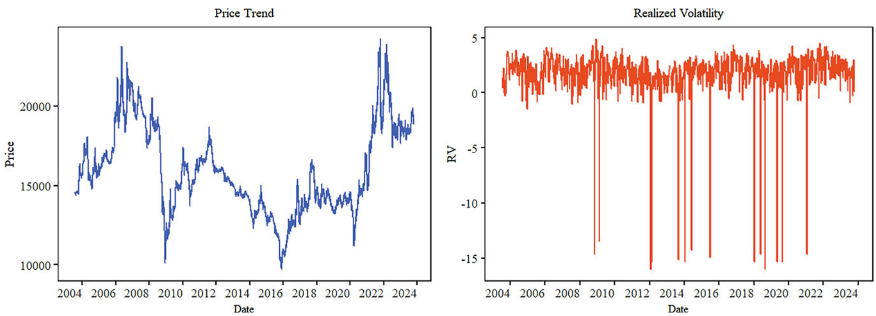

Fig. 9.1 Historical prices and volatility of aluminum ore

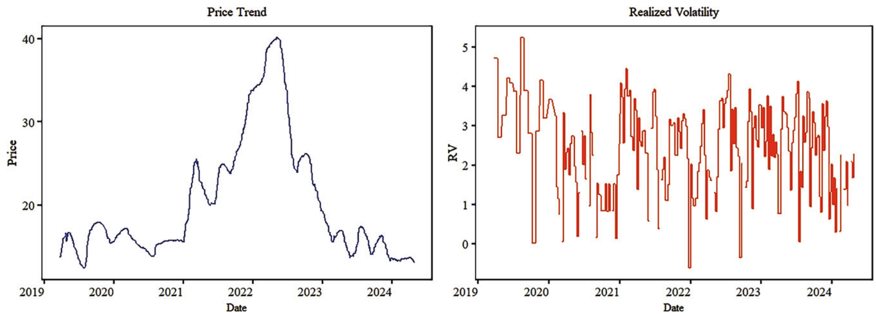

Fig. 9.2 Historical prices and volatility of cobalt ore

continues to fluctuate with a consistent frequency but remains mostly between 0 and 4.

As shown in Fig. 9.3, the spot price of copper showed a sharp upward trend from 2000 to around 2008, which was related to the rapid development of emerging market economies, such as China and India, which led to a surge in demand for copper and other base metals. After a sharp decline in 2008 due to the financial crisis, the global economy recovered and showed an upward trend by 2010. After reaching a peak in 2012, it began a gradual decline and fell to a trough point in 2015. After 2020, there was another sharp rise, reaching a peak around 2022. The spot price volatility of copper is similar to that of aluminum, with significant changes before 2010 and after 2015. The spot price of iron gradually declined after July 2013, plummeted in 2016 and then rebounded, reached a peak after 2019 in the shock change, and gradually rose to a peak in 2021 before falling again.

As shown in Fig. 9.4, iron spot price volatility fluctuated between 0 and 5, with large fluctuations during 2014–2015. During 2017–2018, various factors, such as recovery of the global economy, increases in steel production, and increased demand led to a rise in the spot price of iron. However, at the same time, the spot price was affected by other factors, such as trade friction and environmental protection policies. As a result, the price has fluctuated greatly. After 2021, there was a rapid

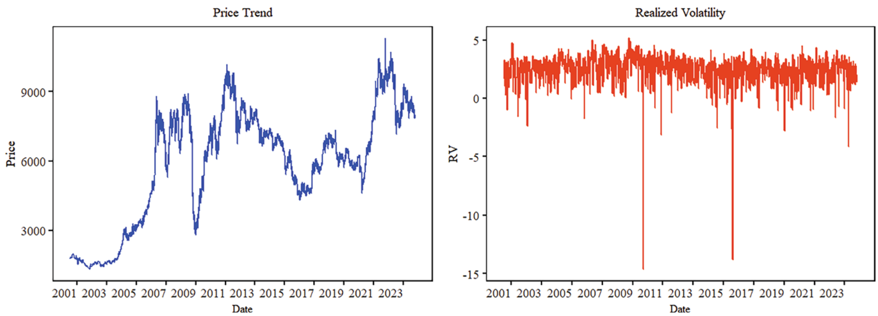

Fig. 9.3 Historical prices and volatility of copper

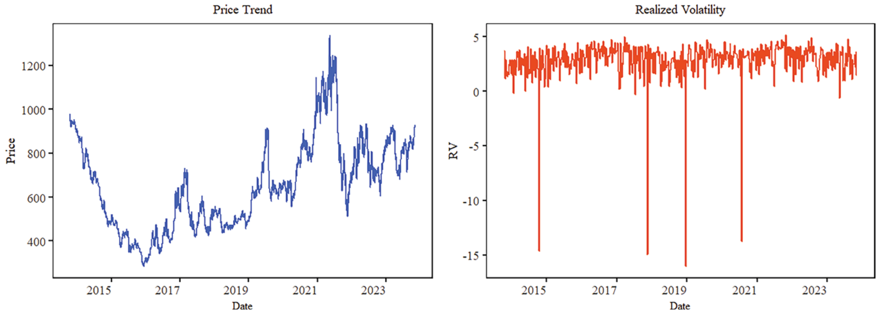

Fig. 9.4 Historical prices and volatility of iron ore

decline in the spot price of iron, followed by a volatile upward trend in the first half of 2022–2024.

According to Fig. 9.5, from 2017 to 2024, lithium spot prices have experienced significant fluctuations. After 2017, prices began to gradually decline, reaching their lowest point in 2021. Subsequently, due to rapid growth of the new energy vehicle industry worldwide, demand for lithium batteries surged, leading to a rapid rise in lithium prices from 2021, reaching a peak in 2022. However, entering 2023, due to an increase in market supply and slowdown in demand growth, the prices began to gradually decline. There were sharp fluctuations in the price of lithium carbonate in 2023, with prices falling from a high at the beginning of the year, before rebounding between April and June, and then beginning a downward spiral again until the price fell sharply at the end of the year. As of 2024, the lithium market continues to face oversupply problems, and prices continue to fall. Volatility of lithium spot prices is less regular. Volatility dropped sharply after 2022 and then rose rapidly after falling to the bottom in 2023, corresponding to the price.

As shown in Fig. 9.6, the spot price of manganese gradually declined after the financial crisis in 2008. Shortly after 2010, global economic recovery led to an increase in demand for manganese ore, and prices began to rise. Between 2015 and

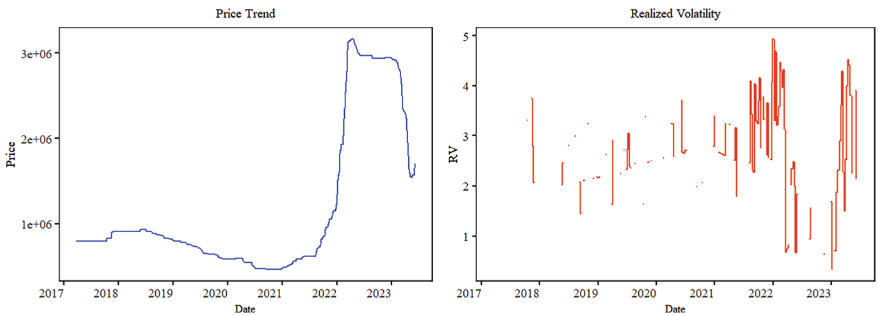

Fig. 9.5 Historical price and volatility trends of lithium ore

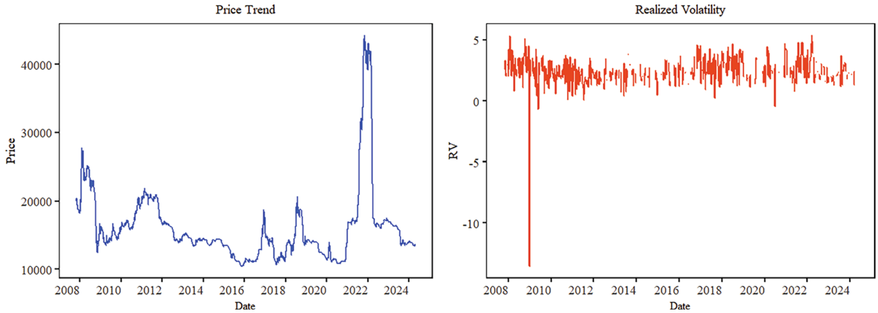

Fig. 9.6 Historical prices and volatility of manganese ore

2016, due to deflationary pressure of the global economy and reduced demand of the steel industry, the price of manganese ore fell, and the cost line of overseas mines was broken down, resulting in many mines being shut down. In 2017, with the recovery of China's crude steel supply and demand, global demand for crude steel gradually increased. As a result, manganese ore production capacity increased. Since then, production has gradually returned to normal levels, and prices have begun to stabilize. After 2020, there was a significant increase in the market. In 2021, the price of electrolytic manganese rose., resulting in steel mills using manganese alloys other than electrolytic manganese. In 2022, the manganese ore market experienced stocking mode and downstream market growth. In addition, manganese ore futures prices increased due to a predicted shortage of high-grade manganese oxide ore and other factors. As a result, the price of manganese ore rose. However, due to weak downstream growth, steel recruitment did not meet expectations, and the number of arrivals growth and other factors, the price was gradually falling. The volatility of manganese spot price has strong regularity, and there are significant changes before and after the financial crisis in 2009.

Nickel spot prices fell sharply after 2007, bottoming out at the onset of the financial crisis in 2009 (Fig. 9.7). Prices recovered gradually and rose to a small peak in 2011. At the beginning of 2022, Shanghai nickel prices continued to rise, mainly due to the extreme market events of London nickel and worsening of the Russia–Ukraine conflict, and nickel prices reached a historic high in March. In July 2022, nickel prices hit a new low, the lowest since the end of 2021, mainly due to the impact of the COVID-19 pandemic and macro factors, resulting in nickel prices returning to previous levels. In the third quarter of 2022, the new energy industry rapidly heated up, the operating rate of battery companies increased, the order situation improved, and the comprehensive impact of the precursor stage on the storage increased more, and the rapid expansion of leading enterprises significantly strengthened support for nickel in the direction of new energy, and the nickel price has opened a low shock. The overall nickel spot price volatility is relatively strong, and there are great changes around 2014 and 2017.

As shown in Fig. 9.8, tin ore spot prices remained steady between 2010 and 2015, benefiting from the popularity of electronic products and the growth in new energy

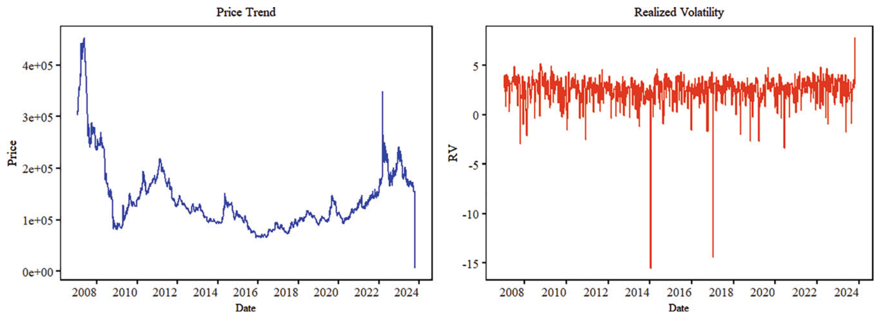

Fig. 9.7 Historical prices and volatility of nickel ore

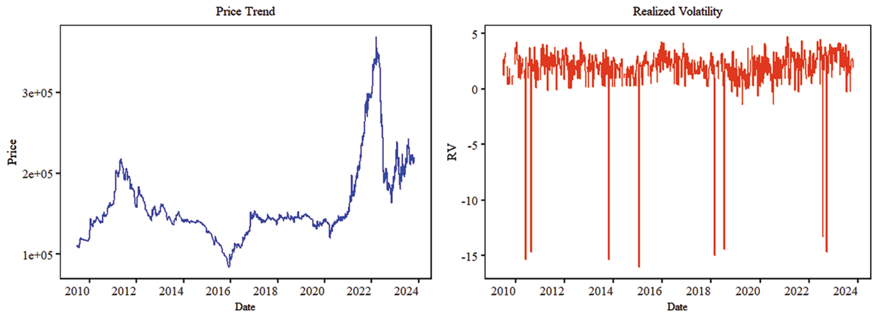

Fig. 9.8 Historical prices and volatility of tin ore

vehicles. After 2016, the global economy faced multiple challenges, such as trade protectionism and geopolitical risks, and tin prices fluctuated sharply. In particular, during the Sino–U.S. trade war in 2018, market uncertainty intensified. The price of tin was significantly impacted, with prices reaching a new low. In subsequent years, with economic recovery and greater environmental awareness, tin recovered gradually and continued to show an upward trend, before reaching a peak. Tin spot price volatility fluctuated markedly after 2010, 2015, 2018, and 2023.

Figure 9.9 shows zinc spot prices and volatility from 2009 to 2023. During this period, China's zinc spot price experienced significant fluctuations. In 2009, as the global economy recovered, demand for zinc increased, and prices rose steadily. However, after 2011, due to a global economic slowdown and oversupply, zinc prices began to fall. After 2015, in the face of strengthening environmental protection policies and weak global economic recovery, zinc prices continued to fall. From 2016 to 2018, supply-side structural reform and environmental protection policies promoted major adjustments of the zinc market, eliminated backward production capacity, and optimized supply. At the same time, emerging application areas drove demand growth, and zinc prices rebounded. After the escalation of the Sino–U.S. trade war in 2019 and the outbreak of the COVID-19 epidemic in 2020, demand for zine declined sharply, and zinc prices fell again in 2021–2022. With global economy recovery and

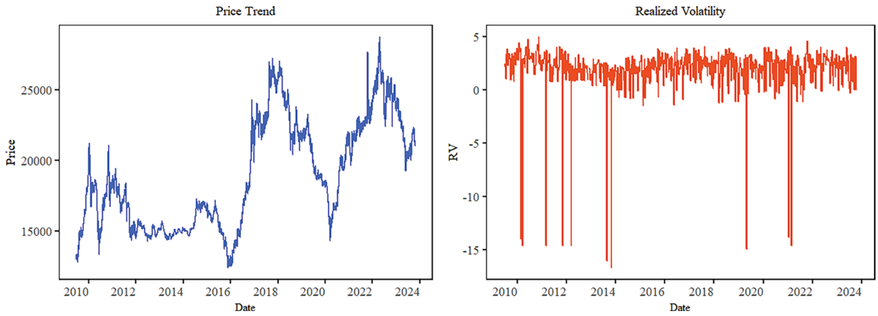

Fig. 9.9 Historical price and volatility trends of zinc ore

growth of domestic demand, especially the promotion of new energy vehicles and photovoltaic and other emerging industries, zinc prices fluctuated and rose. In 2023, affected by slow recovery of the global economy and trade tensions, zinc prices fell first and then rose, with a continued trend in price volatility. The volatility of zinc spot price has changed sharply many times before 2015 and has changed again around 2020, corresponding to the price trend.

9.2.3 Price Volatility of Nonmetallic Minerals

As shown in Fig. 9.10, the spot price of phosphorus rose sharply after 2007 and then fell sharply after the financial crisis in 2008. In 2010, as the global economy gradually recovered and demand for phosphorus began to recover, prices rose again. Around 2012, the relationship between supply and demand in the phosphorus market was relatively balanced, and the price tended to be stable. However, in subsequent years, due to overcapacity and slowdown in demand growth, phosphorus prices gradually declined, reaching a trough around 2016. They rose again around 2012 and then gradually declined, reaching a trough around 2016. After 2018, the phosphorus market fluctuated greatly, mainly due to strengthening of environmental protection policies, changes in raw material costs, and uncertainties in the international trade environment. In 2020, due to the impact of COVID-19 on the global economy and supply chain, phosphorus prices experienced sharp fluctuations. However, prices rose as the economy gradually recovered, and demand increased, peaking in 2020. In 2021, the global economy continued to recover, especially the agricultural sector, and increased demand for fertilizers pushed phosphorus prices up again to their annual peak. However, with an increase of market supply and fluctuation of demand, the price began to adjust again.

Figure 9.11 shows price changes in fluorite The price of fluorite fluctuated, falling to a low at the end of 2019 before rising at a constant rate to a peak before 2023 and reaching the maximum value in 2024. As the price of fluorite rose at a constant rate between 2020 and 2023, there was no change in the price volatility trend.

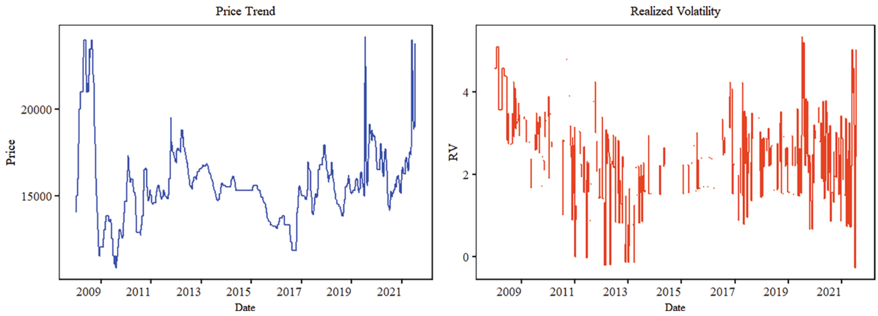

Fig. 9.10 Historical prices and volatility of phosphate rock

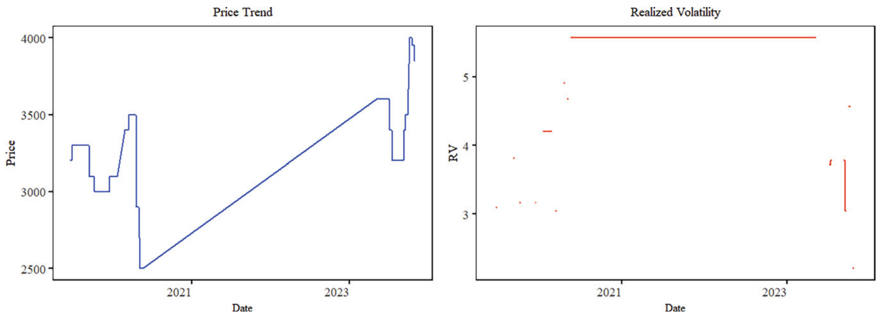

Fig. 9.11 Historical price and volatility trends of fluorite

9.2.4 Price Volatility of Rare Minerals

As shown in Fig. 9.12, from 2005 to 2010, global economic growth led to a steady increase in demand for chromium, and the overall price of chromium increased. After 2010, with global economic fluctuations and market supply and demand changes, chromium prices began to fluctuate to varying degrees. In 2015, due to oversupply in the global chromium market, the price growth was under pressure. Between 2016 and 2018, chromium prices showed a downward trend, partly due to a slowdown in global stainless steel capacity growth, which affected demand for chromium raw materials. In 2019, changes in market expectations and supply-side adjustments caused chromium prices to recover. In 2020, the COVID-19 hit the global economy, and chromium prices experienced a period of instability. However, with gradual recovery of the economy in the late period of the pandemic, and growth in global demand for stainless steel and alloy steel, chromium prices began to rise steadily in 2021. In 2022, the chromium market was tight, and prices remained high, partly due to supply constraints in major chromium-producing countries, including South Africa, while global economic recovery increased demand for chromium. In 2023, China's chromium ore market showed a high and volatile trend, and the fundamentals from

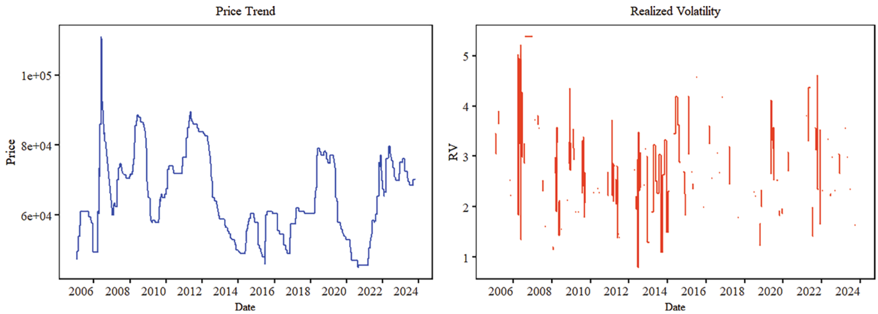

Fig. 9.12 Historical price and volatility trends of the rare earth element chromium

January to October showed a cumulative gap. However, from November to December, due to a surge in imports and port inventories, the early supply gap was closed. In terms of demand, downstream ferrochrome plants continued to increase production, with annual production of ferrochrome reaching about 7.9 million tons, an increase of about 13% from the previous year. Against a background of strong demand for chromium ore, supply did not match the demand of factories, and the domestic chromium ore market remained generally strong during the year. The volatility of chromium moves in much the same direction as its price.

As shown in Fig. 9.13, the price of gallium, a rare metal, exhibited significant volatility from 2017 to 2024. In the first half of 2017, the domestic price of gallium came under pressure due to oversupply, and gallium prices fell below production costs. However, with the main domestic production enterprises to take measures to save the market to reduce production, as well as the combined effect of market speculators and traders, the price of gallium began to rise around the middle of 2017. In 2018, the gallium trade globally comprised mainly spot and zero-order trading, and the price of gallium in China began to dominate global trade prices. Although gallium prices remained relatively stable between 2019 and 2020, the impact of the outbreak on the market in the first half of 2020 resulted in less price volatility. In the second half of 2020, domestic and foreign gallium prices increased rapidly due to an increase in downstream semiconductor demand. In 2021, the gallium market showed a trend of rising prices, followed by a fall in prices. The price increased significantly in the first quarter due to demand for magnetic materials. However, the price then began to fall again after an increase in gallium supply and a decrease in demand. In the fourth quarter, due to a rise in raw material costs and imported bauxite use, the cost of primary gallium increased, supply declined, and prices rose again. In the first half of 2022, gallium market behavior was similar to the fourth quarter of 2021, and the price continued to rise. However, in the third quarter, the price began to fall and continued to decline due to a reduction in demand for terminals downstream and weak demand for semiconductors. In the fourth quarter, demand for semiconductors did not improve significantly, and the market price for gallium further declined until the beginning of January 2023, when the price gradually stabilized. In 2023, the price of gallium rose rapidly after implementation of export controls on August 1.

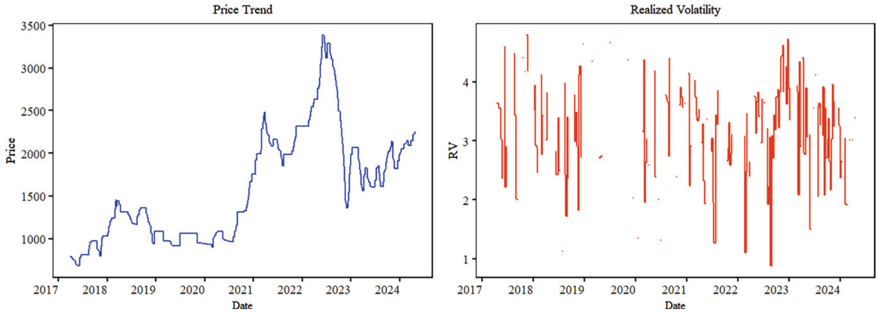

Fig. 9.13 Historical price and volatility trends of the rare earth element gallium

These export controls led foreign enterprises to stockpile goods as soon as possible or prepare application materials for the purchase of gallium and germanium, which increased the willingness of Chinese domestic enterprises to ship export orders, and a large number of gallium and germanium were exported in the short term. There have been no major price movements in 2024. The volatility remains between 2 and 4, with volatility greatest during the period of the price rise.

As shown in Fig. 9.14, from 2005 to 2008, the price of germanium ingots increased, mainly due to the development of high technology, the popularity of the network, and the increase in military demand. In July 2006, the price of germanium ingots rose sharply to 7900 yuan/kg and continued to fluctuate. The financial crisis in 2008 led to a fall in germanium prices, especially when domestic germanium production was stimulated by price increases to 100 tons, and oversupply pushed the price down again. From 2011 to 2012, germanium prices rose sharply once more due to rapid growth in demand for solar photovoltaic cells. However, the subsequent European debt crisis caused prices to fall again. From 2012 to 2013, due to the impact of Hanergy's major contracts, state reserves, and commercial reserves, market demand exceeded supply and germanium prices rose again. In August 2014, the price of germanium reached its highest in history (12,100 yuan/kg). However, between 2015 and 2017, germanium prices fell once again due to overcapacity and weak demand. From 2018 to the first half of 2019, supply and demand were weak to form a balance, and prices stabilized under the support of costs. According to statistics in 2019, although the global limiting capacity of germanium was significantly greater than the demand, the output of Chinese enterprises accounted for more than 70%, making it easy to achieve a balance between supply and demand. As a result, the expected price tended to increase slightly and steadily, fluctuating at 8000–8500 yuan/kg. Since 2022, the germanium industry in China and elsewhere has faced a supply shortage. In 2024, the spot price of germanium ingots rose significantly. As of August 8, 2024, the price was 15,250 yuan/kg, an increase of more than 60% from the beginning of the year. This increase was mainly driven by explosive growth in demand for infrared and satellite solar cells and a supply shortage. The price of germanium is expected to continue to rise in the short term.

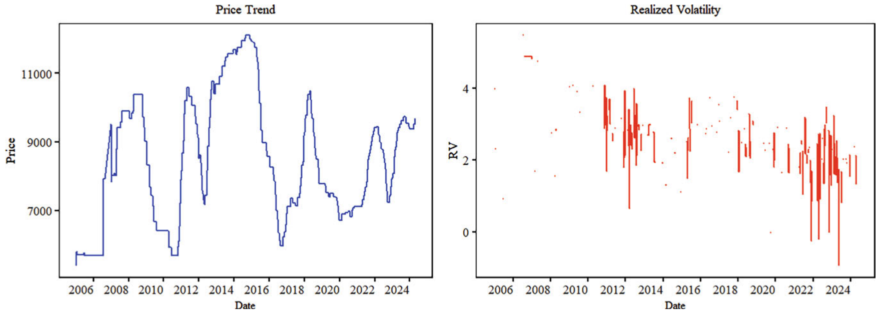

Fig. 9.14 Historical price and volatility trends of the rare earth element germanium

As shown in Fig. 9.15, the price of beryllium, a rare metal, has remained mostly stable compared with the former. In 2008, due to the impact of the global financial crisis, beryllium prices experienced a period of decline. However, with gradual recovery of the economy, prices began to rise to about 6250 yuan/kg. From 2010 to 2020, the price of beryllium hovered round 5800 yuan/kg. During the period 2013–2015, the price rose to around 6850 yuan/kg. The price continued to increase before stabilizing in 2024, with no significant fluctuations. A supply shortage of beryllium, combined with increasing demand for beryllium for use in applications in high-tech fields, has helped to maintain price stability. Similar to price trends in beryllium, the volatility of beryllium prices is relatively stable, with large fluctuations occurring only in the early and current periods, basically maintained between 4 and 5.

As shown in Fig. 9.16, during the global financial crisis of 2008, the price of antimony fell sharply. With gradual recovery of the economy, the price began to recover. Since 2010, the price has shown a clear upward trend, mainly due to the popularity of electronic products and expansion of the electric automobile sector. From 2012 to 2016, changes in the global economy and fluctuations in supply and demand affected the price of antimony, with prices showing a downward trend overall, partly due to oversupply in the market and slowdown of demand. After 2016, antimony prices

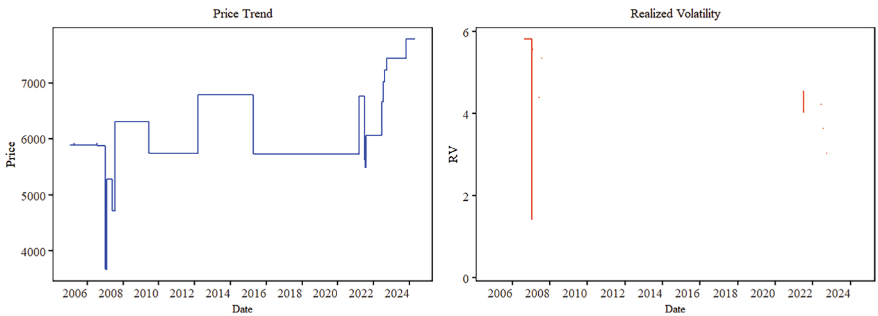

Fig. 9.15 Historical price and volatility trends of the rare earth element beryllium

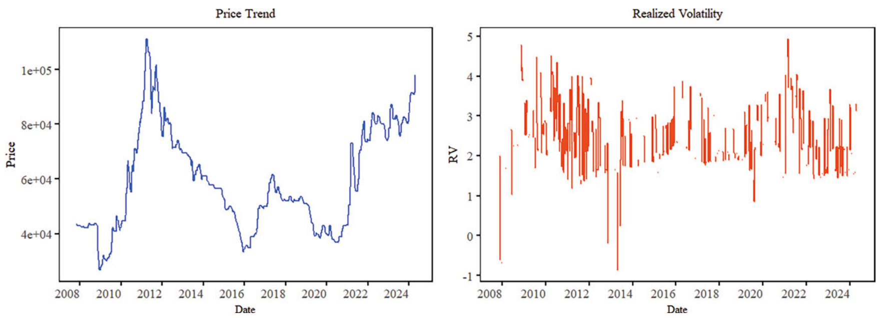

Fig. 9.16 Historical price and volatility trends of the rare earth element antimony

rebounded briefly, and after maintaining a shock, they gradually fell to the bottom. After 2020, as the global economy gradually recovered from the epidemic, antimony prices began to slowly recover. From 2021 to 2022, prices increased significantly. This increase was driven mainly by global economic recovery, strong demand by electric automobile and photovoltaic sectors, and supply shortages. In 2023, antimony prices declined before showing a continuing upward trend in 2024. The volatility of antimony prices is relatively tight, fluctuating around 2.5.

As shown in Fig. 9.17, between 2018 and 2019, the price of the rare metal tantalum first increased and then decreased. From the second half of 2018 to the end of 2019, prices fell sharply from their highest to their lowest levels in recent years. After a short period of low price fluctuations, prices increased sharply in the second half of 2021 and quickly rose to a record high. Prices then remained stable for a short period. After 2023, prices gradually recovered and continued to grow. The volatility of tantalum price is opposite to its price. When the price drops sharply, the volatility is larger and gradually increases. When the price is at a lower level, the volatility is larger.

As depicted in Fig. 9.18, price trends of the rare metal bismuth are similar to those of tantalum, showing a sharp decline followed and then rising in the shock.

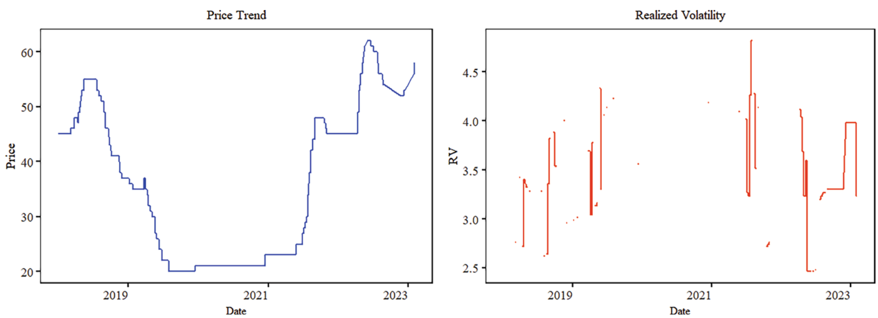

Fig. 9.17 Historical price and volatility trends of the rare earth element tantalum

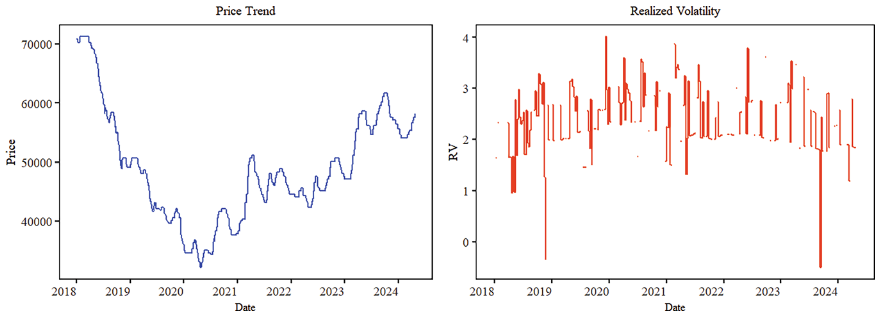

Fig. 9.18 Historical price and volatility trends of the rare earth element bismuth

The lowest price of tantalum was in 2020. Unlike tantalum, bismuth price fluctuations exhibit greater regularity and symmetry.

9.2.5 *Price Volatility of Energy Minerals*

In this chapter, we continue to analyze the price trends and volatilities of three types of energy minerals: crude oil, natural gas, and coal, using the same measurement methods as in Chapter 2.

For crude oil (Fig. 9.19), from 2000 to 2008, the global economy was relatively prosperous, especially in terms of industrialization and urbanization, and demand for crude oil increased significantly. Meanwhile, geopolitical tensions in the Middle East continued to push up crude prices. During this period, the spot price of crude oil showed an overall upward trend, although there were fluctuations in individual years. With the financial crisis in 2008, the global economy fell into recession, and demand for crude oil fell sharply, causing the spot price of crude oil to plummet. This trend was particularly pronounced in late 2008 and early 2009. From 2009 to 2014, with gradual recovery of the global economy, demand for crude oil began to increase, and the spot price of crude oil gradually rose. In addition, some oil-producing countries implemented production reduction policies to stabilize the market, which had a positive impact on crude oil prices. From 2014 to 2016, the crude oil market experienced oversupply, mainly due to an increase in U.S. shale oil production and producers, such as OPEC, failing to effectively cut production. Oversupply caused the spot price of crude oil to fall sharply and remain low for some time. Since 2016, the crude oil market has experienced many fluctuations. On the one hand, global economic recovery and geopolitical events, such as tensions in the Middle East, continue to drive growth in oil demand. On the other hand, production-reduction policies of oil-producing countries and technological advances (e.g., improvements in shale oil extraction technology) have affected the crude oil supply. Therefore, the spot price of crude oil in this stage showed a volatile upward trend. The volatility of crude oil prices was relatively stable, and there was a large change before 2015.

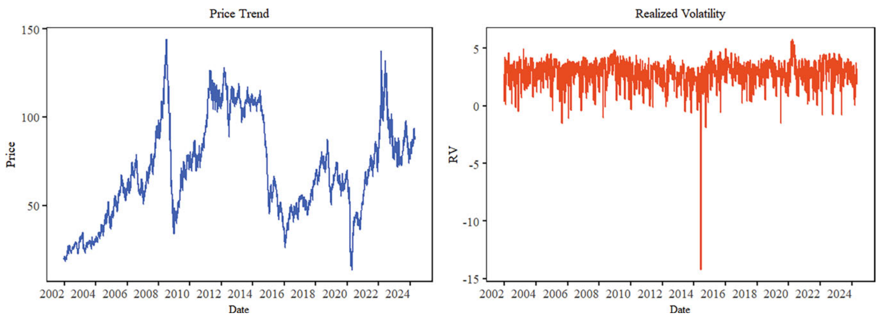

Fig. 9.19 Historical price and volatility trends of crude oil

As displayed in Fig. 9.20, the price of natural gas has generally remained low, with some relatively large increases in certain periods. For example, there was a very large increase in natural gas prices in 2014–2015, with a growth multiple of more than 100. The sharp increase in natural gas prices in 2014–2015 was linked to breakthroughs in shale gas technology in the U.S., which dramatically increased natural gas production, leading to a surge in supply that quickly led to lower prices. However, as production slowed, and demand rose, prices began to rebound. As can be seen in Fig. 9.20, natural gas price volatility remains mostly between 0 and 5, with large fluctuations only in 2015.

As clear from Fig. 9.21, the global financial crisis in 2008 led to a global economic recession and a decline in coal demand, resulting in a sharp drop in coal prices. After 2010, the price of coal showed a relatively stable trend, but the overall price showed a downward trend. In 2020, due to impact of the COVID-19 pandemic on global economic activity, demand for coal fell, followed by price fluctuations. However, with gradual recovery of the economy in the later period of the pandemic, demand for coal began to increase, and coal prices gradually recovered. After 2022, coal prices reached a peak compared to prices in previous years. There was little change in coal price volatility before 2014. However, the volatility density gradually increased after

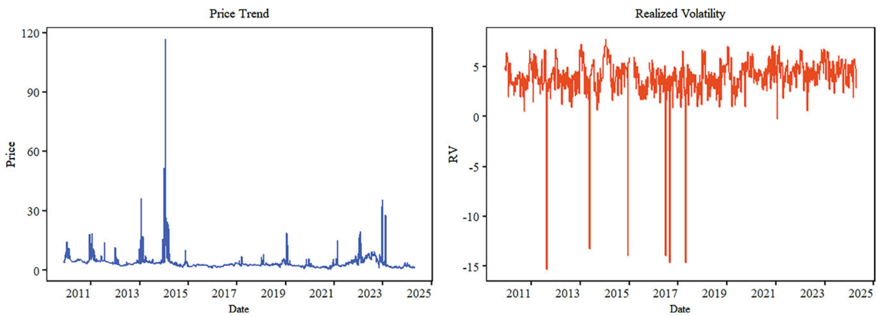

Fig. 9.20 Historical natural gas price and volatility trends

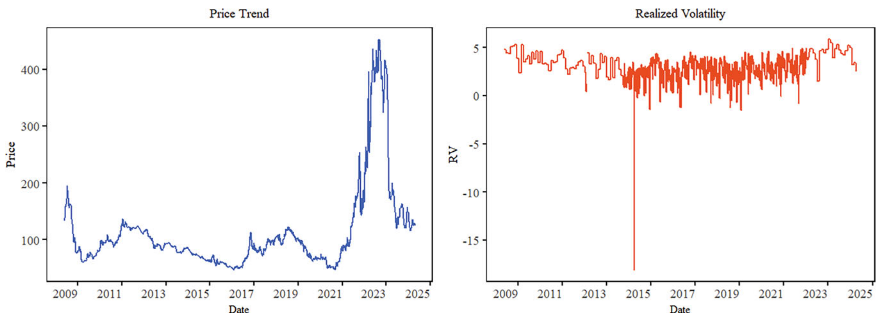

Fig. 9.21 Historical coal price and volatility trends

the big change in 2014. After 2024, coal prices showed a weak operation trend, the market demand side was weak, and coal enterprises, especially coal power enterprises, under the support of Changxie coal and imported coal, inventory remained high, and procurement enthusiasm was low.

9.3 Conclusion

In this chapter, we first presented a detailed theoretical discussion of the various factors that influence mineral pricing, categorizing these into market-, geopolitical-, and social-driven elements. Among the market elements, we cover supply and demand conditions, market competition dynamics, and trading patterns. Social impacts include the expectations of market participants, fluctuations in financial markets, investor strategies, and concerns about environmental sustainability. We then conduct a comprehensive analysis of the trends and volatility of various mineral prices, based on a thorough investigation of historical spot price data and a review of major historical events in the minerals market. Through this approach, our goal is to gain a deeper understanding of the factors that drive and disrupt mineral prices.

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Chapter 10
Risk Spillovers Across the Energy and Critical Mineral Markets

Jingyu Li and Zhan Zhang

Abstract In the global economy, energy and strategic minerals are vital to industrial production and national security. Their market dynamics are crucial for economic stability and represent significant factors in the international economic system. This chapter investigates volatility spillover effects in energy and critical mineral futures markets to reveal market interactions. The volatility spillovers are estimated through a time-varying volatility spillover index framework based on the time-varying parameter vector autoregressive (TVP-VAR) model. The empirical analysis centers on ten pivotal energy or critical mineral futures markets, including gold, silver, copper, natural gas, crude oil, lead, nickel, aluminum, tin, and zinc. The cross-market volatility transmission is delineated by initially disclosing the changes in the dynamic spillover in the whole system in response to significant events. Further, the directional spillovers among these markets are analyzed to figure out the primary roles that each market plays in the volatility transmission. The research aims to enhance understanding of the operational and dynamic aspects of the energy and critical mineral futures markets, offering theoretical guidance for investors in portfolio management and support for government entities in shaping market regulatory policies.

Keywords Energy markets · Critical mineral markets · Volatility spillovers · Time-varying parameter vector autoregressive

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10.1 Research Background

The energy and critical mineral commodity markets are inextricably linked. Energy is a fundamental driver of economic growth and the improvement of living standards, and it is an indispensable resource for modern industrial production and transportation (Moe 2010). The energy market's volatility poses substantial economic risks to businesses and consumers alike. To mitigate these risks, energy futures have become an indispensable instrument, providing a means to manage and hedge against market uncertainties. Crude oil futures, such as West Texas Intermediate (WTI) contracts on the New York Mercantile Exchange, hold a prominent position in the international futures market due to their high liquidity (Hache and Lantz 2013). Additionally, natural gas, a more environmentally friendly energy source, is one of the top three fuels for primary energy consumption and is projected to increase its market share (Al-Yafei et al. 2021). The Intercontinental Exchange (ICE) plays a pivotal role in the international coal futures market (Wong and Zhang 2020), offering contracts for coal from key locations such as Richards Bay and Rotterdam. Similarly, the critical minerals market, which includes metals like copper, aluminium, zinc, nickel, lead, and tin, is a critical component of the global financial market (Zhou et al. 2023). These minerals are extensively used in industrial processes and infrastructure development, making their price dynamics a significant influence on the global economy. As the commodity market system evolves, characterized by an expanding investor base and a diversifying spectrum of transaction types, the intermarket volatility spillover between energy and critical minerals has become increasingly evident.

Spillover effects are a common phenomenon in financial markets, fundamentally representing the transfer of information across various market segments (Tan et al. 2020; Yarovaya et al. 2022). A market's performance is influenced not only by its internal dynamics but also by external market forces. Ross (1989) was among the first to suggest that price fluctuations are linked to the rate at which markets absorb information, with volatility spillover serving as an indicator of market information dissemination. In essence, volatility spillover can be regarded as an alternate metric for gauging information flow. Hamao et al. (1990) provided a clear definition of the volatility spillover effect, emphasizing that it is rooted in the transmission of information. Market participants' reactions to information in different markets lead to shifts in investment behaviour (Huber et al. 2022), causing market volatility to propagate to other markets alongside the flow of information (Gong et al. 2023). The volatility spillover effect quantifies the interplay between markets in terms of volatility, or variance levels. It reveals how price fluctuations in one market impact others through the conveyance of information. The magnitude of the volatility spillover effect between markets can be used to assess the efficiency of information transfer, while its positive or negative direction indicates the flow direction of information. This effect is observable within and across various types of trading markets (see e.g. Jung and Maderitsch 2014; Karali and Ramirez 2014; Li et al. 2022).

This chapter concentrates on the pivotal energy and critical mineral markets, examining the volatility spillover relationships between these diverse markets. It investigates the roles that various energy and critical minerals play within these spillover dynamics, as well as their temporal evolution. The study focuses on ten significant energy and critical mineral commodity futures markets, including crude oil, natural gas, gold, silver, copper, lead, nickel, aluminium, tin, and zinc, spanning from February 23, 2009, to December 29, 2023. Utilizing an extended vector autoregression model with time-varying parameters (TVP-VAR) within a generalized variance decomposition framework (Antonakakis et al. 2018), the time-varying volatility spillover is estimated to elucidate the mechanism of volatility information transmission both within and across the mineral commodity futures markets.

10.2 Measuring the Time-Varying Volatility Spillover

This chapter uses the spillover index based on time-varying parameter vector autoregression to estimate the risk spillovers between energy and critical mineral futures markets.

10.2.1 TVP-VAR Model

The vector autoregressive (VAR) model was first introduced into the field of economic analysis by Sims (1980). However, one of the core assumptions of the model is that the variance of the error term is constant, that is, the same variance. When facing the dynamic changes of economic variables in the real world, this assumption is often too simple to fully reflect the real situation. In contrast, the time-varying parameter vector autoregressive (TVP-VAR) model relaxes the constraint of covariance and allows the coefficient matrix and covariance matrix in the model to evolve over time. Given that global mineral commodity futures prices are affected by a variety of factors, such as economic growth, supply and demand, and so on, showing a more complex fluctuation pattern, the traditional fixed coefficient model may face accuracy loss and systematic deviation when predicting and interpreting these price fluctuations. The advantage of the TVP-VAR model is that it can capture these time-varying effects, improve the accuracy of estimation, and help reveal the dynamic changes of the volatility transmission mechanism.

In order to explore the transmission mechanism in a time-varying manner, the TVP-VAR method is used. This method allows the variance to change through the random fluctuation Kalman filter estimation with the forgetting factor introduced by Koop and Korobilis (2014). The TVP-VAR model can be written as

$$y_t = \beta_t z_{t-1} + \varepsilon_t \quad \varepsilon_t | F_{t-1} \sim N(0, S_t) \tag{10.1}$$

$$vec(\beta_t) = vec(\beta_{t-1}) + v_t \quad v_t | F_{t-1} \sim N(0, R_t) \tag{10.2}$$

where y_t and $z_{t-1} = \left[y_{t-1}, \ldots, y_{t-n}\right]\prime$ represent $N \times 1$-dimensional and $Np \times 1$-dimensional vectors, respectively. β_t is a $N \times Np$-dimensional time-varying coefficient matrix, ε_t is a $N \times 1$-dimensional error perturbation vector, with an $N \times N$ time-varying variance covariance matrix S_t. $vec(\beta_t)$, $vec(\beta_{t-1})$ and v_t are $N^2p \times 1$-dimensional vectors, and R_t is an $N^2p \times N^2p$-dimensional matrix.

10.2.2 Spillover Index

The spillover index is a quantitative index to measure the intensity of the spillover effect proposed by Diebold and Yilmaz (2009, 2012). The essence of this index lies in the application of variance decomposition. The special feature of the spillover index is that it can assess and reveal the direction and intensity of information flow among different financial entities, which is helpful in understanding the dynamic interaction between market participants. Initially, the design of the spillover index relied on the constant coefficient VAR model, focusing on the static spillover effect from the perspective of the overall sample. Subsequently, researchers introduced a rolling window analysis method based on the VAR model to explore the change of spillover effect in the sub-sample period. To more accurately describe the time-varying characteristics of the volatility spillover index, this paper constructs a time-varying volatility spillover effect index based on the TVP-VAR spillover index expansion model.

To calculate the generalized impulse response function (GIRF) and the generalized prediction error variance decomposition (GFEVD), the VAR is converted to its vector moving average (VMA) expression:

$$y_t = \sum_{j=0}^{\infty} L' W_t^j L \varepsilon_{t-j} \tag{10.3}$$

$$y_t = \sum_{j=0}^{\infty} L' W_t^j L \varepsilon_{t-j} \tag{10.4}$$

Wher $L = \left[I_N, \ldots, 0_p\right]\prime$ is a $Np \times N$-dimensional matrix, $W = \left[\beta_t; I_{N(p-1)}, 0_{N(p-1)\times N}\right]$ is a $Np \times Np$-dimensional matrix, and A_{it} is a $N \times N$-dimensional matrix. GIRF represents the response of all variables in variable i after impact. Since there is no structural model, the difference between the J-order forward prediction of primary variable i under impact and that of primary variable B without impact is calculated. This difference can be interpreted as the impact in variable i, which can be calculated by the following formula:

$$GIRF_t\left(J, \delta_{j,t}, F_{t-1}\right) = E\left(Y_{t+J} | \varepsilon_{j,t} = \delta_{j,t}, F_{t-1}\right) - E(Y_{t+J} | F_{t-1}) \tag{10.5}$$

$$\Psi_{j,t}^{g}(J)=\frac{A_{J,t}S_{t}\varepsilon_{j,t}}{\sqrt{S_{jj,t}}}\frac{\delta_{j,t}}{\sqrt{S_{jj,t}}}\delta_{j,t}=\sqrt{S_{jj,t}} \tag{10.6}$$

$$\Psi_{j,t}^{g}(J)=S_{jj,t}^{-\frac{1}{2}}A_{J,t}S_{t}\varepsilon_{j,t} \tag{10.7}$$

where $\Psi_{j,t}^{g}(J)$ represents the GIRF of variable j; J represents the prediction range; $\delta_{j,t}$ represents the selection vector, the j position is 1, otherwise it is 0; and F_{t-1} represents the information set up to $t-1$. Then, calculate GFEVD, which can be interpreted as the variance share of one variable to other variables. The calculation method is as follows:

$$\widetilde{\Phi_{ij,t}^{g}}(J)=\frac{\sum_{t=1}^{J-1}\Psi_{ij,t}^{2,g}}{\sum_{j=1}^{N}\sum_{t=1}^{J-1}\Psi_{ij,t}^{2,g}} \tag{10.8}$$

where $\sum_{j=1}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)=1$ and $\sum_{i,j=1}^{N}\widetilde{\Phi_{ij,t}^{N}}(J)=N$.

Antonakakis et al.'s (2018) work is based on the TVP-VAR model and combined it with the construction method of the DY spillover index. It uses GFEVD to construct the total volatility spillover index to comprehensively evaluate how volatility shocks from multiple markets transmit and produce spillover effects:

$$C_{t}^{g}(J)=100\times\frac{\sum_{i,j=1,i\neq j}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)}{\sum_{i,j=1}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)}=100\times\frac{\sum_{i,j=1,i\neq j}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)}{N} \tag{10.9}$$

There are three following indices for measuring the directional spillover effect of a single market. The first one is the "To" spillover index, which is used to quantify the impact of the i-th market spillover to other markets:

$$C_{i\to j,t}^{g}(J)=100\times\frac{\sum_{j=1,i\neq j}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)}{\sum_{j=1}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)}. \tag{10.10}$$

The second one is the "From" spillover index, for assessing the extent to which the i-th market fluctuation is affected by other markets:

$$C_{i\leftarrow j,t}^{g}(J)=100\times\frac{\sum_{j=1,i\neq j}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)}{\sum_{i=1}^{N}\widetilde{\Phi_{ij,t}^{g}}(J)}. \tag{10.11}$$

Finally, the difference between the "To" and "From" spillover is named as the "Net" spillover index, written as:

$$C_{i,t}^{g}(J)=C_{i\to j,t}^{g}(J)-C_{i\leftarrow j,t}^{g}(J). \tag{10.12}$$

10.3 Data and Pre-analysis

10.3.1 Sample Selection and Data Preprocessing

This chapter focuses on energy and critical minerals and explores the spillover effects of different commodity markets. Samples were selected from ten common commodity markets for research (crude oil, natural gas, gold, silver, copper, lead, nickel, aluminium, tin, and zinc). Among them, gold, silver, and copper futures contracts respectively select the corresponding futures closing prices of the New York Mercantile Exchange (COMEX); the natural gas futures contract selects the corresponding futures closing price of the New York Mercantile Exchange (NYMEX); WTI crude oil from the New York Mercantile Exchange (NYMEX) is selected as the crude oil futures contract; and lead, nickel, aluminium, tin, and zinc futures contracts are selected from the corresponding futures closing prices of the London Metal Exchange. Due to the varying listing dates of the ten futures contracts, the sample period for this chapter is delineated from February 23, 2009, through December 29, 2023. The daily closing price data of each commodity are selected, and a total of 3863 samples are obtained. The data are from the Wind database.

Based on the daily closing price data of each commodity market, this chapter further calculates the weekly realized volatility to estimate the volatility spillover. Realized volatility (RV) is widely used by scholars to measure the daily, weekly, monthly, and annual volatility of assets. Referring to Ji et al. (2018) and Gong et al. (2021) based on the weekly data when studying the volatility spillover in the oil market, this chapter will also calculate the weekly RV. First, calculate the RV of each week according to the daily rate of return RV_t:

$$RV_t = \sum_{i=1}^{M} r_{t,i}^2 \tag{10.13}$$

where $r_{t,i}$ represents the yield on day i within a week. Formally, $r_{t,i} = 100 \times \left(\ln p_{t,i} - \ln p_{t,i-1}\right)$, where $p_{t,i}$ represents the closing price on day i; M stands for the trading day of week t.

Drawing on the methodology of Diebold and Yilmaz (2012), this paper converts weekly volatility data into an annualized percentage format (%). On this basis, considering the possible interference of extreme values on the robustness of the model, we use logarithmic transformation to process the above-annualized volatility data as the basis for measuring the volatility spillover effect. The formula is as follows:

$$\widehat{\sigma_t} = \ln\left(\sqrt{52 \times RV_t}\right). \tag{10.14}$$

10.3.2 Pre-analysis

The weekly volatility of each commodity market is calculated. The RV series of the ten energy or critical mineral futures markets in the sample are shown in Fig. 10.1, and the descriptive statistics are shown in Table 10.1.

Table 10.1 demonstrates that the average RV of these ten mineral commodity futures ranges from 0.871 to 2.888, and the standard deviation ranges from 0.579 to 2.760. The average RV of natural gas commodities is highest, and the standard deviation of the RV of silver is largest, indicating that the fluctuation of silver is largest. The skewness, kurtosis, and Jarque–Bera (JB) results show that the volatility time series still has the characteristics of “fine kurtosis and fat tail distribution”. The JB results are significant at the 1% level, rejecting the original hypothesis, and the volatility time series does not obey the normal distribution.

As shown in Table 10.2, the unit root test shows that the ten series of volatility are stationary series, which can be used for further empirical analysis.

Figure 10.2 shows the correlation coefficient matrix of ten kinds of mineral commodity futures price volatility. It can be observed that the futures volatility of all these commodities shows a certain degree of correlation. This finding preliminarily shows that in the ten commodity futures markets studied, price volatility may not change independently. Instead, there is a certain degree of interaction or spillover effect between them.

10.4 Empirical Analysis

10.4.1 Total Spillover Effect

This subsection applies the method in Sect. 2 to estimate the total volatility spillover between the energy and critical mineral commodity markets (as shown in Fig. 10.3), corresponding to formula (10.9). As depicted in Fig. 10.3, the dynamic nature of the total volatility spillover effect across energy and critical mineral commodity futures markets is pronounced, with values ranging from 31 to 65%. The overall risk information transmission mechanism of the mineral commodity market underwent structural changes during major economic and financial shock events, displaying an obvious short-term upward trend.

In 2009, as the impact of the global financial crisis in 2008 had not been effectively alleviated, the spillover index was at a high level and exhibited an upward trend, with the highest point reaching 64.8%, which was the maximum value in the entire sample period. Investors holding a variety of asset portfolios will adjust their strategies according to market information and cause followers to change their investment behaviour at the same time, thus intensifying the transmission of fluctuation signals between different markets. The spread of negative effects is increasing, and the transmission of volatility between energy and critical mineral commodity markets is

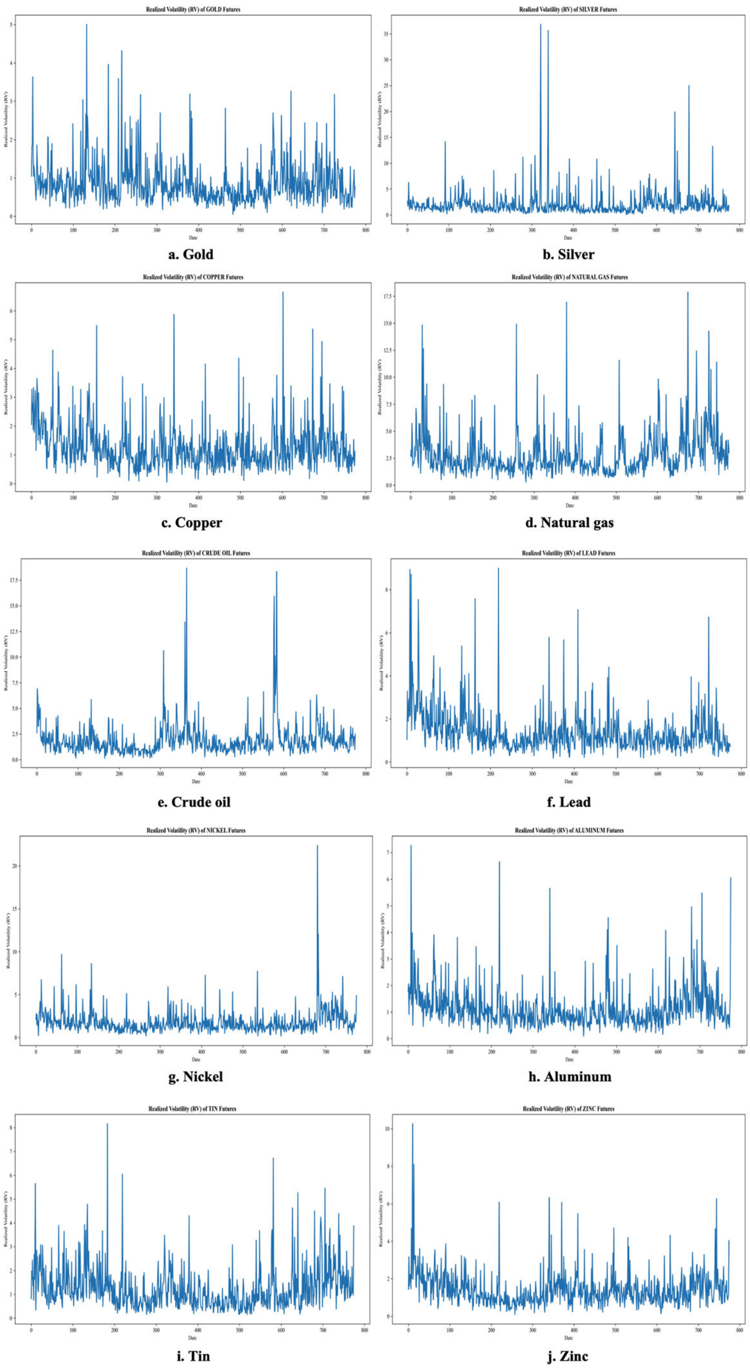

Fig. 10.1 The dynamic volatility of energy and critical mineral futures markets

Table 10.1 Descriptive statistics of volatility series

Variable	Obs.	Mean	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	JB
COMEX Gold	775	0.871	5.003	0.052	0.579	2.353***	8.428***	3009.188***
COMEX Silver	775	2.125	36.825	0.123	2.760	6.993***	69.962***	164,373.714***
COMEX Copper	775	1.278	6.647	0.059	0.799	2.033***	6.839***	2043.996***
NYMEX Natural gas	775	2.888	17.876	0.296	2.088	2.691***	11.133***	4937.431***
WTI Crude oil	775	1.933	18.668	0.162	1.685	4.797***	35.632***	43,971.026***
LME Lead	775	1.417	9.001	0.186	1.039	3.194***	15.637***	9214.274***
LME Nickel	775	1.802	22.379	0.172	1.396	5.789***	66.416***	146,771.234***
LME Aluminum	775	1.158	7.268	0.103	0.787	2.853***	13.100***	6592.554***
LME Tin	775	1.262	8.157	0.159	0.924	2.226***	8.201***	2812.028***
LME Zinc	775	1.440	10.255	0.103	0.926	2.950***	17.167***	10,640.180***

Notes JB is the Jarque–Bera test statistic, where ***, **, and * mean rejecting the original hypothesis of normality at the significance levels of 1%, 5%, and 10%, respectively

Table 10.2 Unit root test of volatility

Data	Inspection type (C, T, L)	ADF statistics	1% horizontal threshold	5% horizontal threshold	10% horizontal threshold	Result
RV_Gold	(1, 1, 0)	−14.474	−3.970	−3.416	−3.130	Stable
RV_Silver	(1, 0, 0)	−21.757	−3.439	−2.865	−2.569	Stable
RV_Copper	(1, 0, 0)	−10.901	−3.439	−2.865	−2.569	Stable
RV_Natural gas	(1, 0, 0)	−8.445	−3.439	−2.865	−2.569	Stable
RV_Crude oil	(1, 0, 0)	−7.183	−3.439	−2.865	−2.569	Stable
RV_Lead	(0, 0, 0)	−3.010	−2.568	−1.941	−1.616	Stable
RV_Nickel	(1, 0, 0)	−13.650	−3.439	−2.865	−2.569	Stable
RV_Aluminum	(1, 0, 0)	−7.216	−3.439	−2.865	−2.569	Stable
RV_Tin	(1, 0, 0)	−10.594	−3.439	−2.865	−2.569	Stable
RV_Zinc	(1, 0, 0)	−10.312	−3.439	−2.865	−2.569	Stable

Notes Inspection types (C, T, L) refer to constant, trend, and lag, respectively

accelerating, which increases systemic risk. In the financial crisis, countries took a series of remedial measures and achieved some results. The spillover index shows a downward trend at the end of 2009. However, in 2010, with the continuing European debt crisis, the volatility spillover index of energy and critical mineral commodity markets rose and fell slightly several times.

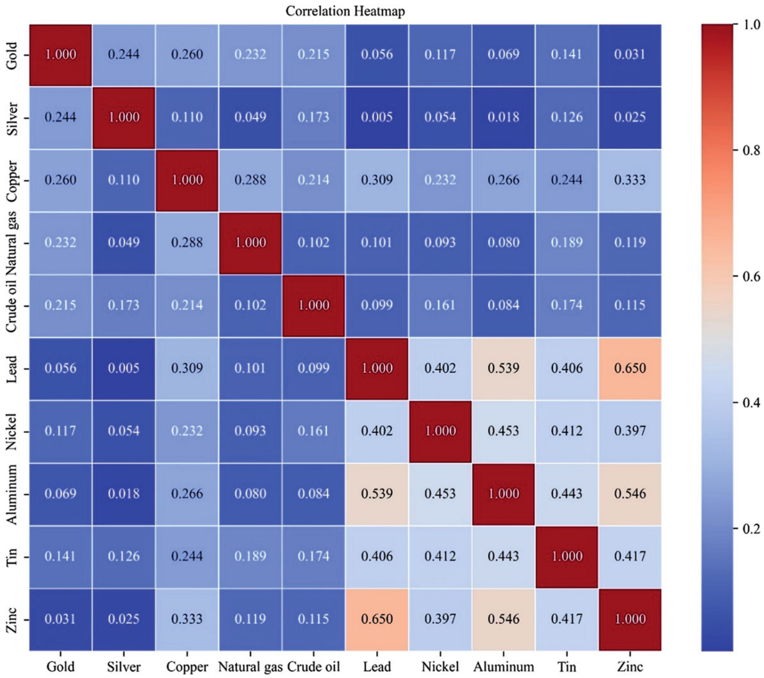

Fig. 10.2 Correlations between the realized volatilities of energy and critical minerals

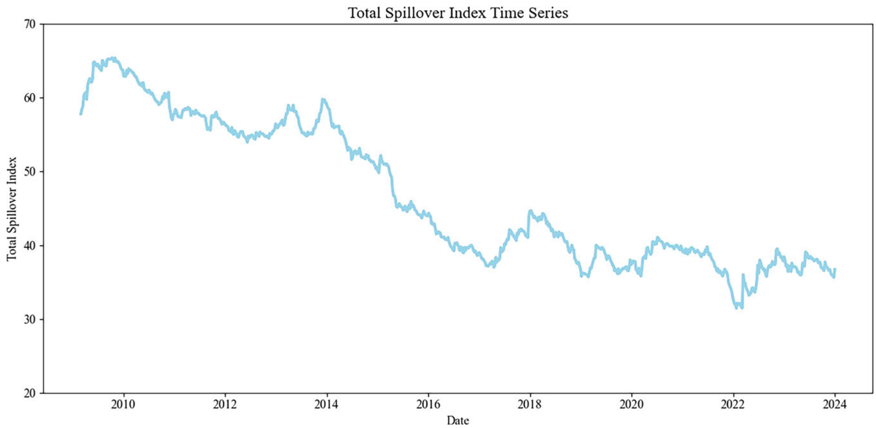

Fig. 10.3 Total time-varying volatility spillover index based on TVP-VAR model (%)

In April 2013, the gold market was hit hard. The Federal Reserve released information stating that hedge funds and institutional investors were selling gold, and Cyprus also said it would sell gold to repay debts. All kinds of negative news brought pessimism about investment. The gold market price fell sharply, and the total volatility spillover index showed an upward trend again. It reached a small peak in May, then began to fall and maintained a gentle period of about 55% at the end of 2013. In November 2014, the United States withdrew its quantitative easing policy, and then the dollar stopped falling and appreciated rapidly. Because the dollar was linked to the price of crude oil, the price of oil plummeted. At the same time, the large-scale exploitation of unconventional oil and gas resources changed the pattern of global oil supply and demand, the influence of OPEC was weakened, and the total volatility spillover effect of energy and critical mineral commodity markets rose again, but the duration of the rise was not long, and it began to fall in 2015.

In 2018, the United States withdrew from the Iran nuclear agreement. In order to make up for the possible oil supply gap caused by sanctions against Iran, the United States pressured Saudi Arabia and other OPEC countries to increase oil production to ensure stable supply in the market. This series of political and economic changes triggered a violent reaction in the market. The crude oil market suffered a sell-off for 12 consecutive days, setting the longest consecutive sell-off record in history, and the oil price plummeted as a result. At the same time, the volatility of natural gas fluctuated greatly, and the total volatility spillover index gradually rose and then reached a new peak, with the volatility spillover index reaching 45%.

From 2020 to 2021, affected by the new coronavirus epidemic, the global demand for crude oil shrank significantly. In addition, at the beginning of 2020, negotiations between “OPEC+ ” countries and Russia broke down, and a price war was imminent. The global crude oil market was oversupplied, and the international oil price fell. With the sharp fall in oil prices and extreme market instability, the volatility spillover effect of energy and critical mineral commodity markets in the sample increased significantly.

The total spillover effect of the energy and critical mineral commodity futures markets selected in this study indicates that continuous change in the global political and economic situation will have a certain impact on these critical mineral markets, resulting in enhanced linkage between different markets. From the perspective of behavioral finance, it can also be seen that due to the increase of uncertainty in the economic environment, irrational investor behavior occurs frequently, and a large number of funds flow in or out of the commodity market, which makes the degree of linkage in the international commodity futures market continue to deepen.

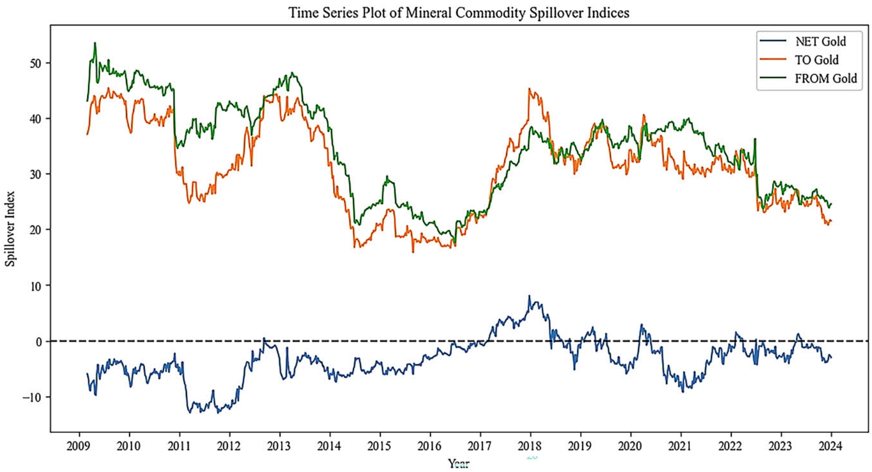

Fig. 10.4 Directional volatility spillover effect of the gold market

10.4.2 Directional Spillovers of Energy and Critical Mineral Markets

The transmission of price fluctuation information is bidirectional. The fluctuation information generated by a single market can be transmitted to other relevant markets, while simultaneously, the market can also receive the fluctuation information transmitted from other markets. Given that each market exerts a distinct impact on the systemic risk as a whole, the net influence of each market is ultimately captured in the net spillover index. The results of the To, From and Net spillover indices for the sample markets are shown in Figs. 10.4, 10.5, 10.6, 10.7, 10.8, 10.9, 10.10, 10.11, 10.12 and 10.13.

From Figs. 10.9, 10.10, and 10.13, it is evident that the lead, nickel, and zinc markets predominantly act as sources of volatility spillover, with a predominantly positive net spillover index in most periods. The lead market boasted the highest volatility spillover and net spillover indexes for most of the time. Especially before 2017, the lead market had a positive net spillover index, acting as the primary transmitter of volatility information, with its contribution to system interconnectedness exceeding 90%. After 2017, the net spillover index fluctuated around zero. The nickel market maintained a positive net spillover index the majority of the time, serving as the key transmitter of volatility information. Periodically, from 2010 to 2011, the nickel market briefly transitioned from a net transmitter to a net recipient of volatility spillover effects. Throughout the entire sample period, the zinc market exhibits a positive net spillover index, signifying its significant role as a transmitter of spillover effects. Its net spillover index was almost always positive and gradually decreased from 2009 to 2011. However, from 2012 onwards, the net spillover index exhibited a marked upward trend, signifying the zinc market's strong spillover effect

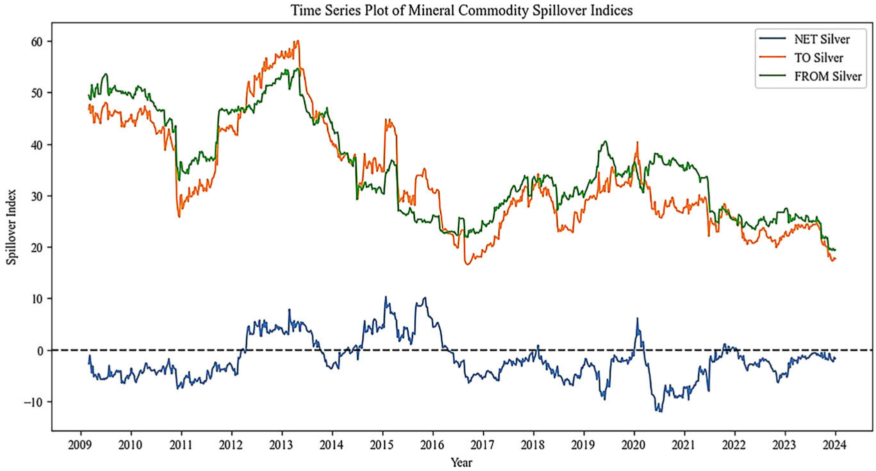

Fig. 10.5 Directional volatility spillover effect of the silver market

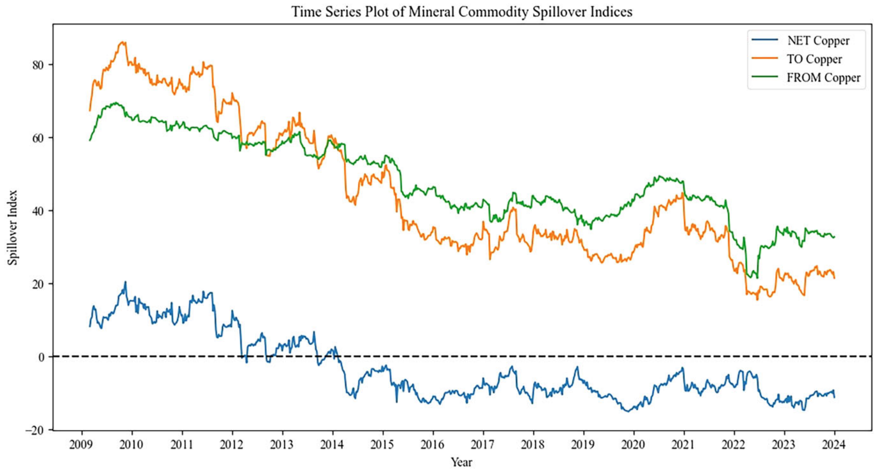

Fig. 10.6 Directional volatility spillover effect of the copper market

on other markets. Particularly around 2017, the net spillover index reached a peak, highlighting the significant influence of the zinc market on other markets during that period.

In contrast, gold, copper, natural gas, and crude oil markets primarily served as recipients of fluctuation information, exhibiting negative net spillovers the majority of the time. As displayed in Fig. 10.4, the gold market, in particular, serves as a negative net spillover index for extended periods, consistently absorbing fluctuation information. Post-2017, however, the market experienced a temporary increase in the influence of external market fluctuations. Between 2017 and 2018, the gold market

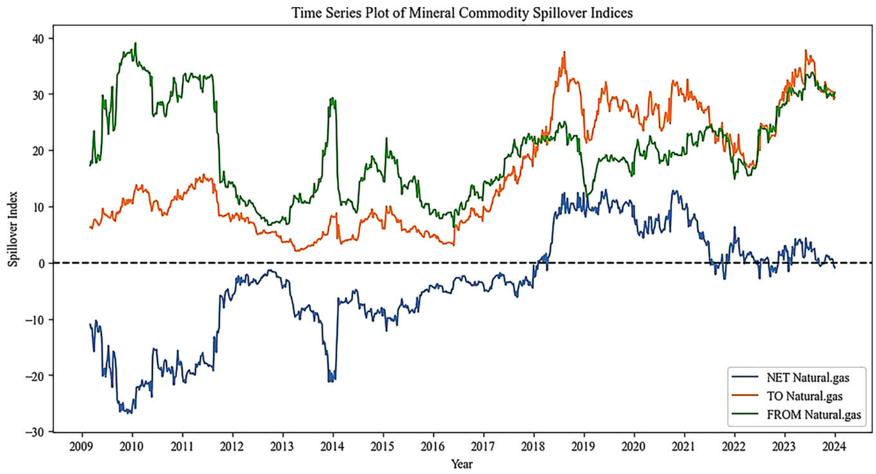

Fig. 10.7 Directional volatility spillover effect of the natural gas market

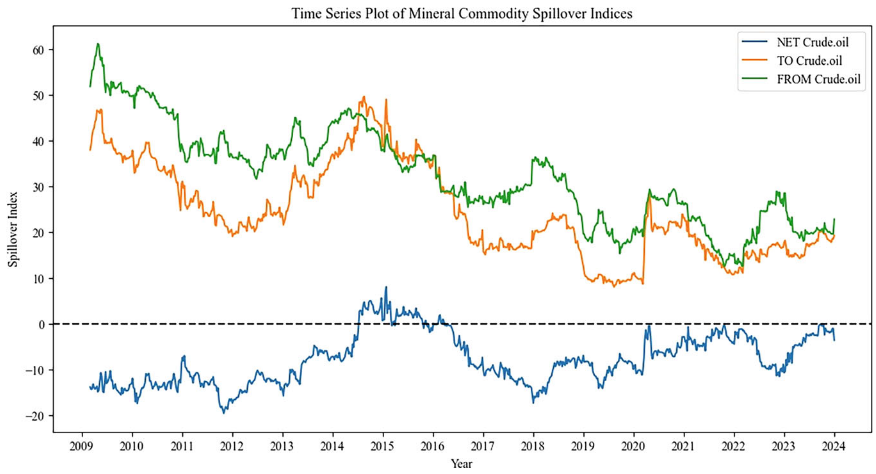

Fig. 10.8 Directional volatility spillover effect of the crude oil market

transitioned from being a net recipient to a net transmitter of fluctuation spillover effects. Differently, given the silver market's important role as a spillover receiver, this market turned to be a spillover sender in 2012–2013, 2014–2016, and the start of 2020, with positive net spillover index (see Fig. 10.5). The copper market consistently featured as the net transmitter of volatility spillover until 2014, after which it assumed the role of a net transmitter of volatility information (see Fig. 10.6). Figure 10.7 demonstrates that the natural gas market was consistently a net recipient of price fluctuation information before 2018. Notably in 2010, it was heavily influenced by other market fluctuations, with the impact reaching nearly 30%. However, since

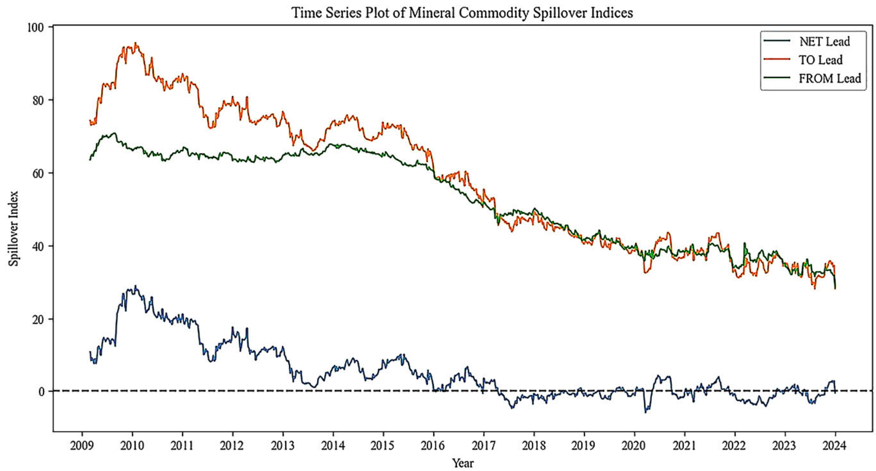

Fig. 10.9 Directional volatility spillover effect of the lead market

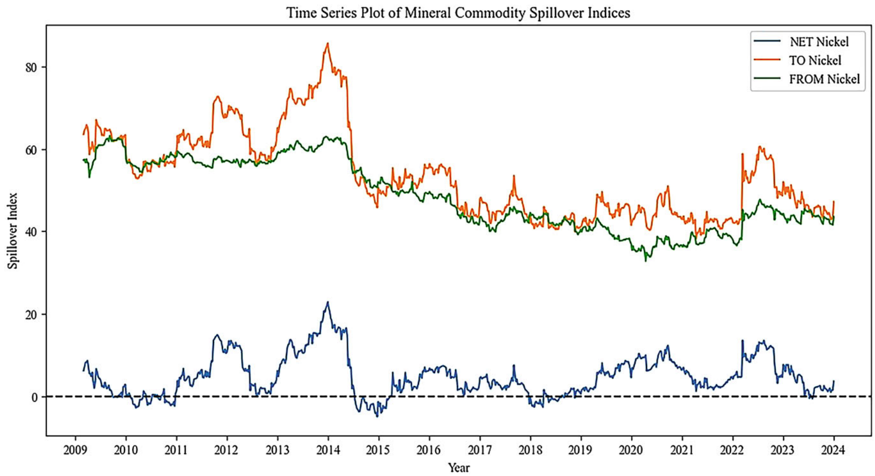

Fig. 10.10 Directional volatility spillover effect of the nickel market

2018, it has transformed into a net transmitter of price fluctuation information, with a significant increase in the spillover index, demonstrating a yearly upward trend. The crude oil market was largely a net recipient of spillover effects, briefly shifting from a net recipient to a net sender of volatility spillover around 2015 before reverting to its original status (see Fig. 10.8).

The aluminum and tin markets have interchanged their roles as risk recipients and transmitters, with the duration of these roles being fairly comparable. Figure 10.11 reveals that the aluminum market functioned as a net transmitter of volatility before

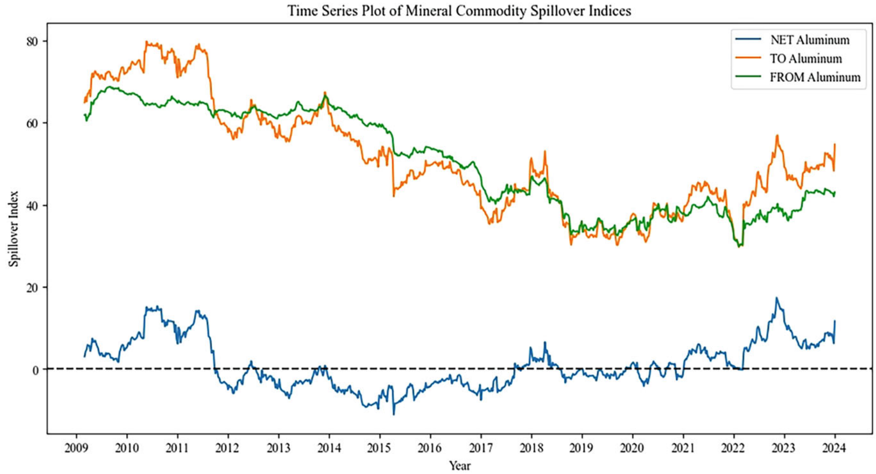

Fig. 10.11 Directional volatility spillover effect of the aluminium market

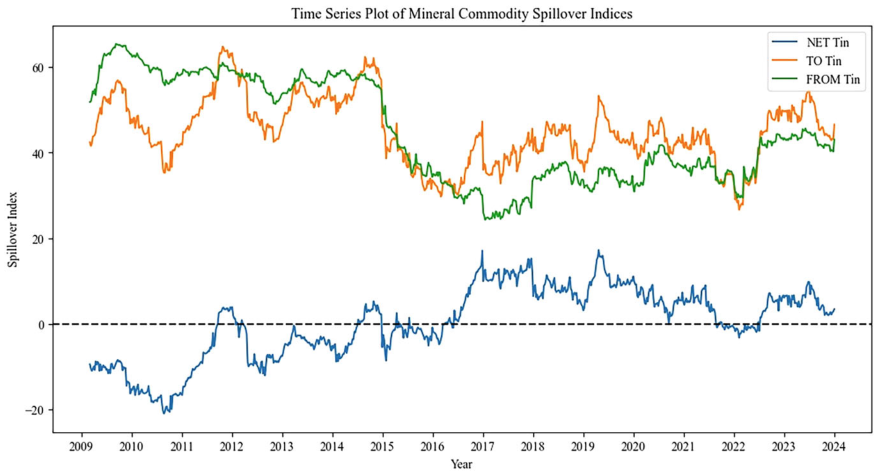

Fig. 10.12 Directional volatility spillover effect of the tin market

2012, characterized by a positive spillover index. Between 2012 and 2018, it transitioned to a net recipient of volatility spillovers. After 2018, the index hovered around zero, though a recent upward trend suggests a strengthening integration with the broader market system. Conversely, as depicted in Fig. 10.12, the tin market predominantly displayed a negative net spillover index before 2016, indicating its role as a net recipient. However, following 2016, an uptick in the volatility spillover index marked the tin market's shift to a net transmitter, with fluctuations generally confined to a range of 0–20%.

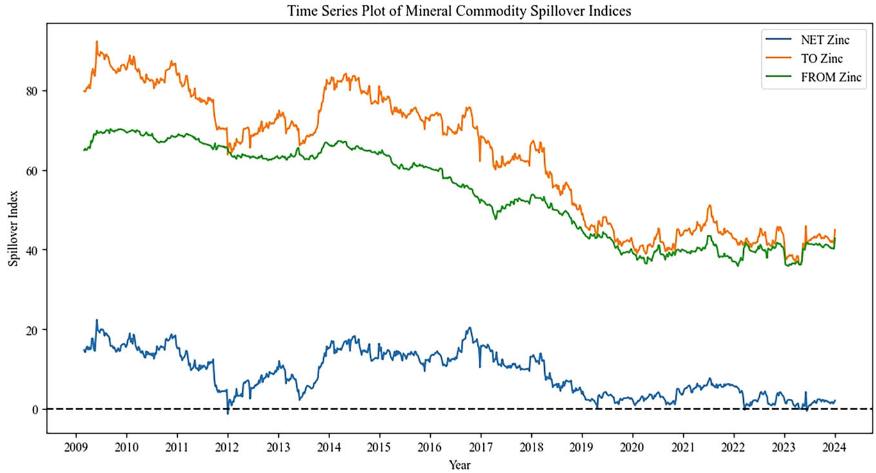

Fig. 10.13 Directional volatility spillover effect of the zinc market

Then, this study delves into the dynamics of directional volatility information transmission during significant events. After the 2008 global financial crisis, the To and From spillover indices of the commodity futures markets showed an upward trend in 2009. The copper, lead, nickel, aluminium, and zinc markets were the net transfers of the volatility spillover effect during this period, while the gold, silver, natural gas, crude oil, and tin markets were the net recipients of the effect. Notably, the From spillover index of the natural gas market surged during the financial crisis, signifying a progressively stronger connection with systemic risk. This development underscored the increasingly prominent 'financialization' aspect of energy commodities amidst the financial turmoil. In line with the theory of financial contagion, due to the high interconnectivity of financial markets, even the most minute pieces of information can disseminate rapidly through financial channels.

Since the U.S. withdrew from quantitative easing policy and the oil price plummeted in 2014, the To and From spillover indices of gold, silver, natural gas, crude oil, nickel, tin, and zinc markets have increased significantly. The main contributors to the overall volatility of the system are the lead, nickel, and zinc futures markets, especially the nickel market. Its spillover to other markets reached the highest value of 85% in 2014, while that of zinc and lead markets reached more than 80% and 70% respectively. Throughout this period, the influence of other markets on the natural gas market intensified progressively. The spillover index for the natural gas market experienced a marked surge over a brief interval, with the net volatility spillover index for the natural gas market dipping to below −20% in 2014.

After the withdrawal of the United States from the Iran nuclear agreement in 2018, the To and From spillover indices of the gold, natural gas, crude oil, aluminium, and tin markets exhibit an obvious upward trend, reaching a peak. Gold, natural gas, tin, and zinc serve as primary conduits for the volatility spillover effect, with natural gas playing a particularly significant role. Since 2018, the net spillover index for these commodities has transitioned from negative to positive, transforming them from recipients to transmitters of volatility. This shift aligns with the pronounced drop in oil prices and the sustained selling pressure in the crude oil market, which spanned 12 consecutive days. Concurrently, the volatility in natural gas experienced considerable fluctuations.

The above analysis indicates that the influence of each mineral commodity futures market on the system's overall volatility is not constant but evolves over time. There exists an asymmetric nature in the directional volatility spillovers, with individual markets alternating between sending and receiving volatility information. This asymmetry is dynamic, shifting across different time periods. For effective risk management, selecting assets with pronounced heterogeneity can help in diversifying investment risks. Moreover, during certain periods, volatility exhibits strong intermarket correlations, which can be utilized to forecast price movements in bulk commodities with lower liquidity.

10.5 Conclusion

This chapter investigates the time-varying volatility spillover dynamics among a selection of energy and critical mineral commodity markets (totaling ten). Utilizing a time-varying volatility spillover index model grounded in the TVP-VAR framework, it delineates the mechanism through which volatility information is transmitted across the futures markets of energy and critical minerals.

The empirical analysis of mineral commodity market data from February 23, 2009, to December 29, 2023, reveals that total volatility spillover effects are characterized by time-varying and periodic dynamics, with significant structural shifts occurring in response to major economic and financial events. These include the post-financial crisis period, the U.S. exit from quantitative easing in 2014, the surge in shale oil production, the U.S. withdrawal from the Iran nuclear deal in 2018, and the COVID-19 pandemic in 2020. These events coincide with notable peaks and troughs in volatility spillover, highlighting the impact of global political and economic shifts on the interconnectedness of international mineral commodity futures markets.

Moreover, the results reveal varying roles of mineral commodity markets in fluctuation risk and system-wide influence. The lead, nickel, and zinc markets predominantly act as information providers with consistently positive net spillover indices. In contrast, gold, copper, natural gas, and crude oil mainly absorb fluctuation information, exhibiting negative net spillover indices. The silver market's role alternates between sender and receiver, with a notable shift from receiver to transmitter between 2012 and 2016. The aluminium market transitioned from a net transmitter to a receiver post-2012 and has recently shown increased system connectivity. The tin market changed from a net receiver to a sender after 2016, with its spillover index fluctuating within 0–20%. Each market's impact on system fluctuation evolves over time, demonstrating asymmetric and dynamic directional spillover effects.

The examination of spillover dynamics within the energy and critical mineral commodity futures markets provides investors with a valuable resource for making enlightened investment and risk management decisions. Furthermore, it provides commodity market regulators and policymakers with insights to concentrate on market comovement and the proactive prevention of risk spillovers.

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