ESJ Social Sciences Peer-reviewed

Dynamic Evolution of Electric Vehicle Trade Network between China and Europe

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Doi:10.19044/esj.2025.v21n13p1

Submitted: 26 February 2025
Accepted: 15 May 2025
Published: 31 May 2025

Cite As:
Yan S. & Liao Z. (2025). *Dynamic Evolution of Electric Vehicle Trade Network between China and Europe*. European Scientific Journal, ESJ, 21 (13), 1. https://doi.org/10.19044/esj.2025.v21n13p1

Abstract

China and Europe have promoted the development of electric vehicles to reduce carbon emissions and cope with climate change. In recent years, the sales share of Chinese electric vehicle brands in the European market has increased rapidly. Europe has become the largest export market for Chinese electric vehicles. However, the European Union implemented various temporary tariffs on Chinese electric vehicle brands in 2024, which posed a major challenge to the development of electric vehicle trade between China and Europe. The paper conducts a systematic examination of overall structural characteristics, node centrality metrics, core-periphery architecture and community detection of electric vehicle trade network between China and Europe from 2018 to 2022 by using social network analysis. The results indicate a general upward trend in tighter trade groups and increased connectivity efficiency within the network, while the network density and reciprocity display some fluctuations during this period. From a structural perspective, countries holding central positions in both centrality measures and core-periphery indicators show statistically significant convergence patterns in electric vehicle trade network between China and Europe. Moreover, there has formed different communities and undergone significant composition changes in electric vehicle trade network after 2020, highlighting the strengthening of connectivity within the trade network. This study has both

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

theoretical and practical implications. It highlights the dynamic changes in electric vehicle trade network between China and Europe, and providing practical implications for Chinese policymakers and Chinese electric vehicle manufacturers through strategic frameworks to enhance bilateral cooperation, market adaptability, and sustainable trade reciprocity with European countries.

Keywords: Dynamic evolution, electric vehicle, trade network, China, Europe

Introduction

It is widely acknowledged that climate change is one of the serious challenges to realize global sustainable development, and countries have increasingly felt economic losses and other serious consequences caused by climate change (Jiang et al., 2021). At the 2015 United Nations Climate Change Conference (COP 21), more than 190 participating countries signed the Paris Agreement on climate change mitigation, agreeing to limit the global temperature increase in this century to 2 degrees Celsius while pursuing efforts to limit the increase even further to 1.5 degrees (Voituriez et al., 2019; Yu et al., 2021). The transportation industry has created huge carbon emissions and become a key area of carbon reduction concern for major countries around the world. In 2023, the transport sector generated 8.24 billion tons of carbon emissions, accounting for 23.5% of global carbon emissions (Energy Institute, 2024). Transport carbon emissions are mainly from vehicles, ships and aircraft transport, of which vehicle emissions account for 75% of transport carbon emissions (Hannah, 2020). The global trend of de-carbonization and sustainability has prompted governments and automotive manufacturers worldwide to reduce their carbon footprint. Consequently, electric vehicle (EV) emerges as a viable and attractive solution to reduce carbon emissions and cope with climate change (Hu and Pan, 2023). More and more countries have issued policy initiatives to encourage the adoption of EVs.

China has actively promoted the development and application of EV to cope with the challenges of energy security and environmental protection. As early as 2001, the Chinese Ministry of Science and Technology established the “Three Verticals and Three Horizontals” research and development framework for new energy vehicles. The 11th Five-Year Plan (2006-2010) was a critical phase in transition of China’s EV sector to early-stage industrialization, and the 12th Five-Year plan (2011-2015) identified the new energy vehicles as one of the seven strategic industries. China’s 14th Five-Year Plan issued in 2021 explicitly identified the development of EV sector as one of the key priority strategy industry. The Chinese government has implemented a series of policies and regulations to support the production and purchase of EVs, including R&D subsidies, dual-credit policy, purchase subsidies, and charging facility construction (Yao et al., 2024). Due to a

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

national strategy that prioritizes the development of EV sector, China has been the world's largest and fastest-growing producer of EVs since 2015, and has formed industrial chain integration advantages in battery technology and EV manufacturing. In 2023, the number of Chinese EV registrations reached 8.1 million, accounting for 60% of the global EV market (IEA, 2024). To achieve climate neutrality goal by 2050 and green transition, Europe is committed to becoming a global leader in clean, competitive and connected transport. The European Commission and European Parliament have introduced a series of strategies and regulations, including “A European strategy for low-emission mobility” in 2016, “Europe on the move” in 2017, “Europe on the Move: Commission completes its agenda for safe, clean and connected mobility” in 2018, “Sustainable and Intelligent Transport Strategy” in 2020, and “The 2035 ban on the sale of internal-combustion vehicles” in 2023, to promote R&D, market and infrastructure development, and international cooperation of the EV sector. In Europe, the number of EV registrations reached nearly 3.2 million in 2023, with an increase of almost 20% compared to 2022. Europe became the second-largest EV market in the world, accounting for the 25% of the global EV sales in 2023 (IEA, 2024).

In recent years, the sales share of Chinese brands in the global EV market has increased rapidly, from just 4% of global EV exports in 2020 to 21% in 2022 (Boullenois et al., 2023). As for the EV trade between China and Europe, European exports of EVs to China have fallen slightly since 2018, while European imports of EVs from China has accelerated. The market share of Chinese EV brands in the European EV market grew from less than 0.5% in 2018 to 8% in 2023, and Europe became China's largest export market for EVs (Van Wieringen, 2024). China exported over 500,000 EVs to Europe in 2023, accounting for nearly 40% of its total EV exports. According to the European Commission's forecast, this value will further leap to 15% by 2025. The European Commission announced the initiation of EU anti-subsidy investigations into Chinese EV supply chains in October 2023. The Commission concluded in June 2024 that Chinese-made EVs benefited from unfair subsidies and implemented various provisional tariffs in response, ranging from 17.4% to 38.1% (European Commission, 2024). In October 2024, the Commission received the necessary support from Member States to impose definitive duties on Chinese EVs. Through the strategic deployment of import duties and anti-subsidy inquiries, European markets present significant challenges to Chinese EV manufacturers, particularly disrupting their export strategies and market penetration efforts. EV industry embodies the dual strategic value in energy security and climate governance, serving not only as a systematic solution for dismantling the constraints of traditional fossil fuels, but as the key driving force for reconstructing the global low-carbon economy. As nations promote the development of the EV sector,

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greater emphasis must be placed on collaboration and equitable competition to prevent protectionist policies from undermining the industry's progress. As key players in the global EV industry, the collaboration between China and Europe is critical for the sustainable development of the EV market. Based on the social network analysis (SNA), this paper analyzes the evolution characteristics of the EV trade network between China and Europe. The results will provide references for China to adjust its EV trade strategy and optimize its EV cooperation with Europe.

Literature Review

Factors affecting EV trade between China and Europe

Researchers mainly examine the factors affecting EV trade between China and Europe from the perspectives of trade status, subsidy policy, supply chain, and trade policy. The EV trade between China and Europe has grown rapidly in recent years, driven by Europe's green transition and China's manufacturing prowess (IEA, 2024). Boullenois et al. (2023) and van Wieringen (2024) provided an analytical overview of EV trade development between China and Europe during the period of 2019- 2023. In March 2023, the European Commission set out targets for reducing emissions from automobiles as part of its "Fit for 55" plan(Busch et al., 2024). To achieve these goals, the sales of EVs in the European Union (EU) should account for approximately 65% of the total new car sales by 2030, and all new car sales should be all-electric by 2035 (Wingender et al., 2024).

The favorable subsidy policies have been the main driving forces of EV trade between China and Europe. European countries have introduced different levels of tax benefits and purchase incentives for EVs since 2020 (ACEA, 2023). Ingeborgrud et al. (2019), and Santos and Davies (2020) revealed that incentive programs and subsidy policies implemented by European countries significantly promote the adoption of EVs. Munzel et al. (2019) examined the impact of monetary and non-monetary policy interventions across 32 European countries on EV market sales by using panel regression analysis. Their longitudinal study demonstrated that energy price dynamics and fiscal incentives, such as direct subsidies or tax reductions, exerted statistically significant positive effects on EV adoption rates. The European EV market has increased rapidly due to the expanding incentive policies of the EU member states. This provided a good opportunity for Chinese EV brands to enter the European market. However, the phase-out of subsidy policy poses challenges for EV trade between China and Europe. For example, Germany cancelled EV purchase subsidies at the end of 2023, resulting in a 27.4% decline in German EV sales in 2024 (IEA, 2024). This had a certain negative impact on Chinese EV brands entering Germany market.

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The wave of EVs is propelling a rapid restructuring of the automotive industry's value chain. China has leveraged geographic clustering advantages in critical mineral supply chains and EV infrastructure to achieve economies of scale in manufacturing (Dadush, 2024). Complemented by labor cost advantages and breakthroughs in battery technology and smart manufacturing, China's manufacturing sector continues to enhance its cost management capabilities within the global EV industrial chain. China has developed a strategic multidimensional deployment in building the comprehensive EV industrial chain from mineral raw materials to battery production and final assembly (Duthoit, 2023). This deeply embedded industrial interdependence has essentially positioned China as the foundational infrastructure supporting Europe's green transition (Van Wieringen, 2024).

European trade policy has a significant impact on EV trade development between China and Europe. Through tariffs and anti-subsidy investigations, the EU poses a serious obstacle for Chinese EV manufacturers, particularly in terms of their export activities in the short term (Martyn, 2024). On the other hand, the implementation of tariffs is likely to raise consumer prices for EVs, potentially suppressing market demand within the EU. Excessive dependence on protective tariffs may undermine domestic industries' incentives for technological advancement and efficiency improvements, ultimately weakening their global competitiveness (Andersen, 2023). Therefore, Europe needs to seek a strategic balance between curbing over-reliance and maintaining the development of its own EVs through mechanisms such as mutual recognition of standards under the framework of technological sovereignty and alliances for supply chain resilience in the long run,. Faced with the tariff barriers imposed by the EU, Chinese EV manufacturers need to reassess and adjust their market strategies and reconsider the configuration of their global supply chains (ARC, 2024; IISS, 2024).

SNA approach to analyze EV trade network

Social networks serve as critical frameworks for analyzing intricate, interdependent systems that shape human behavioral patterns and social dynamics across diverse domains (Scott, 2000; Rauch, 2001; Lusher et al., 2013; Jackson et al., 2017). SNA involves mapping and measuring the relationships and interactions that exist among individuals, organizations, or systems. Within a social network, nodes symbolize people or entities, whereas edges (or connections) represent relationships, interactions, or connections between them (Newman et al., 2006). SNA provides a deeper understanding of structural patterns and functioning of individuals or entities by analyzing the connections and structural characteristics between them and visualizing the structure of the network (Scott, 2011; Yang et al., 2016). In the 1980s, SNA began to be widely used in sociology and statistics. SNA provides a

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

relational perspective for analyzing trade policy interactions, revealing how inter-state network structures (such as centrality and clustering) shape policy diffusion pathways and negotiation game strategies.

The progression of global economic integration has forged interdependent economic linkages between countries in the world, transforming international commerce into a complex relational matrix. International trade demonstrates the network architecture and interaction patterns, which are consistent with the theoretical structure and methodological tools of network science (Snyder and Kick, 1979; Greif, 1989; Rauch, 2001; Fagiolo et al., 2009). Snyder and Kick (1979) introduced SNA into the study of international trade issues, discussing the dependency of differences in economic growth among countries. Smith and White (1992) divided the participants in the global trade network into different structures, such as core, semi-periphery, and periphery. Since then, SNA has been extensively employed in global and regional trade systems, including energy sectors (An et al., 2014; Du et al., 2016), trade relationships (Kim and Shin, 2002; Garlaschelli, 2005; Song et al., 2018), and automotive industry (Pavlínek, 2021; Cho and Kim, 2023), etc. For example, Kim and Shin (2002) analyzed the international trade network based on international commodity trade data by using SNA. The empirical results revealed the dynamic game between globalization and regionalization, and formed a pattern of regionalization under the framework of globalization. An et al. (2014) examined the structural characteristics and dynamic evolution patterns of global crude oil trade relationships based on SNA. The study showed that the crude oil trade network exhibited a core-periphery structure and a strong dependence on geopolitical factors. Pavlínek (2021) depicted the core structure, semi-peripheral structure, and peripheral structure of the European automotive industry by using SNA.

In recent years, SNA has been used to analyze the trade development in the field of the EV sector, including value chain, technology cooperation network, and trade structure evolution. For example, Shao et al. (2021) analyzed the evolution of the global lithium competition network pattern based on the trade data from 2009 to 2018, and found that the trade network structure of lithium has certain path dependencies with a core-periphery structure. Sun et al. (2018) measured EV-related patents cooperation network in China by using SNA . The results showed that the EV-patents cooperation network has evolved smoothly with a growing network density, stable structure, and more cohesive subgroups. Yao et al. (2024) constructed an industrial network from the perspective of the value chain and employed the SNA to study the characteristics, evolution and formation mechanisms of different value chain networks in the Belt and Road regions. Even though SNA has been widely

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used, few studies have applied it to the EV trade network between China and Europe.

In summary, current research has examined the various factors influencing the trade of EV trade between China and Europe. However, these studies are largely confined to analyzing the relationships at the trade or micro-market level. There exists a gap in the literature regarding the dynamic analysis of EV trade between China and Europe from a regional and national perspective. Therefore, this paper provides a more comprehensive reflection on the evolving characteristics of the EV trade network based on the trade links between China and Europe.

Methods

SNA demonstrates strong methodological advantages in studying the EV trade network between China and Europe. SNA maps out these relationships in the form of networks where nodes stand for countries and edges symbolize connections between them. Its core focus on relational structures and dynamic interdependencies aligns precisely with the multi-level interactions among China and European countries. In the paper, China and European countries are nodes, and the EV import and export relationships are edges, thus forming a topological network. The paper conducts a systematic examination of trade network overall structural characteristics, node centrality metrics, core-periphery architecture and community detection by using SNA. As a specialized software tool designed for SNA, UCINET 6.0 is used to conduct the calculations and analysis of EV trade network between China and Europe in the paper.

Network structure analysis

The complex trade relationships between China and Europe in the EV sector form the trade network, and the overall structure of this network, in turn, influences the development of EV trade. The measurement of EV trade network structure is drawn on the metrics selected in the study of Yao et al. (2024), and covers four indicators, including network density, reciprocity, average path length, and clustering coefficient. Table 1 shows the formula and description of four indicators.

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Table 1: The formula and description of four indicators

Indicator	Formula	Indicator description
Network density (ND)	$ND = \frac{m}{n \times (n-1)}$	m is the actual associated edge between two actual points, n is the number of nodes.
Reciprocity (RY)	$RY = p/m$	p is bidirectional relationships; m is the total number of relationships m in a directed network.
Average Path Length (AL)	$AL = \frac{1}{1/2n(n+1)} \sum_{i \geq j} d_{ij}$	n is the number of nodes, d_{ij} is the shortest path from node i to node j.
Clustering coefficient (CC)	$CC = \frac{2T_i}{k_i(k_i - 1)}$	T_i is the actual number of edges between nodes connected to node i, k_i is the degree of node i.

Network density is used to measure the overall closeness of nodes in the EV trade network. The higher the density value, the closer the overall trade connections are. Reciprocity is the indicator of mutuality and reciprocal exchange, the average path length refers to the average of the shortest path lengths between any two nodes in the EV trade network. The clustering coefficient is a measure of the degree to which nodes in the EV trade network cluster together.

Network node centrality

Centrality is used to measure the importance of nodes in a network in terms of connectivity, identifying nodes that have a critical impact or relevance on the network (Shen et al., 2024). Centrality metrics primarily include degree centrality, closeness centrality, and betweenness centrality. These three centrality metrics possess distinct characteristics and can be employed to shed light on the differential roles and functions of nodes within a network.

Degree centrality measures the number of direct nodes connections in the network, and nodes with high degree centrality are hubs or highly connected entities. Degree centrality can be divided into out-degree centrality and in-degree centrality. Closeness centrality quantifies how close a node is to all other nodes in the network via the shortest paths, and is typically measured by out-closeness centrality and in-closeness centrality. Betweenness centrality measures how often a node lies on the shortest path between pairs of other nodes. Table 2 shows the formula and description of the three centrality metrics.

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Table 2: The formula and description of three centrality metrics

Indicator	Formula	Indicator description
Out-degree centrality(OD)	$OD = \frac{\sum_{j=1,j\neq i}^{n} x_{ij}}{n-1}$	The ratio of the actual trade connection x_{ij} from node$i$to node j to the theoretical maximum value of $(n-1)$.
In-degree centrality (ID)	$ID = \frac{\sum_{j=1;j\neq i}^{n} x_{ji}}{n-1}$	The ratio of the actual trade connection x_{ji} from node$j$to node i to the theoretical maximum value of $(n-1)$.
Out-closeness centrality(OC)	$OC = \frac{1}{(n-1)\sum_{j=1;j\neq i}^{n} d_{ij}}$	The ratio of the shortest path length d_{ij} from node i to node j to the theoretical minimum value of $(n-1)$.
In-closeness centrality(IC)	$IC = \frac{1}{(n-1)\sum_{j=1;j\neq i}^{n} d_{ji}}$	The ratio of the shortest path length d_{ji} from node j to node i to the theoretical minimum value of $(n-1)$.
Betweenness centrality(BC)	$BC = \frac{2\sum_{j=1;k=1;j\neq k\neq i,j<k}^{n} \frac{g_{jk}(i)}{g_{jk}}}{(n-1)(n-2)}$	The ratio of the probability that node i lies on the shortest path between nodes j and k to the theoretical maximum value.

Community detection

Community detection refers to the identification of a set of nodes that are internally closely connected and relatively distant from other parts in network analysis. These sets of nodes are called communities. Modularity is an indicator used to characterize the community structure of the network. A higher modularity value indicates a clearer community division within the network and a better fit. The mathematical expression of modularity is:

$$Q = \frac{1}{2m}\sum_{i,j}\left(A_{ij} - \frac{k_i k_j}{2m}\right)\delta(c_i, c_j)$$

Here, A_{ij} is the adjacency matrix of the network, k_i and k_j are the degrees of node i and node j respectively, m is the total number of all edges in the network, c_i and c_j are the communities to which node i and node j belong respectively. $\delta(c_i, c_j)$ is an indicator function, when $c_i = c_j$, its value is 1; otherwise, it is 0.

Analysis of EV trade network between China and Europe

Data sources

This study examines the trade dynamics in the EV sector, focusing on China, the United Kingdom (UK), and the EU member states with a time span of 2018-2022. The research scope encompasses two core product categories: pure electric buses (HS2017 code 870240) and other electric road vehicles (HS2017 code 870380). Trade data was collected from the United Nations Comtrade Database (UN Comtrade), with a focus on bilateral trade flow statistics between the selected economies during the period of 2018-2022.

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Network structure results of EV trade between China and Europe

The network structure of EV trade between China and Europe included in the paper are ND, RY, AL, and CC. Table 3 shows the empirical results of EV trade network structure between China and Europe. Firstly, the network density of EV trade between China and Europe showed an overall upward trend from 2018 to 2021, reaching its peak at 0.130 in 2021. There was a slight decline in 2022, which suggested potential supply chain disruption in EV trade possibly due to Russia-Ukraine conflict. The relatively low value of network density indicates that the overall connection is sparse and there is still a large space for development. Reciprocity of EV trade network reached a peak of 0.309 in 2020 with an increase of 58.2% compared to 2018, highlighting the enhanced complementarity between Chinese and Europe. Despite a pullback to 0.247 in 2021, the rebound to 0.277 in 2022 indicated a resilient foundation in EV trade dependency.

The average path length decreased from 1.845 in 2018 to the lowest point of 1.637 in 2021, reflecting the reduction of supply chain tiers and the increased direct connectivity between nodes. Despite a slight increase to 1.672 in 2022, this indicator was still 8.1% lower than in 2018. The decreasing trend indicates that trade connections have become more direct over time, with fewer intermediary links. The clustering coefficient showed a steady increase from 2018 to 2022, reaching its highest value of 0.749 in 2022. The increasing clustering coefficient suggests a higher degree of local connectivity and more concentrated trade activities. This trend is indicative of the formation of tighter trade groups, which can enhance the overall network's resilience and efficiency.

Table 3: The network structure results of EV trade between China and Europe

Indicators	Year				
	2018	2019	2020	2021	2022
ND	0.124	0.112	0.127	0.130	0.119
RY	0.176	0.253	0.309	0.247	0.277
A L	1.820	1.769	1.647	1.637	1.672
CC	0.669	0.683	0.700	0.736	0.749

Network centrality of EV trade between China and Europe

The network centrality indicators included in the paper are OD, ID, OC, IC, and BC. Table 4 shows the network centrality results of EV trade between China and Europe from 2018 to 2022. Firstly, Germany shows high centrality scores across all metrics, indicating its dominant role in the EV trade network. Germany ranked the first in both the OD and ID indicators during the period of 2020-2022, indicating its strong export and import activities. The country maintained the highest value of OC from 2018–2022, reflecting core connectivity as an exporter. The country's centrality scores generally increased in IC over time, reaching its highest IC score of 0.839 in 2022. Moreover, the

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country frequently ranked highest in BC indicator, underscoring its role as a critical intermediary in the network. These centrality indicators suggest Germany's growing importance as both a producer and a consumer hub in the EV trade network.

Table 4: The centrality of EV trade network between China and Europe

Year	Country	OD	Country	ID	Country	OC	Country	IC	Country	BC
2018	NLD	0.137	DEU	0.114	DEU	1	DEU	0.667	DEU	0.1
	FRA	0.114	GBR	0.083	NLD	1	NLD	0.65	NLD	0.067
	DEU	0.107	NLD	0.080	FRA	0.929	ITA	0.634	POL	0.061
	AUT	0.063	BEL	0.043	AUT	0.867	ESP	0.634	LTU	0.048
	BEL	0.041	FRA	0.042	CHN	0.867	POL	0.634	CHN	0.044
2019	BEL	0.061	DEU	0.055	BEL	1	POL	0.703	DEU	0.069
	DEU	0.037	NLD	0.032	CHN	1	DEU	0.684	GBR	0.054
	FRA	0.022	GBR	0.026	DEU	1	ESP	0.667	BEL	0.047
	NLD	0.020	BEL	0.013	FRA	1	BEL	0.634	ESP	0.048
	GBR	0.020	FRA	0.012	NLD	1	NLD	0.634	CHN	0.044
2020	DEU	0.119	DEU	0.108	DEU	1	DEU	0.788	DEU	0.084
	BEL	0.071	GBR	0.073	FRA	1	NLD	0.722	BEL	0.044
	SVK	0.048	NLD	0.065	GBR	1	BEL	0.703	NLD	0.038
	FRA	0.041	FRA	0.045	NLD	1	POL	0.703	FRA	0.033
	CHN	0.032	BEL	0.026	AUT	0.963	FRA	0.684	GBR	0.032
2021	DEU	0.137	DEU	0.118	AUT	1	DEU	0.788	GBR	0.058
	CHN	0.099	GBR	0.089	BEL	1	BEL	0.722	DEU	0.056
	BEL	0.061	BEL	0.054	CHN	1	NLD	0.722	BEL	0.026
	SVK	0.038	FRA	0.050	DEU	1	DNK	0.722	NLD	0.022
	CZE	0.021	NLD	0.034	ESP	1	GBR	0.703	DNK	0.022
2022	DEU	0.135	GBR	0.081	BEL	1	DEU	0.839	GBR	0.066
	CHN	0.119	DEU	0.072	DEU	1	NLD	0.813	DEU	0.053
	BEL	0.038	BEL	0.059	ESP	1	DNK	0.813	NLD	0.037
	ESP	0.034	FRA	0.043	FRA	1	BEL	0.788	DNK	0.023
	FRA	0.021	NLD	0.034	GBR	1	HUN	0.788	BEL	0.023

Note: The country name uses the ISO 3166-1 alpha-3 code

Secondly, both Belgium and the Netherlands are strategic hubs in the EV trade network. Belgium maintained a relatively high centrality across all metrics throughout the period, with notable scores in OD, OC and IC. Especially, Belgium emerged as a key intermediary and achieved a significant increase in the IC indicator over the time, indicating critical export connectivity. However, the score of indicator BC appeared to decline slightly over time. The Netherlands had a high OD ranking in 2018 and 2019, and high value of ID over time. The country also had consistently strong IC score, emphasizing its role as a trade gateway. However, the country's centrality scores in OD and BC declined during the period of 2018-2021, suggesting a reduced role in the EV trade network.

Thirdly, both UK and France are key players in the EV trade network. France has a consistent presence in the network with moderate centrality

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scores in OD and ID. Its centrality scores of OC fluctuated slightly but remained significant from 2018 to 2022, indicating a stable role as both a producer and consumer of EVs. The UK had significant centrality scores in BC and ID from 2018 to 2022. UK ranked first in both BC and ID indicators in 2022, suggesting growing import reliance and an intermediary role.

Finally, China's EV exports to the European market demonstrate robust growth, reflecting increasing market interdependence. China's OD ranking rose from the 5th to the 2nd from 2018 to 2022, signaling growing export activity. The country achieved the highest OC scores from 2019 to 2021, suggesting enhanced export network efficiency. In 2022, China had a BC score of 0.053 and an OC score of 0.813, indicating its growing role in the EV trade network. The rising centrality scores suggest that China is becoming a more important player in the trade network, due to its expanding EV production and exports to Europe. Other countries like Austria, Poland, and the Czech Republic had higher centrality scores and played important roles in the EV trade network from 2018 to 2022, particularly in terms of OC and IC indicators.

Network core-periphery structure of EV trade between China and Europe

The paper uses the Core-Periphery algorithm in UCINET 6.0 to conduct a quantitative analysis of the core-periphery structure for the EV trade network between China and Europe. The criteria for identifying core country in the trade network are set as having a coreness value greater than 0.1. Country with a coreness value between 0.05-0.1 is classified as the semi-peripheral country, and all other nodes with a coreness value less than 0.05 are considered to be in the peripheral countries. Table 5 shows the network core countries of EV trade between China and Europe from 2018 to 2022.

Table 5: Network core countries of EV trade between China and Europe

Year	Core country
2018	DEU (0.476), NLD (0.457), AUT (0.420), FRA (0.353), ESP (0.251), GBR (0.237), BEL (0.206), SVK(0.144), POL (0.139), HUN (0.120).
2019	DEU (0.425), NLD (0.398), BEL (0.377), FRA (0.367), AUT (0.366), ESP (0.300), GBR (0.291), SWE (0.129), ITA (0.124).
2020	DEU (0.445), NLD (0.376), FRA (0.372), GBR (0.369), BEL (0.346), ESP (0.317), ITA (0.236), AUT (0.209), CHN (0.162), SWE (0.121).
2021	DEU (0.494), FRA (0.382), BEL (0.346), GBR (0.324), ESP (0.316), ITA (0.307), NLD (0.212), AUT (0.208), CHN (0.203), SWE (0.152).
2022	DEU (0.509), FRA (0.398), BEL (0.356), ESP (0.331), GBR (0.314), ITA (0.286), CHN (0.245), NLD (0.202), SWE (0.133).

Note: The country name uses the ISO 3166-1 alpha-3 code

According to the Table 5, Germany consistently remained the most central country in the EV trade network throughout the period, with its centrality score increasing from 0.476 in 2018 to 0.509 in 2022. This indicates

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Germany's dominant position and growing importance as a core hub in the EV trade network between China and Europe. This advantage stems from the country's strong automotive manufacturing industry, technological leadership in sustainable mobility solutions, and comprehensive international trade facilities.

Secondly, Belgium, France, UK, and the Netherlands were consistently among the core countries, maintaining relatively high centrality scores across the period of 2018-2022. Among the four countries, France maintained a consistently high and stable centrality score, especially ranking second in 2021 and 2022. This underscores France's important role in the EV trade network, driven by its automotive industry and government support for EV adoption and production. Belgium maintained prominent positions throughout the period of 2019-2022, and ranked third in 2021 and 2022 respectively. The UK's centrality score fluctuated but remained significant, particularly in 2020 and 2021. The Netherlands showed a notable decline in centrality from 0.457 in 2018 to 0.212 in 2021, with slight recovery to 0.212 in 2022. This indicates a potential reduction in its role as a core intermediary in the network.

Thirdly, China's rising centrality scores, especially as it moved to the forefront of the trade network in 2021 and 2022, signal its increasing prominence in the EV trade network. This changing role of China is mainly attributed to its expanding EV exports to Europe and increasing technological capabilities in the EV sector. Austria, Spain, Italy, and Sweden also maintained high centrality scores, indicating their important roles in the EV trade network. These countries contribute to the network through their automotive industries, trade infrastructure, and strategic locations.

Community detection of EV trade between China and Europe

This paper uses the community detection module in UCINET 6.0 to analyze the trade networks of EVs in China and various European countries. The networks from 2018 to 2020 exhibited low modularity (0.177, 0.15, and 0.18 respectively), making them difficult to divide into distinct communities. The modularity in 2021 and 2022 was 0.28 and 0.23, respectively. The community detection results of EV trade between China and Europe are shown in figure 1 (the same community is represented by the same color, and the countries with missing data are not included).

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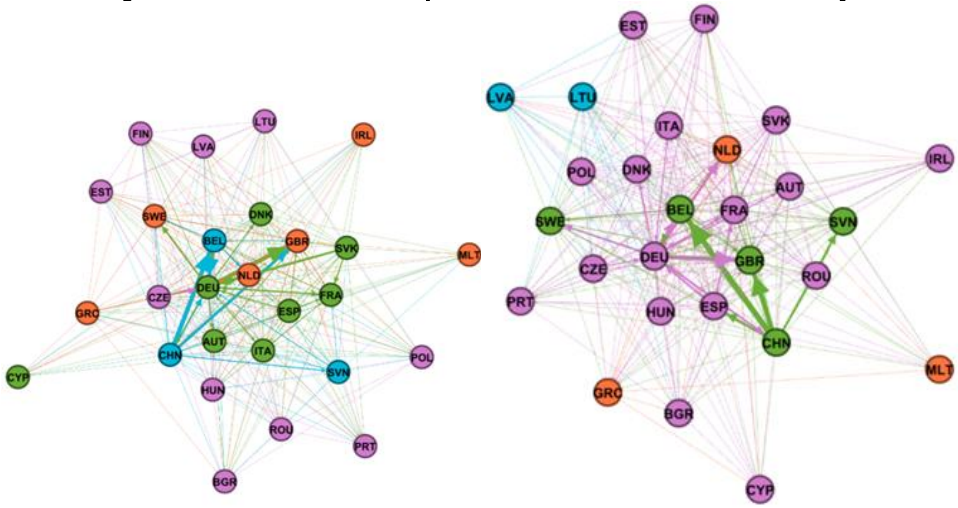
Figure 1: Networks community of EV trade between China and Europe



2021 2022

Note: The country name uses the ISO 3166-1 alpha-3 code

It can be seen from the Figure 1 that divisions of different communities are closely related to the development level of each country in the field of EVs and the relevant geographical locations. In 2021, the EV trade networks between China and European countries were divided into four groups. The largest cluster (depicted in pink) consisted of Poland, Portugal, Romania, Bulgaria, Hungary, the Czech Republic, Finland, Latvia, Lithuania, and Estonia. These countries are mainly situated in Eastern Europe and represent those that have demonstrated limited investments and possess underdeveloped technological capabilities in the field of EVs. The second-largest group, represented by green, included Cyprus, Denmark, Germany, Austria, Italy, Spain, France, and Slovakia. These countries are mainly located in Western Europe, covering those that have made significant investments and high technological levels in the field of EV sector. The third cluster was indicated in orange, covered Greece, Sweden, the Netherlands, and the UK. Finally, the smallest group was formed by China, Belgium, and Slovenia, indicating that China's main reliance path for EV exports to Europe

In 2022, there was a significant change in the community composition of this trade network. The largest community expanded its membership from 10 countries in 2021 to 16 countries by 2022, spanning Western, Central, and Eastern Europe. This community is spearheaded major European automobile countries, such as Germany, France, and Italy. The second community was composed of China, Belgium, the UK, Slovenia and Sweden, indicating the deepening of strategic interaction between China and Europe in the EV trade. The remaining countries occupied relatively peripheral positions within the trade network.

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Discussion

The paper constructs a China and Europe EV trade network and conducts a systematic examination of overall structural characteristics, node centrality metrics, core-periphery architecture and community detection by using SNA.

The overall structure of China and Europe trade network in the field of EV sector is undergoing continuous dynamic changes. Although the network density and reciprocity fluctuated, there was an obvious trend of tighter trade groups and improving connectivity efficiency. The dynamic changes of EV trade network are driven by combinations of the policy and regulatory environment, market demand, geopolitical and economic factors, and the value chain. China is the world's largest and fastest-growing producer, consumer and battery producer of EVs, and has formed an industrial chain integration advantage in battery technology and EV manufacturing. European countries have provided support measures such as purchase subsidies, tax incentives, and the construction of charging networks, which have promoted the popularity of EVs. Especially, the European Commission launched the "Sustainable and Intelligent Transport Strategy" in 2020, which aimed to have at least 30 million zero-emission cars on European roads by 2030 (European Commission, 2021). The increasing market demand has provided a broad market space for Chinese brands EV to enter European countries.

In the context of EV trade between China and Europe, countries that exhibit a high degree of centrality and coreness in the network tend to overlap significantly. The EV trade forms a core-periphery network structure, with Germany, Belgium and other major European automobile countries as the center countries. Firstly, Germany has a dominant position in the EV trade network, which is matched by the country's share of the European market. According to the IEA (2023), Germany is the largest EV market in Europe with 830,000 EVs sold in 2022. The country also serves as the headquarters for globally renowned automotive manufacturers such as Volkswagen and Mercedes-Benz Group. Secondly, France, Belgium, UK, and the Netherlands are countries with developed automotive industries, and their manufacturing advantages and larger market space have become the basis for the core countries of EV trade network between China and Europe. Moreover, Belgium and the Netherlands maintain significant positions in EV trade network due to their advantageous geographic positioning and developed transport system. Thirdly, the geographical redistribution of core countries within the EV trade network demonstrates significant structural realignment during the period of 2018-2022. For example, the Netherlands experienced a progressive decline in network centrality, ultimately falling outside the top five influential nodes in 2022. China has experienced the dynamic change from a semi-marginal country to a core country. China's share in the EV trade network has increased

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rapidly since 2020 and became the core country in the trade network by the end of 2022.

The community detection of EV trade between China and Europe indicates that distinct communities emerged after 2020, with substantial shifts in the composition of each group over time, highlighting the evolving nature of inter-country associations and their dynamic realignment. In major automotive industrial countries of Europe, the demand for EVs has been continuously increasing with the support of policies for the development of EVs, the advancement of EV technology and the improvement of consumers' environmental awareness. The status of these countries in the community has become more important due to the expansion of market demand. For example, as the largest automotive market in Europe, Germany's increased acceptance and demand for EVs have enhanced its influence in the trade community. Moreover, the continuous deepening of trade cooperation between China and European countries has prompted some European countries to establish closer ties with China in the EV trade community. The share of Chinese EV brands in the European market has gradually expanded since 2020, promoting the adjustment of the trade communities between China and Europe.

This research acknowledges several limitations that should be addressed in subsequent studies. Future investigations should prioritize incorporating more updated data to enhance the precision and dependability of the China and Europe EV network analysis. A second limitation lies in the absence of a comprehensive examination of mechanisms behind EV trade network within the China and Europe, especially the impact of the Russia-Ukraine conflict on the supply chain of China and Europe EV trade. Thirdly, there is a critical need to integrate predictive analysis into future research frameworks, employing scenario-based modeling or machine learning approaches to forecast EV trade patterns and market evolution between China and Europe under varying geopolitical and economic conditions. These gaps necessitates targeted investigation in future research to shed light on the underlying mechanisms shaping cross-regional EV market interactions.

Conclusions

EV as a strategic emerging industry has become an important measure to achieve green and sustainable development. Based on the SNA, the paper analyzes the dynamic evolution characteristics of EV trade network between China and Europe from 2018 to 2022. Empirical findings demonstrate an overall upward trend in tighter trade groups and increased connectivity efficiency, although network density and reciprocity exhibit certain fluctuations. From a structural analysis perspective of the EV trade network between China and Europe, countries occupying central positions in both core-periphery indicators and centrality metrics demonstrate statistically significant

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convergence patterns. Moreover, different communities emerged in the EV trade network between China and Europe after 2020. The composition of each community has undergone substantial changes over time, highlighting the further improvement in the connectivity of EV trade between China and Europe.

From a theoretical perspective, this paper provides a multidimensional assessment of trade patterns, actor influence, and hierarchical dynamics by examining the overall structural characteristics, node centrality indicators, core-periphery structure and community detection of EV trade network between China and Europe. The study finds that the overall structure of the trade network is dynamically evolving, with increasing connectivity efficiency despite fluctuations in network density and reciprocity. This evolution is driven by factors such as policy support, market demand, economic conditions, and the value chain. The rapid development of China as a core country in the trade network, along with the dominant positions of major European automotive countries like Germany and Belgium, highlights the significance of industrial chain integration and geographic advantages. The detection of distinct communities and their dynamic realignment after 2020 underscores the evolving nature of inter-country trade associations in the EV sector. These findings contribute to the broader international trade literature in highlighting the dynamics changes in the EV trade network between China and Europe.

From a managerial perspective, this paper intends to provide actionable insights for decision makers and industry stakeholders in the field of EV sector. Firstly, Chinese government agencies should engage in strategic dialogue with the EU to address subsidy concerns. Simultaneously, they should transparently demonstrate the consistency of China's EV subsidy policies with international trade norms. The Chinese government should highlight the key role of Chinese EVs in accelerating the global shift to sustainable transportation, including emission reduction and technological innovation. The EU and China agreed to consider minimum pricing for Chinese EVs, offering an alternative to current tariffs in April 2024. Joint government efforts could now advance a reciprocal market access protocols and fair competition standards to balance market access and equitable growth. Secondly, Chinese EV manufacturers could explore strategic partnerships with firms in key European markets, such as Germany, France, and Belgium through joint ventures, technology-sharing arrangements, and collaborative R&D programs. By integrating the regulatory expertise and localized supply chains of European strategic partners, Chinese manufacturers, such as BYD and Geely, can mitigate geopolitical risks while accelerating the time-to-market of EV models in specific European countries. This strategy cooperation will transform transaction-based exports into embedded value

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chain participation, aligning with the EU's strategic autonomy agenda while ensuring China's foothold in the decarbonized mobile ecosystem. These alliances would facilitate smoother market penetration and technology acquisition while mitigating risks through shared responsibilities. Establishing localized production and supply chains in Europe could help circumvent tariff barriers and improve operational responsiveness. For instance, constructing manufacturing facilities in Germany, Belgium, and Central and Eastern European countries like Hungary and Slovakia would enhance supply chain adaptability and regional market responsiveness.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

Funding Statement: The research is supported by Major Project of the Chinese Ministry of Education (No. 2024JZDZ012), Fundamental Research Funds for the Central Universities (No. 3162024ZYKA01) and China Foreign Affairs University First-class Disciplinary Innovation Platform “Quantitative Research on Global Economic Governance”.

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