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Impacts of the U.S.-China Trade War on Lithium-ion Battery Supply Chains: A Network Analysis Approach

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ABSTRACT

Lithium is a critical strategic resource essential for electric vehicles and lithium-ion batteries, both of which play pivotal roles in the transition to renewable energy. This study examines the global lithium supply chain, analyzing four representative products—lithium carbonate, lithium hydroxide, lithium-ion batteries, and electric vehicles—across the upstream, midstream, and downstream sectors from 2012 to 2023. Utilizing complex network theory, the research explores the structural characteristics and dynamic evolution of global trade networks before and after the U.S.-China trade war. The findings reveal that the lithium supply chain exhibits strong small-world characteristics, with high clustering coefficients and relatively short path lengths across all stages. Differences in trade network patterns were observed between products: lithium hydroxide shows more regional concentration, while electric vehicles demonstrate a more globalized trade network. These insights offer important implications for understanding supply chain resilience and vulnerability in the face of geopolitical conflict.

KEYWORDS

U.S.-China Trade War; Complex Network Analysis; Lithium; Lithium-ion Batteries

1. INTRODUCTION

Lithium, a key component of lithium-ion batteries, plays a pivotal role in modern energy storage solutions. Widely used in electric vehicles (EVs), portable electronics, and energy storage systems, lithium-ion batteries are prized for their high energy density, long life cycle, and efficiency. As global industries increasingly shift towards sustainable energy and electric mobility, lithium has become a strategic resource in global supply chains. The stability of the lithium supply chain is thus critical for nations like China, whose economic and technological growth is closely tied to the production of EVs and energy storage technologies.

However, the U.S.-China trade war, which began in 2018, has posed significant risks to global supply chains, including the lithium supply chain. The trade war, aimed at reducing the U.S. trade deficit with China, has disrupted trade flows, leading to increased tariffs on key products such as electric vehicles, which directly impacts China's export competitiveness. This conflict mirrors past U.S. trade disputes, such as the trade friction with Japan in the 20th century, where the U.S. sought to limit imports and open foreign markets to balance trade deficits [1, 2]. As a result, the trade war has brought renewed attention to the vulnerabilities within China's lithium supply chain, especially considering China's reliance on imported upstream lithium materials and salts. Understanding the structural risks and dynamics of the lithium trade network during and after the trade war is vital for developing strategies to safeguard supply chain stability.

Supply chain risks can arise from a variety of factors, including geopolitical tensions, market uncertainties, and operational inefficiencies [3-5]. Identifying and analyzing the causes of supply chain disruptions is crucial to mitigating risks and maintaining the flow of goods. Effective risk management strategies require a deep understanding of where risks originate, as incorrect identification can lead to inadequate responses [6]. For instance, in the context of globalized supply chains, organizations must implement comprehensive risk management frameworks that combine both qualitative and quantitative techniques to assess and prioritize risks [7, 8]. These strategies help synchronize supply chain operations, reduce uncertainty, and enhance resilience against potential disruptions. The U.S.-China trade war serves as a critical case study for examining how external risks—such as tariffs and geopolitical conflicts—can ripple through and destabilize global supply chains, including critical industries like lithium production and distribution.

In light of the lithium supply chain's importance to China's future economic growth and technological advancements, this study focuses on the impact of the U.S.-China trade war on global lithium trade networks. By analyzing trade data from 2012 to 2023 and employing complex network theory, this research reveals the structural characteristics of lithium supply chains and the changing roles of China and the U.S. in this global network. Drawing on insights from the trade war and previous U.S.-Japan trade frictions, this study aims to identify the vulnerabilities within the lithium supply chain and propose strategies for improving resilience. By examining these dynamics, the paper contributes to a broader understanding of how geopolitical conflicts shape global supply chains and offers practical solutions for ensuring long-term stability.

2. THE BACKGROUND AND CAUSES OF THE U.S.-CHINA TRADE WAR

2.1. Background

China's rapid development is closely linked to its demographic dividend in recent years. Today, China has become the world's largest manufacturing country, with manufacturing value-added accounting for approximately 30% of the global total, holding the top position globally for 14 consecutive years. Manufacturing requires a well-organized structure and the formation of large-scale industrial economies. Since 1990, China's population has grown significantly (Figures 1), with a large proportion being young people. Coupled with a well-managed and highly qualified labor force, China has achieved economies of scale, enabling a highly efficient and cost-effective industrial model. This abundant and cheap labor force made China a crucial manufacturing base globally, attracting significant foreign investment to set up factories. Through the policy of reform and opening up and joining the World Trade Organization (WTO), China successfully transformed its labor resources into a driving force for economic growth, quickly rising as the "world's factory." As educational attainment levels improved (Figures 2 and 3), China transitioned from labor-intensive to technology-intensive industries, though wage demands have risen concurrently. Alongside the rapid development of the manufacturing sector, China has gradually established a complete industrial and supply chain, upgrading from low-end processing to high-end manufacturing. Government policies supporting the manufacturing sector, such as tax incentives, infrastructure development, and investments in technological innovation, have further solidified China's global position in manufacturing.

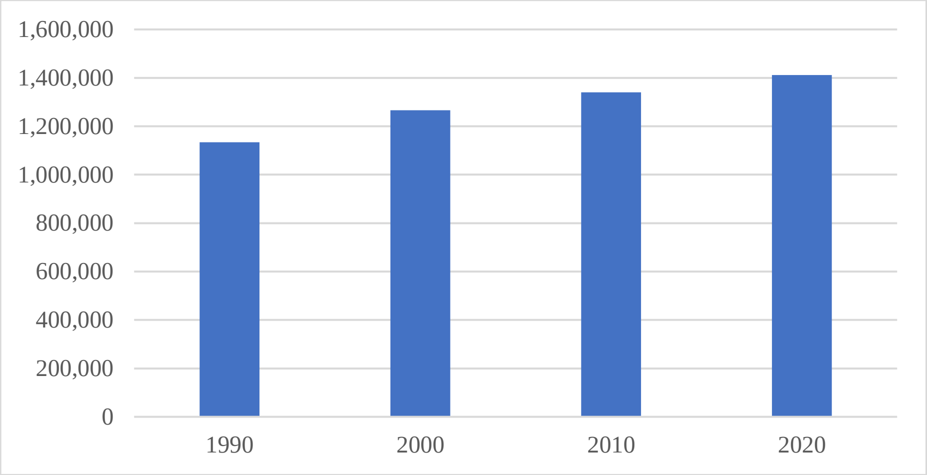

Figure 1. Total Population of China from 1990 to 2020

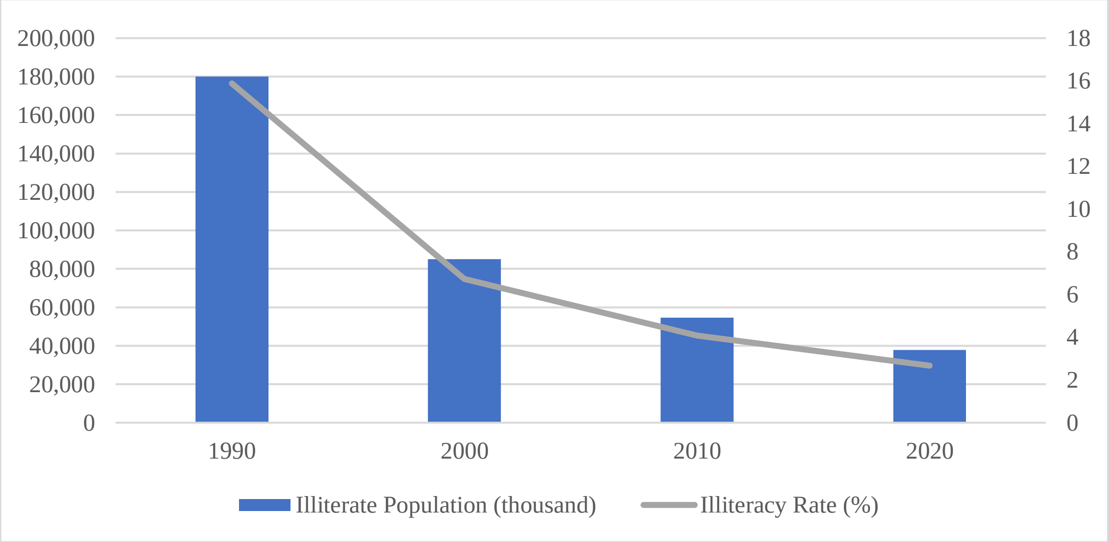

Figure 2. Illiteracy Rate and Number of Illiterates in China from 1990 to 2020

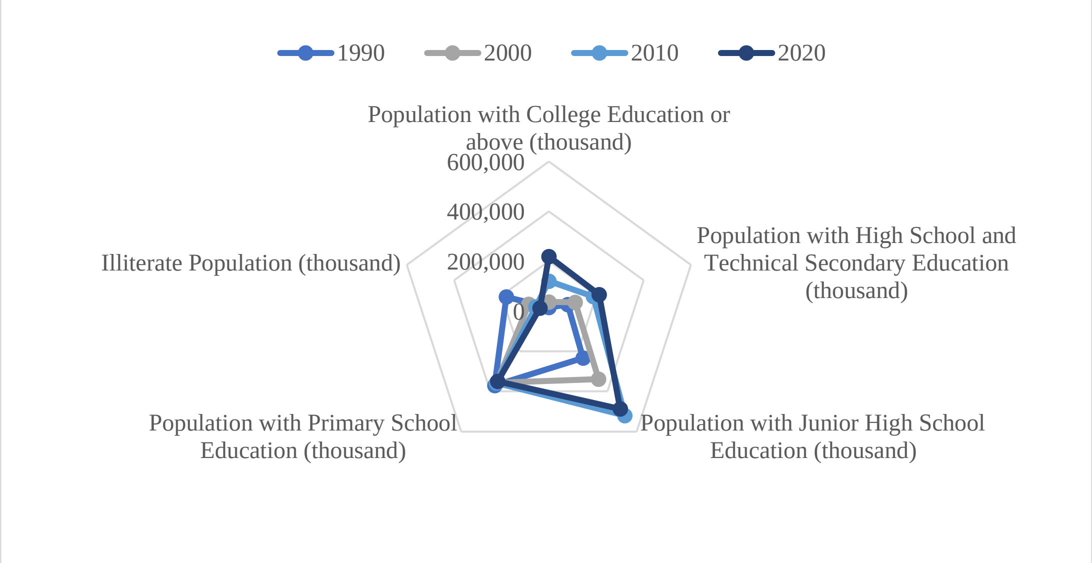

Figure 3. Educational Attainment of the Population in China from 1990 to 2020

2.2. Declining International Competitiveness of U.S. Products

Many U.S. products, particularly those related to manufacturing, have been losing their cost advantages. Compared to China, U.S. manufacturing costs are higher due to elevated wages and stringent environmental regulations. At the same time, as China's manufacturing sector continues to upgrade, the quality of Chinese products has steadily improved, leading to a gradual decline in the competitiveness of U.S. products across several manufacturing sectors. Chinese manufacturing not only enjoys cost advantages but has also made significant strides in technological advancements and production efficiency, further eroding the U.S. market share in these sectors. Today, although the U.S. retains a competitive edge in high-tech industries, China is rapidly catching up in emerging technologies such as 5G, artificial intelligence, and renewable energy. This trend has caused concern in the U.S., as it perceives a threat to its leadership in technological innovation.

To estimate a country's international competitiveness in certain products and industries, we can calculate the Trade Specialization Coefficient (TSC).

$$\text{Tsc}= \frac{\text{The net foreign trade amount of a certain commodity of a country}}{\text{the total foreign trade amount of that commodity}} \tag{1}$$

This value equals the net foreign trade of a specific product divided by the total foreign trade of that product. The formula yields a result between -1 and 1. A positive value, closer to 1, indicates stronger international competitiveness, while a negative value, approaching -1, suggests weaker competitiveness. By calculating the TSC values for over one hundred U.S. trade goods from 2012 to 2018, we can plot trends, as shown in Figure 4 (data source [9]).

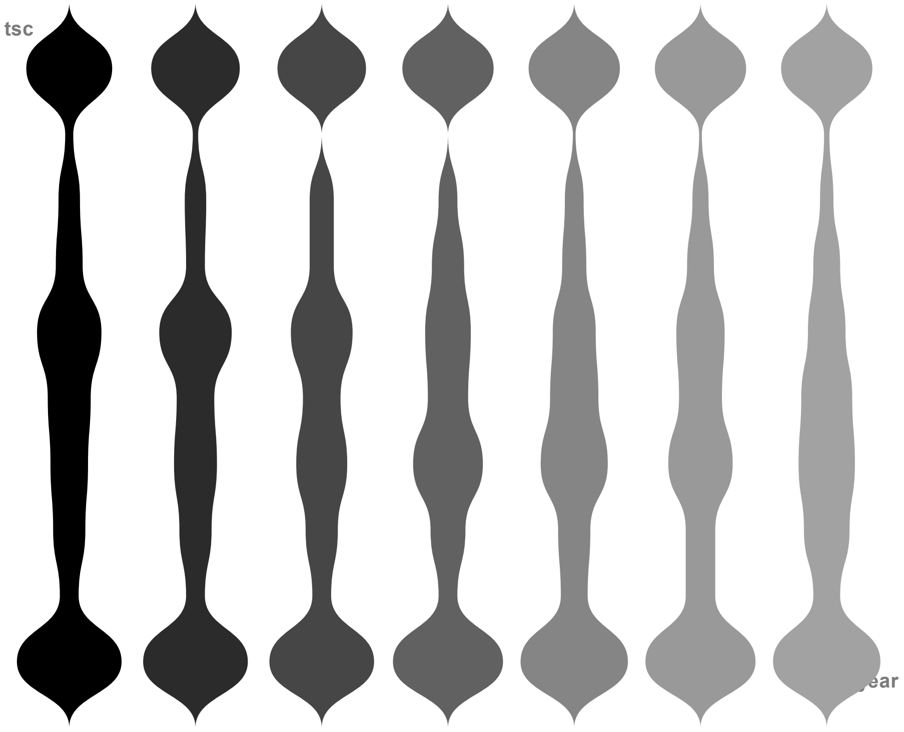

Figure 4. The TSC values of over a hundred types of trade goods of the United States from 2012 to 2018.

Violin plots effectively illustrate the distribution of these values, with the width of the shape indicating the concentration and frequency of specific values. The violin plot for TSC values from

2012 to 2018 shows a growing distribution of negative values, approaching -1, indicating an increase in industries with little to no international competitiveness. Meanwhile, positive values became less frequent, with fewer clustered around any specific value, apart from those at 1. This demonstrates a decline in the international competitiveness of many U.S. industries during this period, suggesting that certain sectors are losing their competitive edge globally.

The U.S. has also accused China of issues related to intellectual property protection and forced technology transfers, claiming that China’s unfair trade practices have harmed American businesses. One of the drivers of the U.S.-China trade war is the U.S.'s desire to pressure China into making changes to its intellectual property protection and technology transfer policies, with the broader goal of slowing China's growth and solidifying the U.S.'s dominance in various fields.

2.3. Risks of Manufacturing Concentration in China

As China's manufacturing scale continues to expand, the U.S. has grown increasingly concerned about the risks associated with over-reliance on China’s manufacturing supply chain, particularly for critical components and raw materials. During the outbreak of COVID-19, over 70% of the world's mask production was sourced from China. However, due to China's domestic demand for masks at the time, much of the production was prioritized for the domestic market. This incident made the U.S. realize the potential risks posed by the concentration of manufacturing in China. If a single product can cause such issues, global supply chains, which consist of multiple interdependent links, are even more susceptible to disruptions. The fragility of concentrating supply chains in one country highlights the vulnerabilities that emerge when supply chains are centralized in a single location, prompting the U.S. to rethink its supply chain strategies. The growing geopolitical tension between the U.S. and China has further heightened U.S. concerns about supply chain security. The U.S. is actively seeking to restructure its supply chains to reduce dependence on China and ensure the safety and security of critical supplies.

2.4. Trade Protection Policies and Electoral Considerations

One of the key drivers of the U.S.-China trade war is the U.S.'s trade protection policies, which are primarily aimed at protecting domestic manufacturing and preserving jobs. By raising tariffs and setting up trade barriers, the U.S. aims to reduce imports and stimulate domestic production. The Trump administration believed that combating unfair trade practices would revitalize U.S. manufacturing and restore the country's economic competitiveness. Trade wars can also serve as political tools, with aggressive trade policies appealing to voters, particularly those in industries negatively impacted by trade. However, in the 2018 midterm elections, the U.S.-China trade war had a negative effect on the Republican Party’s performance, particularly in counties heavily affected by retaliatory tariffs, where Republican support declined. This impact was more pronounced in politically competitive areas. Agricultural subsidies and other policy measures could only partially offset these negative effects.

2.5. Background and Causes of the U.S.-Japan Trade War

The U.S.-Japan trade friction occurred between the 1970s and 1990s. Similar to the U.S.-China trade war, the U.S.-Japan conflict was driven by trade imbalances and fierce competition between the two countries' industries, with the U.S. being the primary party in both disputes. This paper seeks to offer a comparative analysis, examining the U.S.-Japan trade conflict to provide insights into the U.S.-China trade war.

2.5.1. Background of the U.S.-Japan Trade Friction

Following World War II, Japan achieved rapid economic growth through policies focused on economic recovery, technological advancement, and government-led industrial initiatives. Japan emerged as the world’s second-largest economy. Japanese manufacturing gained a significant competitive advantage in sectors such as automobiles, electronics, and steel, leading to large-scale exports to the U.S. and other countries. Japanese companies excelled in product quality, production efficiency, and cost control, allowing Japanese goods to capture an increasing share of the U.S. market. Japanese automobiles and electronics, in particular, gained popularity among U.S. consumers, but this also contributed to the decline of related U.S. industries, causing American manufacturing to lose market share in these fields, leading to growing discontent in the U.S.

2.5.2. U.S. Trade Deficits and Employment Issues

As Japanese exports to the U.S. increased, the U.S.-Japan trade deficit widened. The U.S. accused Japan of unfair trade practices, such as export subsidies and market access restrictions, which diminished the competitiveness of U.S. companies. The enormous trade deficits in sectors where Japanese companies held a competitive advantage, particularly automobiles and electronics, became the focal point of U.S.-Japan trade friction. At the same time, Japan's rise in manufacturing led to the transfer of parts of the U.S. manufacturing supply chain to Japan, resulting in a decline in U.S. manufacturing and the loss of job opportunities, further intensifying discontent within the U.S. At the time, the U.S. government and industries widely believed that Japan employed non-tariff barriers to restrict U.S. products from entering the Japanese market while simultaneously dumping low-priced Japanese goods into the U.S. market, severely harming U.S. economic interests.

2.5.3. Subsequent U.S. Responses

Faced with Japan’s strong competition, the U.S. government implemented a series of trade protection measures, including raising tariffs, imposing quota restrictions, and pressuring Japan to open its markets. In 1981, the U.S. forced Japan to sign the U.S.-Japan Automotive Trade Agreement, limiting Japan's automobile exports and requiring Japanese companies to invest in the U.S. and create jobs. In 1985, the U.S. and Japan signed the Plaza Accord, which adjusted exchange rates by forcing the appreciation of the yen to reduce Japan’s price competitiveness and decrease the U.S. trade deficit. However, the yen’s appreciation fueled an asset bubble in Japan, eventually leading to Japan’s economic recession in the early 1990s.

2.6. Analysis of the Causes and Development of the U.S.-China Trade War

The background of the U.S.-China trade war bears some resemblance to the U.S.-Japan trade friction. Both China and Japan had substantial trade surpluses with the U.S. (Figures 5 and 6). A comparison of the trade data between the three countries shows that Japan began to experience trade surpluses with the U.S. in 1965, and although the surpluses fluctuated over the following decades, the overall trend did not expand significantly. China, on the other hand, has consistently maintained a large trade surplus with the U.S. since 1965, though it has seen some recent declines. Correspondingly, both countries' GDP indices have followed similar patterns (Figure 7). In the 1990s, Japan’s GDP index approached that of the U.S., but after the U.S. took action, Japan's economy stagnated. Similarly, in 2017, China’s GDP index neared the U.S. level, marking the start of the trade war.

A comparison of China and Japan’s shares in U.S. imports shows that Japan’s share peaked in 1987 and then began a steady decline, whereas China’s growth has been more rapid, and the future remains unpredictable. If certain measures are not taken, it is likely that China's trade surplus could also be suppressed.

The following trade dependency formulas effectively demonstrate the degree of trade dependence between the U.S. and China, and the U.S. and Japan.

$$\text{Trade Dependency Ratio} = \frac{\text{Total Trade Amount between Two Countries in One Year}}{\text{Country's GDP for That Year}} \times 100 \tag{2}$$

$$\text{Import Trade Dependency Ratio} = \frac{\text{Annual Import Amount to a Certain Country}}{\text{Country's GDP for That Year}} \times 100 \quad (3)$$

The similarities between the two are evident, as both countries' import dependency ratios are closely aligned with their trade dependency ratios (Figures 8 and 9). After the trade friction, both Japan and China experienced similar downward trends in trade surpluses after periods of significant growth. Additionally, one can conduct a correlation analysis between the trade dependence of the United States on Japan and China and the trade dependence of the United States on Japan and China's imports. It can be seen that both are highly correlated and have achieved their trade dependence by increasing their export volume (Table 1).

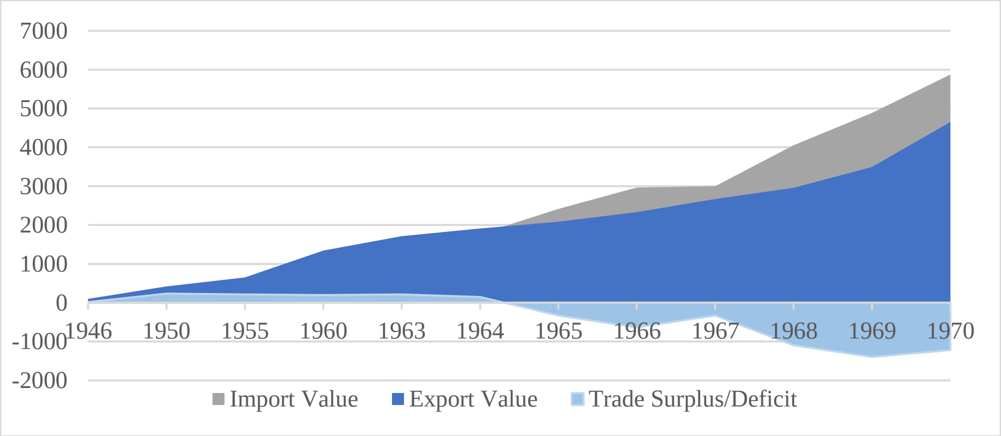

Figure 5. Annual import and export data of the United States regarding Japan from 1946 to 1970.

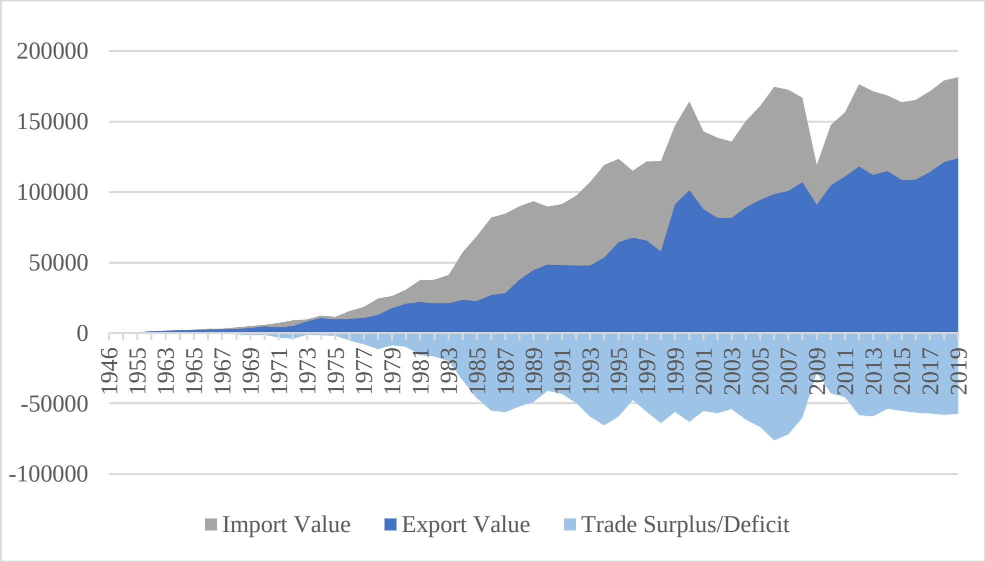

Figure 6. Annual import and export data of the United States regarding China from 1946 to 2019.

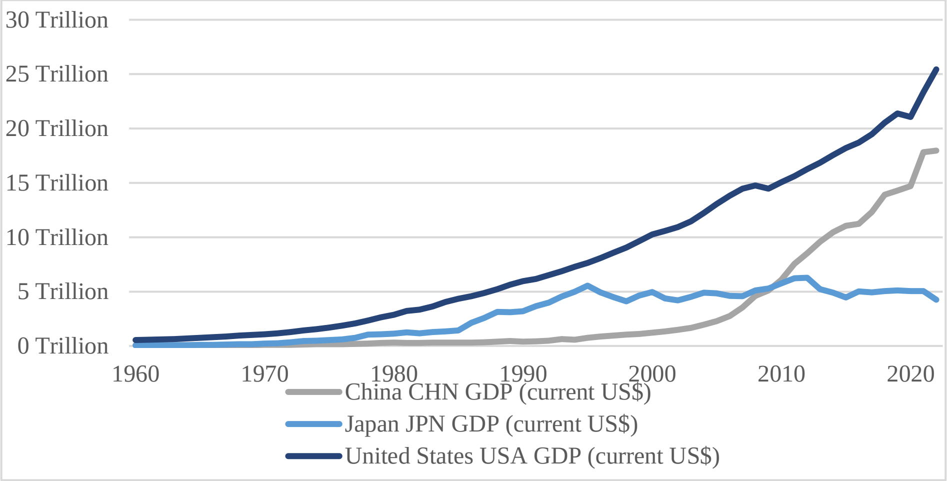

Figure 7. Comparison of GDP indices for China, the United States, and Japan from 1960 to 2022.

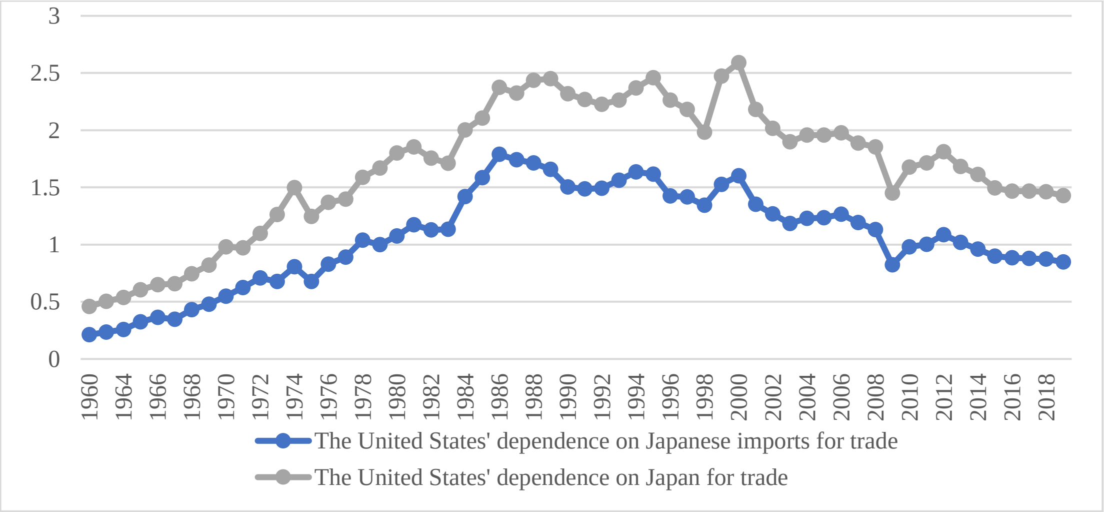

Figure 8. The United States' dependence on Japan for trade

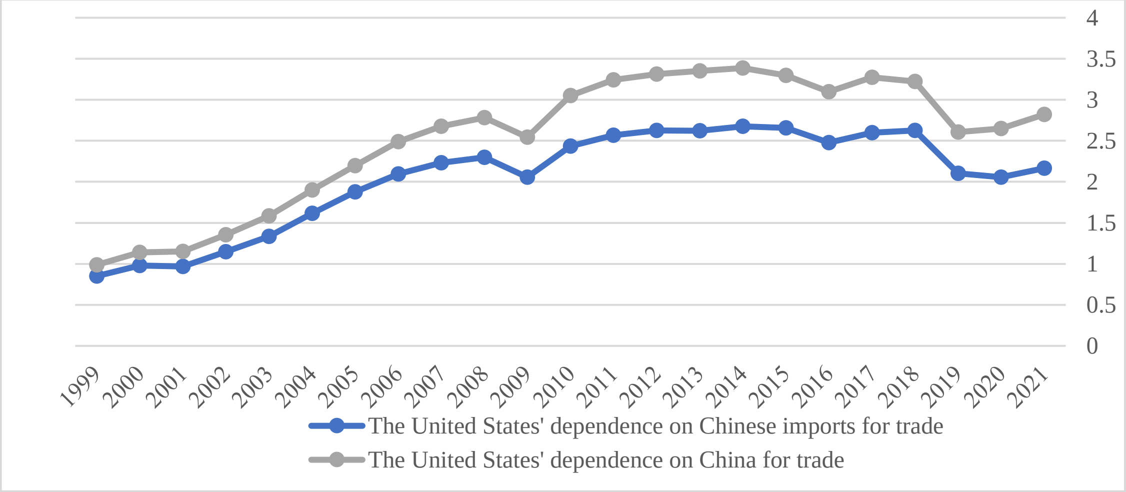

Figure 9. The United States' dependence on China for trade

Table 1. Analysis of the Correlation Between Trade Dependence and Import Trade Dependence

	The dependence of the United States on imports from Japan	The dependence of the United States on imports from China
Correlation coefficient	0.984	0.997
Sample size	58	23

2.7. Comparison of U.S.-Japan Trade Friction and the U.S.-China Trade War

In terms of economic development stages, the U.S.-Japan trade friction occurred when Japan had already become a highly developed economy and held a leading position in global manufacturing. By the 1980s, Japan was the world's second-largest economy. The U.S.-China trade war, on the other hand, took place as China was transitioning from a middle-income country to a high-income country. Although China's manufacturing sector rose rapidly, its global economic position and technological level still lag behind Japan's at the time. Furthermore, the U.S.-Japan trade friction primarily centered on traditional manufacturing industries, such as automobiles, electronics, and steel. Japan dominated the U.S. market in these sectors through efficient production and high-quality products. In contrast, the U.S.-China trade war spans a broader range of industries, including not only traditional manufacturing but also high-tech sectors like 5G, artificial intelligence, and semiconductors. China's rapid advancements in these emerging technologies have sparked intense reactions from the U.S. While the U.S. remains concerned about its trade deficit, it is also deeply worried about China's technological advancements, which threaten its global leadership in innovation.

There are also differences in the triggers of the two conflicts. U.S.-Japan trade friction was primarily driven by economic factors, with political pressure playing a secondary role. The core issues were the trade deficit and market competition. However, the U.S.-China trade war is more deeply intertwined with political factors, particularly during the Trump administration, where the trade war was used as a tool to garner domestic political support and to curb China's rise as a global power.

The different historical contexts also shaped the nature of the trade disputes. The U.S.-Japan trade friction occurred during the early stages of globalization, when global supply chains were not yet highly integrated. The trade issues were primarily bilateral. In contrast, the U.S.-China trade war is unfolding in a highly globalized world, where complex global supply chains amplify the impact of trade conflicts, affecting multiple facets of the global economy.

3. THE LITHIUM SUPPLY CHAIN

In 2022, China produced 7.058 million new energy vehicles (NEVs) and sold 6.887 million units, representing year-on-year increases of 96.9% and 93.4%, respectively. China has now become the world's largest producer and consumer market for NEVs. Lithium-ion batteries are a key component of NEVs, functioning as the energy source for charging and discharging these vehicles. Similarly, lithium-ion batteries dominate energy storage technology for various applications, ranging from consumer electronics to electric vehicles and grid storage. The high energy density, efficiency, and long cycle life of lithium-ion batteries make them a crucial element in the proliferation of electric vehicles and the integration of renewable energy. Compared to other commonly used secondary batteries, such as lead-acid, nickel-metal hydride, and nickel-cadmium batteries, lithium-ion batteries maintain a comparative advantage, offering higher operating voltage, greater energy density, and longer cycle life.

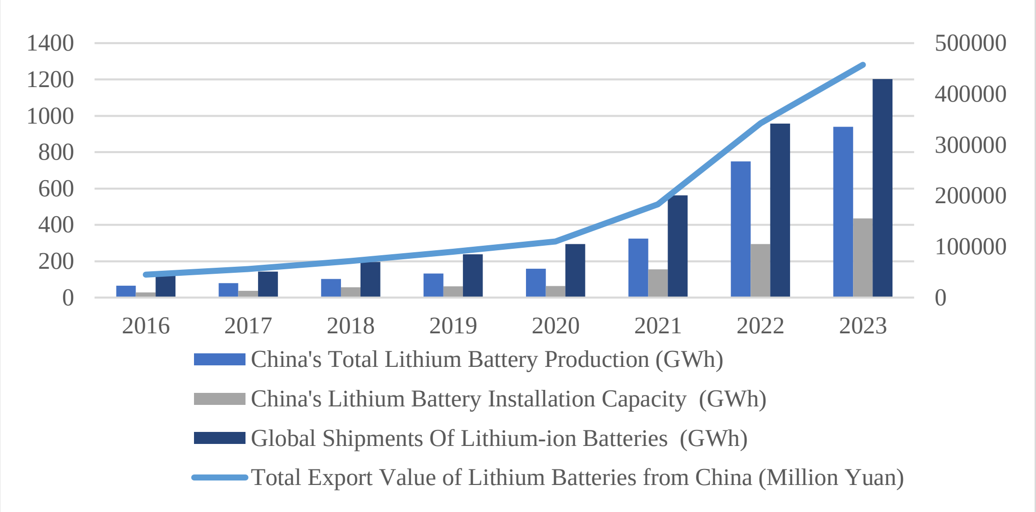

Figure 10. Lithium-ion Battery Production and Trade Data (Institute Data Source: Ministry of Industry and Information Technology of the People's Republic of China, General Administration of Customs of China, EVTank, Prospective Industries. Export values denominated in US dollars are converted to RMB using the annual average exchange rate.)

With the rapid development of China’s NEV industry in recent years, the country has secured a pivotal role in the global NEV sector. According to the National Development and Reform Commission of China, the country's NEV production and sales volumes account for over 60% of the global total, ranking first in the world for nine consecutive years [10]. This is an achievement that China did not accomplish during the era of fuel-powered vehicles. The automotive industry, being a technology-intensive sector with massive demands for raw materials, equipment, and components, plays a crucial role in promoting the development of infrastructure, energy, transportation, and services, while occupying a significant position in the economy. NEVs, in particular, contribute to the realization of the "carbon neutrality" goal and align with the future development trends of sustainability and environmental protection. Consequently, the stability of the lithium-ion battery supply chain—a core component of NEVs—directly impacts national economic development and security. In this context, the effects of the U.S.-China trade war on China’s global supply chain position cannot be overlooked.

3.1. Data Sources

To specifically examine the risks within the lithium supply chain and the characteristics of the trade networks for China, the U.S., and the world before and after the trade war, this paper employs complex network theory to conduct supply chain risk analysis. This methodology allows for the evaluation of the strength and evolution of different links in a supply chain from a holistic network perspective, enabling the prediction and mitigation of potential risks—a comprehensive approach to analyzing the root causes of supply chain risks from a network-wide perspective [11]. The data used in this study encompasses global trade statistics from 2012 to 2023 for the lithium-ion battery industry. The lithium supply chain is segmented into upstream, midstream, and downstream stages, with lithium carbonate, lithium hydroxide, power batteries, and NEVs selected as representative products. Complex network theory was applied to construct global trade networks for the three stages of the lithium supply chain. Based on this framework, the study analyzes the overall characteristics of the trade networks across different stages, as well as the node characteristics of China and the U.S., examining changes in the network and node attributes before and after the trade war. These analyses reveal the impacts of the U.S.-China trade war on the overall trade network and on China and the U.S., while also identifying the weak points in China’s lithium industry and proposing corresponding risk mitigation strategies.

The trade data used in this paper is sourced from the International Trade Center's TRADE MAP database, capturing trade volumes and values from 2012 to 2023, covering import-export relationships for lithium products across 252 countries and regions. Some countries or regions with small trade volumes or incomplete data were not included in the database. The trade network for the lithium industry chain is built based on export volume data.

To enhance analytical efficiency, the data underwent preprocessing. First, China’s data was divided into four regions: Mainland China (excluding Hong Kong, Macao, and Taiwan), Hong Kong, Taiwan, and Macao. Bilateral trade relationship data was formed using export data from the reporting countries (or regions) in TRADE MAP to construct bilateral trade networks. Second, any data with zero or missing statistics was excluded from further analysis to ensure its validity in the network. Additionally, when analyzing average path lengths, clustering coefficients, and network density, the twelve-year dataset was averaged to study the overall characteristics of the lithium trade network from 2012 to 2023. For metrics such as betweenness centrality, closeness centrality, and core-periphery structures, the data was divided into averages for the six years before and six years after the onset of the U.S.-China trade war to facilitate a comparative analysis of the trade war’s impact on the lithium industries in China and the U.S. To avoid discrepancies due to differing country standards for HS codes and product classification, this paper used only the 6-digit international HS codes from the TRADE MAP database and mapped them to the corresponding supply chain products (Table 2). Additionally, due to the data coverage of a large number of countries in TRADE MAP and slight differences in the statistical scopes, there are products with multiple measurement units (e.g., electric vehicles and lithium-ion batteries, which are measured by both units and tons), making it difficult to unify trade volume data. Thus, this paper adopts trade value data for analysis.

Table 2. Lithium containing product categories and HS codes

HS code	Product Name	Category Name
283691	Lithium carbonates	Lithium carbonates
282520	Lithium oxide and hydroxide	Lithium oxide and hydroxide
850760	Lithium-ion accumulators	Lithium-ion accumulators (excl. spent)
870380	Electric vehicle	Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with only electric motor for propulsion (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 8703.10)

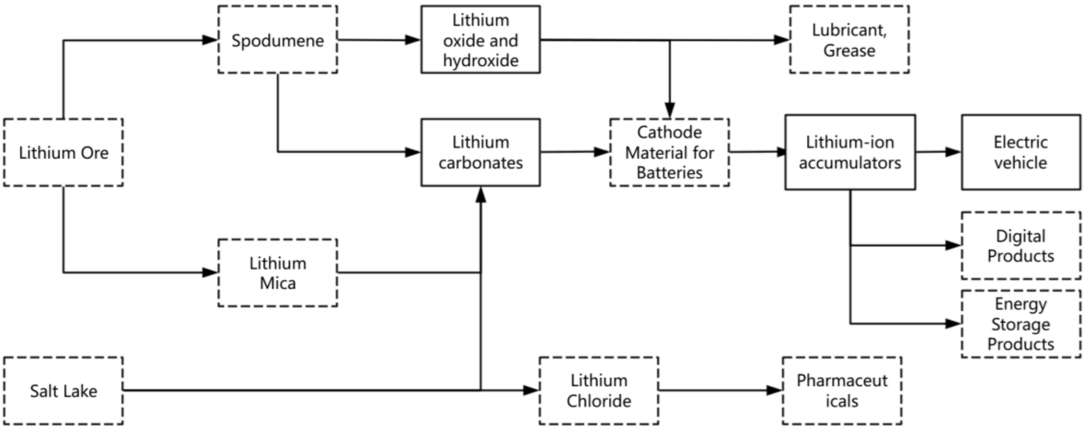

Figure 11. Structure diagram of Lithium supply chain

The lithium industry chain encompasses multiple stages, including lithium ore mining, lithium extraction from salt lakes, lithium salt processing, downstream battery cathode material processing, electrolyte manufacturing, battery production, and the end-use of electronics, vehicles, and energy storage systems. The key lithium-related trade products include spodumene, lepidolite, brine from salt lakes, lithium carbonate, lithium hydroxide, power batteries, and NEVs. Since upstream products such as spodumene, lepidolite, and brine from salt lakes are less widely recognized, lack standard international HS codes, or have newly added codes with limited data, these products were not included in this study. Instead, four representative products with large trade volumes—lithium carbonate, lithium hydroxide, power batteries, and NEVs—were selected to construct the supply chain (Figure 11). Rectangular blocks represent lithium-containing products, while dashed lines indicate lithium products not included in the study. Finally, bilateral trade volume data from 2012 to 2023 was processed based on the 6-digit HS codes to construct annual trade networks for the four products.

3.2. Complex Network Model

Table 3. Meaning and calculation formula of complex network indicators

Indicator Name	Meaning	Calculation Formula
Degree	The number of edges associated with vertex v, including in-degree and out-degree. In-degree is the number of directed edges with vertex v as the endpoint, out-degree is the number of directed edges with vertex v as the starting point.	$TO_{(V)} = ID_{(V)} + OD_{(V)}$ where: $ID_{(V)}$ is the in-degree of vertex v; $OD_{(V)}$ is the out-degree of vertex v; $TD_{(V)}$ I is the degree of vertex v.
Average Path Length	The average value of the distance between any two nodes in the network. The larger the value, the greater the distance between countries and the more dispersed the distribution.	$L = \left(2\sum_{i\geq j} d_{ij}\right)/[N(N-1)]$ Where: N is the number of nodes; d_{ij} is the number of edges in the shortest path between nodes i and j.
Clustering Coefficient	The clustering coefficient can reflect the strength of connections between neighboring countries and the expected degree of trade occurrence. The larger the value, the higher the connection strength.	$C_i = n_i/[k_i(k_i-1)]$ Where: C is the clustering coefficient; i is the node; k is the degree of the node; n is the actual number of edges between neighbors.
Network Density	Measures the sparsity or density of points in the network. Combined with the network diameter, it can depict the closeness of trade between parties.	$\rho = 2M/[N(N-1)]$ where: M is the number of actual edges in the network; N is the number of nodes. The larger the value, the denser the network. Combined with the network diameter, it can depict the closeness of trade between parties.
Betweenness Centrality	Measures the regulatory and control ability index of a node between other nodes.	$g(v) = \sum_{s\neq v\neq t} \sigma_{st}(v)/\sigma_{st}$ $\sigma_{\mathcal{A}}(v)$ is the number of shortest paths between vertex s and vertex t that pass through v; $\sigma_{\mathcal{A}}$ is the total number of shortest paths between vertex s and vertex t.
Closeness Centrality	Represents the counter-control ability of a point in the network. The larger the value, the shorter the distance, and the less susceptible to control.	$z = (\mathrm{n}-1)/\sum_{i\neq j}^{n} d_{(i,j)}$ where: n is the total number of nodes in the network; $d_{(i,j)}$ is the distance from node i to node j.

A complex network is characterized by a large number of nodes, edges with varying weights, and directional properties. The primary metrics of such a network include average path length, clustering coefficient, network density, betweenness centrality, closeness centrality, coreness, and centralization. The definitions and formulas for these metrics are provided in Table 3.

4. CURRENT STATUS OF LITHIUM TRADE

To examine the current state and trends of lithium supply chain products, this paper compiles trade volume and value data for lithium supply chain products from 2012 to 2023, displaying the trends of each product over time (Figure 12).

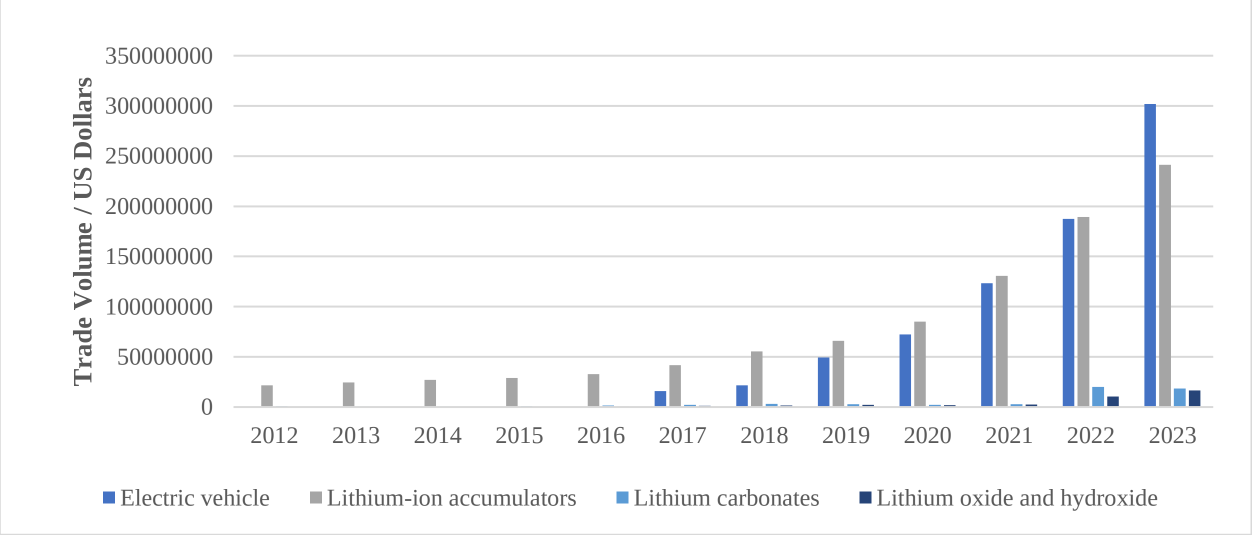

Figure 12. Trade Volume of Key Products Across Lithium-ion Battery Supply Chains: 2012-2023

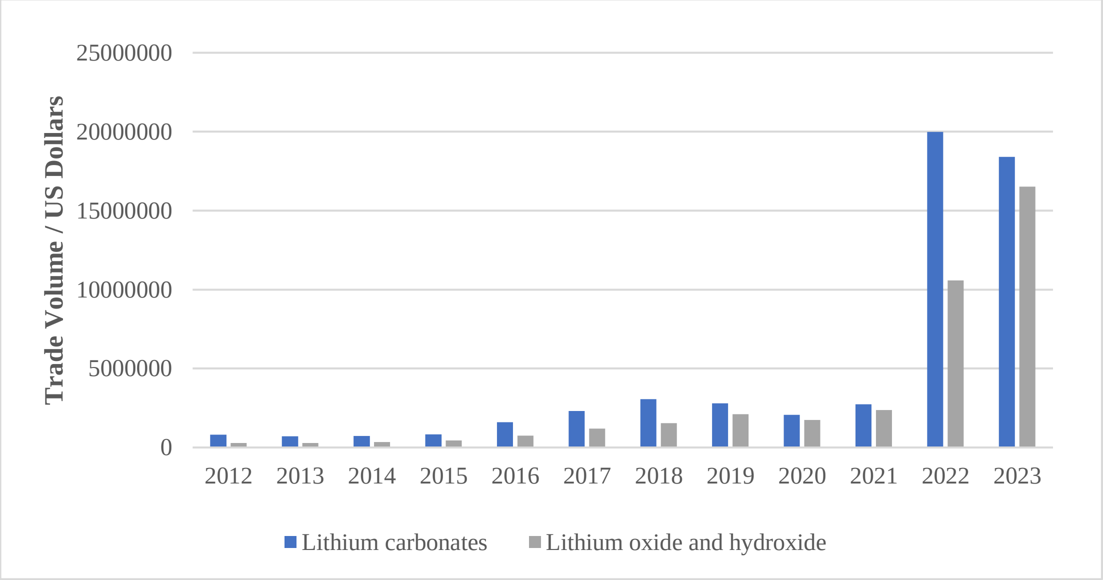

Figure 13. Trade Volume for Lithium Carbonate and Lithium Hydroxide: 2012-2023

As shown in Figure 12, during the period from 2012 to 2023, the trade value of downstream products such as electric vehicles (EVs) and lithium-ion batteries fluctuated significantly. EV trade saw a remarkable surge after 2016, growing from almost negligible trade volumes to becoming the product with the highest trade value among the four analyzed products. Similarly, lithium-ion batteries experienced notable growth after 2019. The growth of lithium carbonate and lithium hydroxide is also noteworthy. Although these two products serve as upstream raw materials in the supply chain and thus are not as valuable in comparison to downstream products, their trade value growth is still significant. When comparing these two products individually (Figure 13), it is evident that both lithium carbonate and lithium hydroxide achieved rapid growth in 2022, with their trade values being several times higher than in 2021. Following this rapid increase in 2022, the trade value of lithium carbonate slightly declined in 2023, whereas lithium hydroxide continued its upward trajectory. The fluctuations in the trade value of lithium carbonate and lithium hydroxide in recent years can likely be attributed to advancements in battery technology, which have led to changes in the raw materials used. Both lithium carbonate and lithium hydroxide are widely used in the cathode materials of lithium-ion batteries. With the increasing demand for lithium-ion batteries and downstream NEVs, the demand for better and more efficient battery cathode materials has risen as well. The slight decline in lithium carbonate trade value in 2023 and the continuous rise in lithium hydroxide may be related to changes in raw material usage driven by new materials. High-nickel ternary cathode materials, which offer higher energy density and lower overall costs, have become an ideal choice for high-end NEVs. While regular ternary cathode materials tend to use lithium carbonate as the lithium source, high-nickel ternary cathode materials are more suitable for using lithium hydroxide. This is because lithium hydroxide monohydrate has a lower melting point than lithium carbonate, allowing it to blend more uniformly and thoroughly with the ternary precursor during sintering, reducing surface lithium residues and enhancing the material's discharge capacity. Using lithium hydroxide and a lower sintering temperature also reduces cation mixing, improving cycle stability [12].

In terms of trade value trends, the inflection points for different products vary. For lithium carbonate, the trade value turning points occurred in 2018 and 2022, while lithium hydroxide saw a small turning point in 2019, though both began to grow again in 2021. On the other hand, EVs and lithium-ion batteries have been on a steady upward trend, indicating that the U.S.-China trade war had a more significant impact on the trade values of lithium carbonate and lithium hydroxide, but less on the other products.

To illustrate the flow of lithium resources in the global trade network, this paper identifies the major import and export countries for each product from 2012 to 2023 based on trade volume (Table 4). As shown in Table 4, from 2012 to 2023, the leading exporters of lithium carbonate globally were Chile, China, South Korea, and Norway, with these four countries accounting for more than 70% of the world's lithium carbonate trade volume. Chile, which possesses nearly 50% of the world's lithium reserves, holds a significant resource advantage due to the extraction of lithium salts, primarily lithium carbonate. During this period, the top four lithium ore exporters remained relatively stable, while the fifth-ranked country fluctuated, with Argentina being a possible candidate based on previous trade data. However, due to missing data for certain years, this position remains uncertain. Another critical midstream raw material is lithium hydroxide. The primary exporters of lithium hydroxide were China, Chile, the U.S., South Korea, and Russia. Thanks to advancements in large-scale extraction technology from salt lakes in recent years, China has achieved a significant advantage in lithium hydroxide exports, accounting for more than 70% of the trade value in recent years. South Korea only expanded its lithium hydroxide export scale significantly after 2022. China has consistently been the world's largest exporter of lithium-ion batteries, with minimal imports, primarily due to its competitive production capacity in the lithium-ion battery industry. Germany, however, ranks first in terms of lithium-ion battery imports, possibly due to its large-scale production of electric vehicles for export. EVs are the product with the highest trade volume in the global lithium supply chain. Germany, China, Belgium, South Korea, and Japan are the primary exporters of EVs, with most of these countries, except China, being traditional automotive powerhouses. The leading EV importers are mainly European and American countries, including the U.S., Germany, the U.K., Belgium, and France, which may be related to economic development levels and environmental concerns.

Table 4. Main Importing and Exporting Countries of Lithium-containing Products from 2012 to 2023

Lithium carbonates		Lithium oxide and hydroxide		Lithium-ion accumulators		Electric vehicle	
Importing Countries	Exporting Countries	Importing Countries	Exporting Countries	Importing Countries	Exporting Countries	Importing Countries	Exporting Countries
China	Chile	Korea, Republic of	China	Germany	China	United States of America	Germany
Korea, Republic of	China	Japan	Chile	United States of America	Poland	Germany	China
Japan	Korea, Republic of	China	United States of America	Korea, Republic of	Hungary	United Kingdom	Belgium
United States of America	Netherlands	Sweden	Korea, Republic of	—	Korea, Republic of	Belgium	Korea, Republic of
Netherlands	—	Netherlands	Russian Federation	—	Germany	France	Japan

Note: The "—" indicates substantial fluctuation in the country's ranking from 2012 to 2023, making it indeterminate.

5. ANALYSIS OF OVERALL NETWORK STRUCTURE

To study the characteristics of lithium resource trade networks, this paper treats countries or regions as nodes, trade relationships between countries or regions as edges, and trade volumes for each product as edge weights to construct trade networks for the lithium supply chain products from 2012 to 2023. Using metrics such as degree (Table 4), network density, average path length, and clustering coefficient (Figure 14), the overall structure of the global lithium supply chain network from 2012 to 2023 was analyzed.

As shown in Table 4, among the four lithium supply chain products, China and the U.S. were often ranked in the top five for both in-degree and out-degree, indicating relatively diverse trade partners. However, there are some exceptions. For example, China was not among the top five countries for lithium carbonate in-degree before the trade war and was also not among the top five for EV in-degree in the later stages of the trade war. The former is mainly due to the immaturity of China’s lithium carbonate-related industrial chain from 2012 to 2017, while the latter is because China’s domestic NEV market has grown extremely competitive, supported by policy subsidies, making it difficult for foreign EVs to gain significant market share. The countries or regions involved in the import and export of midstream lithium salts differ somewhat from those involved in the trade of midstream and downstream lithium products. In the case of upstream lithium salts, the resources available to each country or region are relatively fixed, with lithium salt extraction occurring mostly at the source of raw materials. Since extraction requires a certain degree of technological expertise, the flow of lithium salts tends to remain stable. The U.S., China, Chile, and South Korea are the main exporters of lithium salts.

The degree of industrial development in battery and electronic component systems greatly influences the ranking of countries in terms of lithium-ion battery in-degree and out-degree. Countries such as China, the U.S., Japan, South Korea, and Poland, with robust industrial systems related to batteries and electronic components, occupy the top ranks for midstream and downstream lithium product degrees. China has long ranked first in lithium-ion battery out-degree, with the largest number of export partners, reflecting its industrial strength in this field.

Countries with strong economic power, mostly developed nations, dominate the rankings for EV in-degree and out-degree. Germany ranks first for both in-degree and out-degree in the EV trade, having the most export partners.

Table 5. The top 5 countries(regions) in terms of access to Lithium-containing products before and after the trade war

Product	Phase	Indicator	Top 5 countries (regions) in Product stage index				
Lithium carbonates	Pre-Trade War (2012—2017)	In-degree	Korea, Republic of	Mexico	Area, Nes	Brazil	Indonesia
		Out-degree	United States of America	China	Germany	Chile	Korea, Republic of
	Post-Trade War (2018—2023)	In-degree	China	Korea, Republic of	Japan	Mexico	Brazil
		Out-degree	China	Chile	United States of America	Korea, Republic of	Türkiye
Lithium oxide and hydroxide	Pre-Trade War (2012—2017)	In-degree	China	United States of America	Chile	Russian Federation	Korea, Republic of
		Out-degree	China	United States of America	Japan	Korea, Republic of	Chile
	Post-Trade War (2018—2023)	In-degree	China	Chile	United States of America	Russian Federation	Belgium
		Out-degree	China	Korea, Republic of	Japan	Chile	United States of America
Lithium-ion accumulators	Pre-Trade War (2012—2017)	In-degree	China	Hong Kong, China	United States of America	Germany	Viet Nam
		Out-degree	China	Hong Kong, China	United States of America	Korea, Republic of	Japan
	Post-Trade War (2018—2023)	In-degree	Germany	United States of America	Korea, Republic of	China	Netherlands
		Out-degree	China	Hong Kong, China	United States of America	Korea, Republic of	Poland
Electric vehicle	Pre-Trade War (2012—2017)	In-degree	China	Norway	United States of America	Germany	United Kingdom
		Out-degree	United States of America	Germany	China	Netherlands	Norway
	Post-Trade War (2018—2023)	In-degree	Germany	United Kingdom	United States of America	Belgium	France
		Out-degree	Germany	Belgium	China	United States of America	United Kingdom

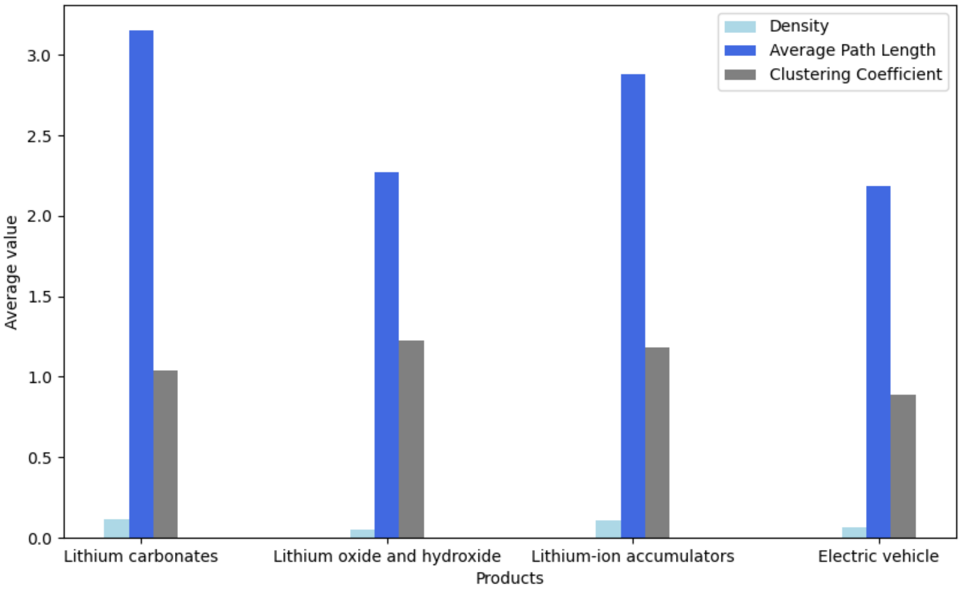

Figure 14. Average value of complex network indicators for Lithium-containing products from 2012 to 2023

As shown in Figure 14, from 2012 to 2023, upstream products such as lithium carbonate and lithium hydroxide exhibit relatively dispersed trade network characteristics. The average path length for lithium carbonate is 3.15, with a clustering coefficient of 1.04 and a network density of 0.114, indicating that although the trade network is widespread, the distances between countries are relatively large and the distribution is scattered. In contrast, the average path length for lithium hydroxide is shorter at 2.27, with a clustering coefficient of 1.23, and although its network density is relatively low (0.047), it shows stronger regional clustering, suggesting that the trade network for this product exhibits more pronounced regional agglomeration.

Downstream products, such as lithium-ion batteries and EVs, demonstrate different levels of globalization. The network density for lithium-ion batteries is 0.110, with an average path length of 2.88 and a clustering coefficient of 1.18. This suggests that while the trade network is broad, its distribution remains relatively concentrated, with some regional clustering characteristics. In contrast, the network density for EVs is 0.063, with an average path length of 2.19 and a clustering coefficient of 0.89, indicating that the EV trade network is more globalized, with shorter distances between countries and closer connections. While there is less regional clustering, global trade links are more developed.

The average path length for lithium supply chain products ranges between 2.19 and 3.15, meaning that the shortest path between any two countries (or regions) in the trade network typically involves three intermediaries. The average clustering coefficient ranges from 0.89 to 1.23, demonstrating that the lithium supply chain trade network possesses strong small-world characteristics—high clustering coefficients but relatively short path lengths. In small-world networks, the larger the average clustering coefficient and the shorter the average path length, the more compact the network.

Additionally, there are differences in the small-world characteristics of different lithium supply chain products. For example, the average clustering coefficient for lithium-ion batteries is higher than that of EVs, but its average path length is also longer. In contrast, EVs have the shortest average path length, making the trade network more compact. Likewise, lithium hydroxide, with the shortest average path length and the highest average clustering coefficient, forms the most compact trade network among the four products.

To examine the role and value of China and the U.S. in the trade network before and after the trade war, this paper used Python's NetworkX package to calculate the betweenness centrality and closeness centrality of various products using export data from the trade network (Tables 6 and 7). As shown in Table 6, China's betweenness centrality for lithium hydroxide is relatively higher compared to other products in the supply chain, indicating that China plays a key role in regulating and controlling the trade network for lithium hydroxide. Similarly, the U.S. also has strong control over the lithium hydroxide trade network, ranking even higher than China.

A comparison of pre- and post-trade war data reveals that for both China and the U.S., the rankings for all three lithium products, except for lithium hydroxide, dropped significantly after the trade war. China's betweenness centrality for lithium-ion batteries experienced the largest decline, indicating that the U.S.-China trade war had a significant impact on both countries, particularly reducing their ability to regulate and control the trade networks for lithium carbonate, lithium-ion batteries, and EVs. Among these, China's position in the lithium-ion battery trade network was the most affected. The sharp decline in both countries' ability to control and influence other nations in these three products after the trade war also suggests that the conflict indirectly affected other countries and regions. In response, these countries may have adjusted their supply chains to avoid potential tariffs or non-tariff barriers and rising trade costs, or to reduce uncertainty, leading them to establish new trade links with third-party countries and form new trade hubs, thereby reducing their dependence on trade routes involving China and the U.S.

As shown in Table 7, China and the U.S. have the lowest closeness centrality in the EV sector, and their closeness centrality values for all products were relatively similar before and after the trade war, with slight increases post-trade war. This indicates that China's ability to resist external control in the EV sector is the weakest, making it a vulnerable point in China's lithium supply chain. However, in other lithium supply chain products, China and the U.S. had comparable resistance to external control, and the trade war had a minimal impact on China's ability to resist control in the lithium trade network.

Table 6. Pre- and Post-Trade War Center Degree of China and the U.S. in the Trade of Lithium-containing Products

Product	Country	Phase	Rank	Betweenness centrality
Lithium carbonates	China	Pre-Trade War (2012—2017)	14	0.049
		Post-Trade War (2018—2023)	32	0.03
	United States of America	Pre-Trade War (2012—2017)	2	0.109
		Post-Trade War (2018—2023)	22	0.039
Lithium oxide and hydroxide	China	Pre-Trade War (2012—2017)	8	0.062
		Post-Trade War (2018—2023)	5	0.101
	United States of America	Pre-Trade War (2012—2017)	6	0.093
		Post-Trade War (2018—2023)	2	0.129
Lithium-ion accumulators	China	Pre-Trade War (2012—2017)	2	0.057
		Post-Trade War (2018—2023)	60	0.013
	United States of America	Pre-Trade War (2012—2017)	4	0.056
		Post-Trade War (2018—2023)	16	0.037
Electric vehicle	China	Pre-Trade War (2012—2017)	3	0.083
		Post-Trade War (2018—2023)	15	0.041
	United States of America	Pre-Trade War (2012—2017)	4	0.081
		Post-Trade War (2018—2023)	21	0.029

Table 7. Closeness centrality of Product Trade between China and the United States: A Pre- and Post-Trade War Analysis

Product	Country	Phase	Betweenness centrality
Lithium carbonates	China	Pre-Trade War (2012—2017)	0.417
		Post-Trade War (2018—2023)	0.441
	United States of America	Pre-Trade War (2012—2017)	0.432
		Post-Trade War (2018—2023)	0.444
Lithium oxide and hydroxide	China	Pre-Trade War (2012—2017)	0.641
		Post-Trade War (2018—2023)	0.617
	United States of America	Pre-Trade War (2012—2017)	0.652
		Post-Trade War (2018—2023)	0.583
Lithium-ion accumulators	China	Pre-Trade War (2012—2017)	0.350
		Post-Trade War (2018—2023)	0.412
	United States of America	Pre-Trade War (2012—2017)	0.383
		Post-Trade War (2018—2023)	0.465
Electric vehicle	China	Pre-Trade War (2012—2017)	0.145
		Post-Trade War (2018—2023)	0.287
	United States of America	Pre-Trade War (2012—2017)	0.162
		Post-Trade War (2018—2023)	0.294

6. SUMMARY

This study provides a comprehensive analysis of the lithium supply chain's global trade network from 2012 to 2023, utilizing complex network metrics such as clustering coefficient, average path length, and centrality. Several key conclusions have been drawn regarding the structure and dynamics of the lithium supply chain, particularly in the context of the U.S.-China trade war.

Firstly, the analysis reveals that the lithium supply chain exhibits pronounced small-world characteristics across its various stages. The trade networks for lithium products are marked by high clustering coefficients (ranging from 0.89 to 1.23) and relatively short average path lengths (between 2.19 and 3.15). These findings indicate that the lithium supply chain is both tightly interconnected and efficient in terms of trade flows, as countries can quickly connect through a small number of intermediaries. This small-world structure facilitates resilience and flexibility within the global lithium supply chain.

Secondly, the study found nuanced differences in trade patterns between the four key lithium products. Lithium carbonate, as an upstream product, is characterized by a widely distributed but less concentrated trade network, with countries spread out and trade partners relatively dispersed. In contrast, lithium hydroxide shows strong regional clustering, indicating a tighter concentration of trade relationships within specific regions. For downstream products, lithium-ion batteries exhibit a moderately concentrated network with regional clusters, while electric vehicles have a more globalized trade network. Although electric vehicles display weaker regional clustering, their trade connections are spread more evenly across the globe, reflecting the widespread adoption of this technology.

Finally, the U.S.-China trade war has reshaped the trade dynamics of the lithium supply chain, particularly in terms of network centrality. While China remains a core player in the supply chain, its intermediary role, especially in lithium-ion batteries, has been weakened post-trade war, as reflected by its declining betweenness centrality. The U.S. has also experienced a decline in its control and influence over upstream products such as lithium carbonate, with a significant reduction in its betweenness centrality. This shift indicates a broader diversification of trade partners, as countries seek to mitigate risks associated with U.S.-China trade tensions by adjusting their supply chains.

This study emphasizes the importance of building a more resilient and diversified supply chain, especially for critical resources like lithium. China's vulnerability stems from its reliance on imported upstream lithium raw materials and lithium salts, rather than high-end lithium products. Should geopolitical instability escalate, this dependence could pose a strategic disadvantage. To mitigate such risks, China should focus on securing stable supplies of lithium raw materials and salts, which are crucial for supporting the growth of its electric vehicle and lithium-ion battery industries. Additionally, China should explore ways to bypass the effects of tariffs on Chinese products, such as electric vehicles, which face significant export challenges due to high tariffs. Strengthening trade relationships with other countries and developing alternative trade routes for both upstream and downstream products in the lithium supply chain will be essential to maintaining global trade connectivity and ensuring long-term supply chain security. Similarly, other nations involved in the lithium supply chain should prioritize diversifying their trade partnerships to reduce dependency on a few key players. As the world moves toward a future reliant on renewable energy, securing a resilient and adaptable lithium supply chain will be critical to sustaining economic and technological progress.

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