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Evolution and proximity analysis of oil and natural gas trade networks among the Belt and Road Initiative countries

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Based on 2009–2018 BRI countries' oil and natural gas trade, this paper uses social network analysis to construct and compare the topological, spatial, and community structures of oil and gas trade networks. It extends the gravity model to analyze proximity effects in both networks. The findings are as follows: Both the oil and natural gas trade networks exhibited a trend toward densification. However, the oil trade network showed higher national participation, network cohesion, and trade accessibility. The spatial structure of the oil trade network is characterized by a “dual-core export and tri-core import” distribution, while the natural gas trade network is characterized by a “dual-core export and single-core import” distribution. Both networks displayed a significant “rich club” phenomenon. The oil trade network evolved into four major communities with stable spatial distribution, whereas the natural gas trade network evolved into six major communities with considerable changes in spatial distribution. Two networks exhibit vulnerability under deliberate attacks, but the oil trade network demonstrates higher robustness than the natural gas trade network. Both the oil and natural gas trade networks exhibited cultural and organizational proximity, but geographical proximity posed a barrier to the evolution of both networks. Economic and institutional proximity had different impacts on the oil and natural gas trade networks, with their influence directions being opposite. Based on the research findings, this study proposes a “DURC” policy framework centered on diversification, strategic alliances, institutionalized rules, and improved connectivity to foster the efficient, resilient, and sustainable evolution of oil and natural gas trade networks within the BRI region.

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Introduction

Throughout the history of energy development, fossil fuels, particularly oil and natural gas, have been the foundational drivers and essential raw materials for national economic development. They have increasingly become pivotal variables in the evolution of international relations and special commodities in national market transactions (Yergin, 2006, 2011). The Belt and Road Initiative (BRI), as the “heartland” of oil and natural gas supply, accounted for nearly 60% and 80% of the world’s proven oil and natural gas reserves, respectively, as of 2020 (Dale, 2021). On one hand, the non-renewability and scarcity of oil and natural gas make the BRI the focal point most affected by geopolitical influences. From the oil crisis of the 1970s to the Gulf War in the 1990s, the Iraq War and the Afghanistan War in the early 21st century, and the ongoing Russia-Ukraine conflict, these significant energy-related geopolitical games influencing the international order have all occurred in this region. On the other hand, the heterogeneous geographical distribution and the spatial mismatch between production and consumption of oil and natural gas make international trade a crucial avenue for the movement of these resources between supply and demand countries along the BRI. According to statistics from the International Energy Agency, in 2020, the global oil flow amounted to approximately 3.8 billion tons, and the global natural gas flow was about 1.3 billion tons, accounting for 59% and 19% of the global fossil energy flow, respectively. Among these, one-third of the oil flow and half of the natural gas flow occurred in the BRI. The oil and natural gas trade in this region is vital to the development of international relations and the world economy, attracting widespread attention from scholars and governments worldwide.

As the fossil energy trade becomes more integrated into the process of globalization, the global fossil energy trade is becoming increasingly complex and networked, gradually forming a massive system characterized by self-organization, dynamism, and orderliness. The energy relationships among countries are becoming increasingly intertwined and interdependent (Niu et al., 2023; Zhang et al., 2019). An et al. point out that viewing international oil trade as a complex network, rather than from traditional perspectives, can reveal new features and patterns in the topology, trading modes, and roles of countries in oil trade (An et al., 2014). Zhang et al. (2019) emphasize that while stable, orderly, and efficient oil trade relations are influenced by resource distribution, international political situations, and market price fluctuations, they are also heavily dependent on the structural changes in the oil trade network. The network characteristics of natural gas trade are even more pronounced, with half of the international natural gas being transported via pipeline networks. Constructing a natural gas trade network to assess the global natural gas cooperation landscape and outline the global natural gas transportation network has become a hot topic in current international energy trade discussions (Chen et al., 2016; Han et al., 2023). In recent years, global energy trade has confronted significant challenges. International events such as the COVID-19 pandemic, geopolitical conflicts, and rising trade protectionism have reshaped energy trade relations under the BRI, triggering energy supply crises and rendering the multilateral trade relationships of oil and natural gas among the BRI countries increasingly complex. These dynamics have profound implications for major energy net-importing nations such as China and Europe, as well as for key energy-producing regions including Central Asia, West Asia, and North Africa. Given the increasingly globalized and geopolitically charged nature of energy trade, analyzing oil and gas exchanges within BRI through the lens of traditional international trade theories is no longer sufficient. There is a pressing need to transcend bilateral frameworks and adopt a network-oriented perspective that captures the systemic

complexity and interdependencies inherent in contemporary energy markets. Moreover, the differences between the oil trade and the natural gas trade mean they cannot be discussed uniformly. For example, oil trade encompasses more flexible trading methods such as spot, futures, long-term contracts, and entitlement oil, whereas the transportation and storage of natural gas are relatively complex, with trade relying more on long-term contracts and pipeline transportation, making long-term stable supply relationships crucial. Therefore, grounded in complex network theory, clarifying the divergent evolutionary trajectories of oil and natural gas trade networks within the BRI, comparing their robustness under structural perturbations, and identifying the heterogeneity in their underlying driving mechanisms carries profound strategic significance for differentiated guidance of energy cooperation and the advancement of high-quality, sustainable development across the BRI region.

The remainder of this paper is organized as follows. “Literature review” presents a literature review, summarizing and synthesizing existing studies on the evolutionary patterns and driving factors of oil and natural gas trade networks. “Methodology” outlines the study region, research methodology, and model assumptions. “Results” provides a results analysis, comparing the heterogeneity in topological, spatial, community, and robustness evolution between the oil and natural gas trade networks among the BRI countries, as well as examining differences in proximity effects across the two networks. “Discussion” discusses the findings, draws conclusions, offers policy implications, and acknowledges the study’s limitations, while also suggesting directions for future research.

Literature review

Structure of oil and natural gas trade networks. Oil and natural gas trade, as concrete manifestations of complex networks, have topological structures that significantly influence the stability and operational efficiency of energy supply and demand systems. Scholars have employed metrics such as graph density, clustering coefficient, and average path length to quantify network topology and uncover underlying patterns in energy trade networks (Chen et al., 2018; Hao, 2023). Research indicates that bilateral relationships in the global oil market are increasingly dense, resulting in a more tightly connected trade network with enhanced reciprocity. These structural characteristics have become key drivers of market expansion and have substantially improved the efficiency of oil trade resource allocation as the network topology grows more complex (An et al., 2013; Wei et al., 2022a). In contrast, due to inherent challenges such as difficult storage and transportation, high technological requirements, substantial investment, and long payback periods, the development of natural gas trade networks has lagged behind that of oil, and its topological structure remains in a developmental phase (Geng et al., 2014). Although the evolutionary stages of oil and gas trade networks differ, both exhibit a distinct “core-periphery” structure, with trade systems dominated by a small number of countries (Du et al., 2017; Han et al., 2023; Niu et al., 2023). Energy trade along the BRI has also evolved into a tightly connected, structurally complex, and heterogeneous network, with continuous growth in both the number and weight of connections (Chen et al., 2023). Morphologically, liquefied natural gas (LNG) trade among the BRI countries follows a “chain-like” pattern, while pipeline gas trade exhibits a “star-shaped” configuration, radiating outward from production hubs (Guo et al., 2023). In terms of hierarchy, the oil and gas trade network among the BRI countries already demonstrates a clear core-periphery structure, with resource allocation dominated by a few major powers. The

network's structural stability is profoundly influenced by major international events, and the pipeline gas network has been found to be more stable than the LNG network (Li et al., 2021; Wang et al., 2022).

The geographical imbalance in energy supply and demand, coupled with the immobility of production locations, makes energy trade an essential mechanism for balancing spatial energy structures. The spatial configuration of energy trade networks has thus become a critical indicator for assessing global energy patterns and energy power. Investigating the patterns of internal network organization and operational dynamics within regions is essential to understanding the interdependence and interactions among components of the network system (Krivitsky and Handcock, 2014). Following the Iraq War and the global financial crisis, the United States' dominance in oil trade weakened, leading to a restructuring of the global energy power landscape. The center of gravity in energy trade has shifted from net exporters to net importers, with countries such as China, Japan, and South Korea steadily rising in network prominence (An et al., 2013; Niu et al., 2023). Zhang et al. (2014) examined the evolutionary dynamics of global oil trade competition, revealing that countries in the Asia-Pacific region have assumed increasingly important roles in the evolution of the oil trade network, emerging as key players and critical conduits in resource competition. However, while the framework of an integrated global gas market is beginning to emerge, the spatial structure of natural gas trade remains largely regionalized (Shirazi and Šimurina, 2023). Compared to oil, the natural gas trade network exhibits a multipolar layout, with ten major trade hubs identified (Hou et al., 2023). As energy competition in the Middle East intensifies, significant changes have occurred in the energy trade network among the BRI countries. Although Central Asian nations maintain a degree of regional monopoly due to their advantageous gas production locations, major gas-consuming countries such as those in ASEAN, China, and India are gaining increasing prominence within the network (Li et al., 2021; Zhang et al., 2019).

Globally, energy trade networks, particularly oil trade networks, are shifting from globalization toward regionalization, forming smaller clusters or blocs. These blocs exhibit a pattern of close cooperation within groups and intense competition between them (Deng and Jiang, 2025; Ji et al., 2014). Zhong (2014) identified three major blocs in the global oil trade network, with member countries showing strong geographical proximity. Ji et al. (2014) observed similar clustering, dividing the network into the South America, West Africa, and North America bloc; the Middle East and Asia-Pacific bloc; and the former Soviet Union, North Africa, and Europe bloc. Kitamura and Managi (2017) classified the global oil trade network into five blocs: crude oil exporters, major European importers, major Asian importers, the United States, and other residual countries, based on relational similarity. These studies successfully illustrate the bloc structure of the oil trade and reveal production-coordination mechanisms between oil-producing and oil-consuming nations. The WTO, through theoretical modeling and CGE simulations, argues that the global energy trade network is evolving toward regionalization and fragmentation, gradually forming energy trading circles centered on Europe and the United States, another centered on Japan, the United States, Australia, and India, and a third in Central Asia (Xing et al., 2023). However, due to high transaction costs, particularly the substantial infrastructure requirements for pipeline gas, the natural gas trade tends to occur intensively among neighboring countries and exhibits strong temporal inertia. This has led to the formation of five major natural gas trade blocs: North America and South America; Russia and Europe; Asia-Pacific, Africa, and

South America; and Asia-Pacific and the Middle East (Li et al., 2021; Zhong et al., 2017).

Robustness of oil and natural gas trade networks. Energy trade does not consist of isolated bilateral transactions but instead exhibits a chain-like structure across regions. Disruptions triggered by extreme events can propagate through the system, leading to significant alterations or even the collapse of energy trade relationships and network architectures (Wei et al., 2022a). International “black swan” events such as political instability in oil- and gas-producing countries, the global financial crisis, the COVID-19 pandemic, the Russia–Ukraine conflict, and the Israel–Palestine conflict, as well as environmental shocks caused by extreme weather conditions, have all demonstrated the potential to disrupt or paralyze the global energy trade system. The Libyan civil war provides a salient example. Extensive damage to oil production infrastructure during the conflict resulted in a severe supply disruption, directly affecting global oil supply and demand dynamics. The shock propagated to other major oil-producing economies in the Middle East and North Africa, exacerbating political instability and triggering sharp declines in their oil exports. In this context, rising risk aversion in international markets, significant reductions in production from key exporters, and rapid increases in global oil prices emerged as critical factors undermining market stability. This pattern of risk transmission and diffusion arises from cascading effects inherent in interconnected systems (Kim et al., 2017), rendering the global energy trade network increasingly sensitive, vulnerable, and unstable. Consequently, the stability of energy trade systems is central to global energy security and represents a critical research theme that warrants systematic scholarly inquiry.

To assess the evolving resilience of energy trade networks, identify key risk factors, and enhance trade security, many scholars have adopted a network-based approach to model energy trade systems (Cappelli and Carnazza, 2023; Wei et al., 2025). Among network properties, robustness is a fundamental indicator of system stability. A trade network is considered robust if it maintains its core functionality and operational efficiency under both internal failures and external perturbations (Ma et al., 2020; Wei et al., 2022b). Node importance and changes in network-level metrics are essential variables in evaluating network robustness. In assessing node importance, most studies rely on single topological measures such as degree centrality, betweenness centrality, or closeness centrality, or apply weighted aggregation methods to rank node significance (Ji et al., 2024; Ma et al., 2020; Wei et al., 2022b). However, recent research emphasizes the need to move beyond undirected metrics by incorporating directional attributes such as out-degree and in-degree, or by developing multidimensional evaluation frameworks to ensure that robustness simulations reflect real-world trade dynamics (Liu et al., 2025). For instance, certain energy-importing countries may exert substantial influence despite low node degrees, owing to their large import volumes and strategic market positions. In terms of robustness assessment, researchers commonly employ metrics such as graph density, betweenness centrality, and closeness centrality to evaluate how energy trade networks respond to different types of disturbances. Sun et al. evaluated the robustness of oil and gas trade networks by systematically removing nodes under both random and targeted attack scenarios and monitoring changes in the size of the largest connected component. Their results indicate that the oil trade network is more resilient to deliberate attacks than the natural gas trade network (Sun et al., 2023). Chen et al. used accessibility and connectivity as indicators to assess the robustness of China's energy import network. Their findings reveal that the Chinese oil import network is significantly

more vulnerable to targeted attacks than to random failures, underscoring its high dependence on a limited number of supplier countries and its associated fragility (Chen et al., 2022). Moreover, some scholars argue that network efficiency, which reflects both resistance to disruptions and the capacity for recovery, should be regarded as a core metric in evaluating the resilience of energy trade networks (Wei et al., 2022b). In summary, a comprehensive understanding of node importance through multidimensional indicators, the selection of context-appropriate robustness metrics based on network type, and the simulation of diverse disruption scenarios are crucial for generating realistic and policy-relevant insights. These methodological advances provide a scientific foundation for formulating effective energy security strategies in an increasingly volatile and interconnected global environment.

Determinants of oil and natural gas trade networks. Global energy trade constitutes an emergent complex system, formed through localized interactions among individual actors. National energy trade systems often exhibit distinct trade preferences and are profoundly shaped by a range of factors, including regional economic development, energy mix, international market prices, resource endowments, and geopolitical dynamics (Guan and An, 2017). A growing body of research identifies geopolitical and domestic political stability as central determinants of energy trade flows (Cappelli et al., 2023; Deng and Jiang, 2025; Kim et al., 2025). Geopolitical conflicts can challenge and disrupt established trading mechanisms, while geopolitical risks arising from potential supply disruptions, investment uncertainty, and shifts in trade routes can significantly impact bilateral trade relationships and expose partners to heightened risk (Hao et al., 2016; Liu et al., 2024). Kitamura and Managi (2017) demonstrate that internal conflict and social instability in oil-producing countries are the primary drivers behind sharp declines in oil exports. Yagi and Managi (2023) highlight that the most significant current geopolitical risk to global energy trade stems from the Russia–Ukraine conflict, which has intensified price volatility in international oil markets. This finding is corroborated by Nguyen and Do, whose analysis confirms a substantial reduction in Russian oil supply and export volumes following the outbreak of the conflict (Nguyen and Do, 2021). The natural gas trade is similarly sensitive to political risks. Scholars have developed geopolitical risk indices to assess their impact on natural gas trade, revealing that rising geopolitical tensions increase transportation costs, elevate transaction prices, and ultimately reduce international trade volumes (Caldara and Iacoviello, 2022; Michail and Melas, 2022). However, some studies suggest that although political risk exerts a negative influence on natural gas trade, this effect has weakened since the 2008 global financial crisis, possibly due to improved risk mitigation strategies or institutional adaptations (Zhang et al., 2018).

The existing literature has extensively explored the factors influencing energy trade across multiple dimensions, including economic, institutional, infrastructural, and geographic aspects. First, at the economic level, energy-exporting countries often rely heavily on large-scale energy exports to support domestic economic growth and social welfare. In contrast, energy-importing countries face supply-demand imbalances that drive their need to source energy from external markets. Consequently, economic conditions serve as a foundational driver of energy trade flows. Empirical evidence confirms a significant relationship between international oil prices and national economic development (Shi and Variam, 2017). Zhang et al. demonstrate that a country's GDP, domestic energy supply and demand conditions, and energy import prices all exert significant influence on the

volume of energy imports (Zhang et al., 2018). As the economic development of importing nations advances, rising energy demand, particularly for oil, leads to increased import dependency. China exemplifies this pattern, where rapid economic growth has been accompanied by a substantial rise in oil imports (Guo et al., 2023). Second, at the institutional level, structural arrangements such as trade liberalization and the formation of regional or multilateral trade blocs are key determinants of energy trade patterns, primarily through the reduction of tariff and non-tariff barriers. Scholars have examined how institutional linkages, such as market integration (Geng et al., 2014; Ji and Fan, 2016), membership in international organizations (Zhang et al., 2018), and the signing of formal trade agreements (Barnes and Bosworth, 2015), facilitate energy trade. The emergence of supranational institutions, including the European Union (EU) and the North Atlantic Treaty Organization (NATO), has further deepened energy cooperation among member states. Robinson highlights the EU's establishment of a unified and liberalized European natural gas market, noting that market integration has driven convergence in natural gas prices across member countries, thereby reshaping trade dynamics (Robinson, 2007). Similarly, the BRI has become a significant platform for enhancing cross-border energy collaboration. Guo et al. (2023) apply a dynamic exponential random graph model (ERGM) to show that trade facilitation measures significantly promote both liquefied natural gas (LNG) and pipeline gas trade among BRI participating countries. Third, at the infrastructural level, the availability and quality of energy infrastructure are critical enablers of trade, especially for natural gas, which depends on specialized systems such as liquefaction terminals, pipelines, and regasification facilities. Dieckhöner et al. (2013) evaluate various scenarios of European natural gas infrastructure development and find that such investments enhance regional market integration and expand trading volumes. Furthermore, broader improvements in transportation infrastructure play a vital role in reducing logistics costs. Moryadee et al. (2014) assess the impact of the Panama Canal expansion on global LNG trade and show that increased transit efficiency significantly reduces natural gas prices in key Asian markets, particularly Japan and South Korea. Fourth, at the geographic level, geographic distance remains a salient factor shaping energy trade. Distance directly affects transportation costs, especially for natural gas, whose delivery systems are capital-intensive and logistically complex, making trade flows highly sensitive to spatial proximity. Neumann (2009) compares the responsiveness of pipeline gas and LNG trade to geographic distance and finds that, unlike pipeline gas, which is constrained by fixed networks, LNG benefits from maritime transport flexibility and is less sensitive to distance, enabling it to support a more globally integrated market. Zhang et al. (2019) investigate the structure of oil trade networks within the BRI context and find that geographically proximate countries are more likely to form robust bilateral oil trading relationships.

Despite significant advances in energy trade research, particularly in examining the structural, hierarchical, and nodal characteristics of energy trade networks, several critical gaps remain. Most existing studies focus on single-energy systems, offering limited comparative insight into the distinct dynamics of oil versus natural gas trade. Given the fundamental physical, logistical, and infrastructural differences between these two energy carriers, countries occupy different positions and play varying roles in oil and gas networks, with divergent trade processes, modes, and market structures. Yet, some questions remain unaddressed: How do the topological, spatial, and community structures of oil and natural gas trade networks differ? How do these networks respond to external shocks, and what mechanisms underlie their differential resilience? Moreover,

Table 1 The scope of the research.

| Regions | Countries |
|----------------------------|--|
| East Asia | Mongolia, China |
| Southeast Asia | East Timor, Philippines, Cambodia, Laos, Malaysia, Myanmar, Thailand, Brunei, Singapore, Indonesia, Vietnam |
| South Asia | Afghanistan, Pakistan, Bhutan, Maldives, Bangladesh, Nepal, Sri Lanka, India |
| West Asia and North Africa | UAE, Oman, Azerbaijan, Egypt, Palestine, Bahrain, Georgia, Qatar, Kuwait, Lebanon, Saudi Arabia, Türkiye, Syria, Armenia, Yemen, Iraq, Iran, Israel, Jordan |
| Central and Eastern Europe | Albania, Estonia, Belarus, Bulgaria, North Macedonia, Bosnia and Herzegovina, Poland, Russia, Montenegro, Czech Republic, Croatia, Latvia, Lithuania, Romania, Moldova, Serbia, Slovakia, Slovenia, Ukraine, Hungary |
| Central Asia | Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan |

Table 2 Network topology inference models.

| Indicator | Connotation | Geographical Significance | Equation |
|--------------------------------|---|--|--|
| Degree | The average number of edges connected to all nodes in the network | The activity level of oil and natural gas trade networks | $C_d(x) = d(x)$ (1) |
| Weighted Degree | The average weight of the connecting edges of all nodes in the network | The scale of the oil and natural gas trade networks | $DC = \frac{1}{n-1}k_i$ (2) |
| Graph density | The ratio of the actual number of edges possessed by the network to the maximum possible number of edges | The completeness of the oil and natural gas trade networks | $d(G) = \frac{2m}{n(n-1)}$ (3) |
| Average clustering coefficient | The ratio of the number of edges between a node and all its adjacent points to the maximum possible number of edges | Parameters of oil and natural gas trade networks aggregation | $C = \frac{1}{n} \sum_{i=1}^n \frac{\sum_{j,k \in N_i} e_{jk} e_{ik}}{k_i(k_i-1)/2}$ (4) |
| Average path length | The average distance between any two nodes | The accessibility efficiency of oil and natural gas trade networks | $L = \frac{\sum_{i,j} d_{ij}}{N(N-1)}$ (5) |

while complex network and social network methodologies have gained traction in energy research, many studies continue to rely on conventional network metrics, offering insufficient insight into the evolutionary mechanisms of energy trade. Critical factors shaping bilateral trade preferences, such as geographic, economic, institutional, and cultural proximity, and their relative importance compared to resource complementarity, remain under-explored, limiting the theoretical depth of energy trade analysis.

To address these gaps, this study conducts a comparative analysis of oil and natural gas trade networks among the BRI countries, a pivotal region in global energy supply and trade, using a complex network approach grounded in proximity theory. We make three key contributions. First, we adopt a multi-layered, heterogeneous comparative perspective by explicitly modeling both oil and gas trade networks, enabling a nuanced assessment of energy-specific structural and evolutionary differences. Second, we develop a multidimensional proximity framework that elucidates the evolutionary mechanisms of both networks, revealing distinct risk transmission pathways and identifying the dominant drivers of network formation. This advances theoretical understanding of energy trade heterogeneity. Third, we propose a strategic policy framework named DURC (Diversification, Unification, Regulation, Connectivity) to guide policymakers and market participants in building more resilient and sustainable energy trade systems, offering practical implications for energy security in an era of geopolitical and market volatility.

Methodology

Study area. According to the report “Vision and Actions on Jointly Building the Silk Road Economic Belt and the 21st Century Maritime Silk Road,” the key routes of the Silk Road Economic Belt extend from China through Central Asia and Russia to Europe (reaching the Baltic Sea); from Central Asia and West Asia to the Persian Gulf and the Mediterranean; and southward to Southeast Asia, South Asia, and the Indian Ocean. The main direction of the 21st Century Maritime Silk Road is from Chinese

ports through the South China Sea to the Indian Ocean, extending to Europe, and through the South China Sea to the South Pacific. The overall spatial trajectory aligns closely with the Second Eurasian Continental Bridge and China’s westward ocean routes, traversing almost all the major strategic hubs of the continent from the heartland in the north to the rimland in the south, moving east to west. Based on existing research literature (Li et al., 2021; Muhammad et al., 2020), this study selects 65 countries from regions including Northeast Asia, Southeast Asia, South Asia, West Asia and North Africa, Central and Eastern Europe, and Central Asia as the research subjects (Table 1).

Research methods

Network topology structure. Social network analysis has become a research hotspot in the fields of economics and geography in recent years, with an increasing number of studies exploring the network structure, attribute functions, and impact mechanisms of international commodity trade (De Benedictis and Tajoli, 2011; Fagiolo, 2007; Pan, 2018). In this study, we abstract the countries along the BRI as nodes, and the oil and natural gas trade flows between these countries as directed and weighted edges. We construct oil and natural gas trade networks for the BRI countries from 2009 to 2018 using data from the trade database of Chatham House. Based on the total oil and natural gas export amounts between the BRI countries from 2009 to 2018, we generate an adjacent matrix using R language. Firstly, we construct a set of nodes $V_i = [v_i^t] (i = 1, 2, 3, \dots, n)$ and $V_j = [v_j^t] (j = 1, 2, 3, \dots, m)$, where t represents different years, i represents country i , and j represents country j . Secondly, we construct a weighted edge matrix $W_j = [w_{ij}^t] (i = 1, 2, 3, \dots, n; j = 1, 2, 3, \dots, m)$, where w_{ij}^t represents the oil or natural gas export amount from country v_i to country v_j in year t . Finally, we construct the energy trade network $G = v_i^t, v_j^t, w_{ij}^t$. After constructing the energy trade networks, we utilize social network analysis methods with tools such as Pajek, UCINET, and Gephi. By introducing social network topology models (Table 2), we examine the topological

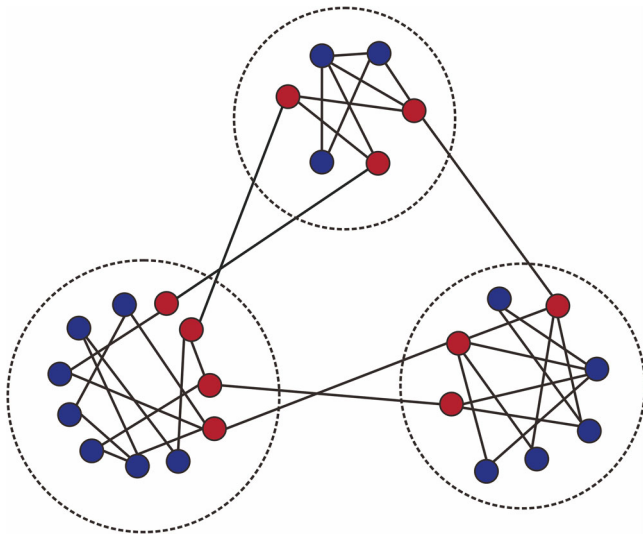


Fig. 1 Schematic diagram of community structure. Red nodes are connected to other communities, whereas blue nodes are not.

evolution process of the oil and natural gas trade networks among the BRI countries.

Network community. Social networks commonly exhibit community structures, which represent groups of nodes with closer relationships (Fig. 1). Within the same community, the connections between nodes are relatively dense, whereas connections between nodes in different communities are sparser (Barigozzi et al., 2011). Community detection was first proposed by Newman and Girvan (2004), followed by various algorithms for community division, including the fast modularity optimization algorithm, random walk algorithm, and label propagation algorithm. In this study, we use the fast modularity optimization algorithm to divide the community structures of the oil and natural gas trade networks among the BRI countries (Blondel et al., 2008). The steps are as follows: Initially, each country is considered as a single community, resulting in the number of communities being equal to the number of countries. Then, the increase in modularity is calculated to determine the community affiliation of different countries. If the increase in modularity is negative, the country remains in its original community; if the increase is positive, the country is merged into the community with the highest modularity increase. This process is repeated until the community divisions no longer change. The increase in modularity is given by Eq. (6). Subsequently, A new network is constructed, with each node assigned to the community determined in the first step. In this new network, the total edge weight between nodes equals the total edge weight between the corresponding countries in their respective communities from the original network. The first step is then repeated on this new network. This iterative process continues until the modularity value no longer increases, yielding the optimal community division of the network. The algorithm is primarily implemented using the igraph package in the R language.

$$\Delta Q = \left[\frac{\sum in + 2k_{i,in}}{2m} - \left(\frac{\sum tot + k_i}{2m} \right)^2 \right] - \left[\frac{\sum in}{2m} - \left(\frac{\sum tot}{2m} \right)^2 - \left(\frac{k_i}{2m} \right)^2 \right] \quad (6)$$

Where, $\sum in$ denotes the sum of edge weights connecting clusters; k_i represents the sum of edge weights for node i ; $k_{i,in}$ signifies the sum of edge weights from node i to internal nodes within the cluster; m denotes the total sum of edge weights in the network;

and $\sum tot$ indicates the sum of edge weights among internal nodes within the cluster.

Network robustness metrics. Robustness refers to the ability of a network or system to maintain its proper operational state and normal functionality under abnormal conditions, unexpected events, or external disturbances (Wei et al., 2022b). Perturbations to networks typically include random attacks, which involve the stochastic removal of nodes or edges without considering their individual attributes, and intentional attacks, which selectively target nodes or edges based on their ranking in terms of structural or functional importance. In this study, a cumulative node-attack approach is employed to analyze the robustness of the oil and natural gas trade networks among countries along the BRI, aiming to assess the overall resilience and tolerance of these networks. Two attack scenarios are considered: random attacks and intentional attacks. Random attacks simulate node disruptions caused by exogenous shocks such as natural disasters or public health crises, under which all BRI countries are assumed to have an equal probability of being affected, regardless of their network centrality. In contrast, intentional attacks represent targeted disruptions, such as terrorist attacks, geopolitical conflicts, economic sanctions, or policy shifts, that strategically target critical nodes to maximize systemic impact, thereby propagating disturbances through the network. For the intentional attack scenario, node importance is ranked according to three criteria: degree (i.e., the total number of energy trade relationships a node participates in), in-degree (i.e., the number of import-related energy trade links), and out-degree (i.e., the number of export-related energy trade links). This approach enables a systematic investigation into the structural roles and functional asymmetries between energy-producing and energy-consuming countries, offering insights into their respective positions within the trade network and their capacity to withstand external shocks. To evaluate the resilience of the oil and natural gas trade networks under disruption, two quantitative metrics are adopted: connectivity robustness and global network efficiency. These metrics jointly assess the structural integrity and functional performance of the networks. Specifically, connectivity robustness measures the extent to which the network remains connected following random or intentional attacks. The calculation is defined as follows:

$$R = \frac{c}{N - N_r} \quad (7)$$

where R denotes the connectivity robustness of the network; c represents the number of nodes in the largest connected component of the oil or natural gas trade network after removing a subset of nodes; and N_r is the number of removed nodes.

Global efficiency measures the operational efficiency of the oil and natural gas trade networks following intentional or random attacks. The calculation is defined as follows:

$$E = \frac{1}{N(N - 1)} \sum_{i \neq j} d_{ij} \quad (8)$$

where E denotes the global network efficiency; N is the total number of nodes in the oil or natural gas trade network; and d_{ij} represents the shortest path length between node i and node j . A higher network efficiency indicates denser trade linkages, implying that oil and natural gas supply and demand are more effectively fulfilled across the network. Conversely, a low network efficiency reflects poor transmission performance, characterized by sparse trade connections among countries and an inability to meet the energy demands of most nations. Under such conditions, energy security becomes critically compromised.

Table 3 Description of the Worldwide Governance Indicators (WGI).

| Indicators | Description | Value |
|---|--|-------------|
| Voice and Accountability | The indicator captures perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media. | -2.5 to 2.5 |
| Political Stability and Absence of Violence/Terrorism | The indicator measures perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism. | -2.5 to 2.5 |
| Government Effectiveness | The indicator captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. | -2.5 to 2.5 |
| Regulatory Quality | The indicator captures perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development. | -2.5 to 2.5 |
| Rule of Law | The indicator captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. | -2.5 to 2.5 |
| Control of Corruption | The indicator captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. | -2.5 to 2.5 |

Model construction

Revised gravity model. This study extends the gravity model by incorporating variables such as economic, geographic, cultural, institutional, and organizational proximity. Through the logarithmic transformation of the gravity model, a linear relationship between the dependent and independent variables is established. The extended gravity model for the oil and natural gas trade networks along the BRI countries is formulated as follows:

$$\ln Tra_{ij} = \beta_0 + \beta_1 Eco_{ij} + \beta_2 \ln Discap_{ij} + \beta_3 Cul_{ij} + \beta_4 \ln WGI_{ij} + \beta_5 Org_{ij} + \mu \tag{9}$$

Where, Tra_{ij} represents the trade volume of oil or natural gas between country i and country j ; Eco_{ij} denotes the economic proximity between countries i and j ; $Discap_{ij}$ measures the capital distance between countries i and j , inverted to reflect stronger geographic proximity with smaller distances; Cul_{ij} indicates the cultural proximity between countries i and j ; WGI_{ij} signifies the difference in institutional quality between countries i and j , inverted such that smaller differences indicate stronger institutional proximity; Org_{ij} represents the organizational proximity between countries i and j ; Economic, cultural, and organizational proximities are treated as binary discrete variables without logarithmic transformation.

The oil and natural gas trade networks among the BRI countries involve relational data that exhibit structural autocorrelation. Ordinary Least Squares (OLS) regression analysis is not suitable for modeling such relational data due to the presence of autocorrelation, which leads to internal structural dependencies. The Quadratic Assignment Procedure (QAP) is an appropriate method for analyzing these networks because it compares elements across two or more relational matrices. As a non-parametric approach, QAP provides relatively unbiased statistical results in the presence of autocorrelation (Gui et al., 2019). The QAP regression process involves three main steps: (1) Standard Regression Analysis: Perform a standard regression analysis on independent and dependent variables. (2) Random Permutation: Randomly permute the rows and columns of the matrix to compute test statistics for each permutation. (3) Distribution Generation and Significance Testing: Generate a distribution of statistics from multiple permutations, then determine whether the observed values fall within the acceptance

or rejection region of this distribution to assess the significance of the variables.

Variable descriptions. Economic proximity (Eco_{ij}) data are sourced from the World Bank, which categorizes countries into four income groups based on their per capita gross national income: low-income, lower-middle-income, upper-middle-income, and high-income countries. Two countries are considered economically proximate if they are in the same income group. Geographic proximity ($Discap_{ij}$) is reflected through the distances between the capital cities of countries, with smaller distances indicating greater geographic proximity. The data are sourced from the CEPII database. Cultural proximity (Cul_{ij}) is characterized by shared official languages and colonial historical ties, with countries sharing an official language or having a colonial history in common indicating greater cultural proximity. The data are sourced from the CEPII database. Organizational proximity (Org_{ij}) indicates countries that are co-members of the International Energy Agency (IEA), the Organization of the Petroleum Exporting Countries (OPEC), the Gulf Cooperation Council (GCC), or have jointly signed the Energy Charter Treaty. The data were compiled by the author. The institutional environment is mainly indirectly reflected by the Worldwide Governance Indicators (WGI) released by the World Bank. The WGI features six aggregate governance indicators for over 200 countries and territories over the period 1996–2022: Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption. The index ranges from -2.5 to +2.5, with higher values indicating a better institutional environment (Table 3). The institutional difference between countries is calculated according to Equation (10), with smaller values indicating closer institutional proximity (WGI_{ij}).

$$WGI_{ij} = \sum_k^6 \left| \frac{I_{i,k} - I_{j,k}}{\max I_k - \min I_k} \right| \tag{10}$$

Where, k denotes the six dimensions of global governance, $I_{i,k}$ and $I_{j,k}$ represent scores of countries i and j on dimension k , and $\max I_k$ and $\min I_k$ represent the highest and lowest scores globally on dimension k .

Model assumptions. In the twentieth century, Newton's law of universal gravitation was introduced into international trade

theory, leading to the development of the gravity model of international trade. The model posits that the scale of trade between two countries is negatively correlated with geographical distance and positively correlated with the product of their economic sizes. Subsequently, scholars extended this framework by incorporating additional variables such as institutional distance and organizational distance (De Groot et al., 2004; Silva and Nelson, 2012). Drawing on proximity theory, this study extends the notion of physical distance in energy trade to “virtual distance” and proposes the following hypotheses concerning energy trade proximities.

Economic proximity refers to the similarity in economic development levels between two countries: the smaller the gap, the stronger the proximity (Peltrault and Venet, 2005). While some studies show that economic proximity fosters trade (Lu et al., 2014; Nunn, 2007), others suggest that large economic differences stimulate trade because firms prefer trade over foreign direct investment when development gaps exist (Linders, 2006). Energy trade, as a global commodity exchange, follows similar dynamics. Fossil energy is characterized by resource inertia and often forms the basis of “resource curse” dependence in producing countries (Robst et al., 2007). At the same time, many states restrict foreign investment in energy, making cross-border trade the dominant channel of energy flows. Given that economic scale also reflects energy consumption capacity, trade in oil and gas frequently occurs between economically disparate producers and consumers. Based on these insights, the following hypothesis is formulated:

H1 Economic proximity negatively affects the oil trade and natural gas trade of countries along the BRI.

Geographical proximity captures the spatial relationship between nations, with shorter distances facilitating stronger trade ties. Traditional trade theory holds that trade flows are inversely proportional to distance. Shorter distances reduce transport costs and foster cooperation (Robst et al., 2007), whereas long distances increase costs and barriers (Disdier and Head, 2008). The oil and gas trade is inherently constrained by spatial distance, as longer transport routes raise costs and reduce efficiency. Hence, countries often prefer nearby partners, leading to pronounced regionalization. The degree of this effect, however, may vary between oil and natural gas. Based on these insights, the following hypothesis is formulated:

H2 Geographic proximity positively affects the oil trade and natural gas trade of countries along the BRI.

Cultural proximity measures the similarity in cultural values, traditions, and languages between nations, with smaller differences implying stronger proximity (Ellis, 2007). Beyond physical distance, cultural closeness fosters trust, reduces transaction costs, and strengthens consumer preferences. Cultural factors such as customs, consumption patterns, and language directly shape trade behavior. Shared colonial histories often produce stronger cultural ties and more frequent trade (Bastos and Silva, 2008). Language, as a key cultural feature, reduces communication barriers, contractual misunderstandings, and regulatory risks, thereby enhancing trade volumes (Lameli et al., 2015; Melitz, 2008). Based on these insights, the following hypothesis is formulated:

H3 Cultural proximity positively affects the oil trade and natural gas trade of countries along the BRI.

Institutional proximity reflects the degree of similarity in legal, regulatory, and governance frameworks across countries (Kostova, 1996). According to transaction cost theory, greater institutional divergence increases costs in negotiation, adaptation, enforcement, and dispute resolution (Miura and Takechi, 2014). Institutional differences also influence property rights protection, transparency, and corruption, thereby shaping trade flows.

Empirical studies show that wider institutional gaps significantly suppress trade (Angkinand and Willett, 2011), while similarity enhances contractual enforcement and reduces uncertainty (Bojnec and Fertő, 2015). In the global energy trade system, convergent institutional arrangements strengthen guarantees for oil and gas trade, optimize the contractual environment, and expand trade volumes. Based on these insights, the following hypothesis is formulated:

H4 Institutional proximity positively affects the oil trade and natural gas trade of countries along the BRI.

Organizational proximity denotes the extent to which two countries participate in the same international organizations or institutional frameworks. The French school of proximity dynamics, it emphasizes relational embeddedness and structural proximity within organizations (Oerlemans and Meeus, 2005). Membership in the same international institutions facilitates consensus on rules, enhances predictability, and lowers transaction risks (Zhuo et al., 2025). For example, trade between members of the International Energy Agency, OPEC, the Gulf Cooperation Council, or signatories to the Energy Charter Treaty is significantly more frequent than trade outside these organizations. Shared organizational ties therefore reduce geopolitical uncertainties and strengthen bilateral energy cooperation (Liu et al., 2020). Based on these insights, the following hypothesis is formulated:

H5 Organizational proximity positively affects the oil trade and natural gas trade of countries along the BRI.

Results

Comparison of evolution in oil and natural gas trade networks

Comparison of topological structure evolution. Overall, rapid economic development among the BRI countries has led to rigid demands for oil and natural gas, coupled with domestic pressures for green ecological environments. This has compelled these countries to continuously seek external cooperation in oil and natural gas. Both oil trade networks and natural gas trade networks exhibit a trend towards densification (Table 4). From 2009 to 2018, the degree of the oil trade network increased from 21.892 to 25.446, and the natural gas trade network increased from 7.185 to 8.538. The weighted degree also increased significantly from 46.530 to 79.165 for oil and from 6.308 to 13.037 for natural gas. There was a slight decline observed between 2014 and 2017, indicating that while more countries participated in these networks, the intensity of trade showed a declining trend. The degree and weighted degree of the oil trade network are substantially higher than those of the natural gas trade network, indicating greater participation and intensity in the oil trade. From 2009 to 2018, the graph density of the oil trade network increased from 0.342 to 0.398, and for natural gas, it increased from 0.112 to 0.133. The average clustering coefficient also increased from 0.620 to 0.672 for oil and from 0.417 to 0.457 for natural gas. This suggests that the oil trade network is denser and more complete compared to the natural gas trade network. The graph density and average clustering coefficient of the oil trade network are higher than those of the natural gas trade network, indicating that there is still significant trade potential in natural gas. From 2009 to 2018, the average path length of the oil trade network decreased from 1.687 to 1.617, and for natural gas, it decreased from 2.411 to 2.270. This indicates enhanced trade accessibility for oil and natural gas among the BRI countries. The average path length of the oil trade network is lower than that of the natural gas trade network, implying higher trade accessibility for oil compared to natural gas.

In summary, the characteristic indicators of the oil trade network are superior to those of the natural gas trade network.

Table 4 Network characteristics of oil and natural gas trade among BRI countries, 2009–2018.

| | Degree | | Weighted Degree | | Graph density | | Average clustering coefficient | | Average path length | |
|------|--------|-------------|-----------------|-------------|---------------|-------------|--------------------------------|-------------|---------------------|-------------|
| | Oil | Natural Gas | Oil | Natural Gas | Oil | Natural Gas | Oil | Natural Gas | Oil | Natural Gas |
| 2009 | 21.892 | 7.185 | 46.530 | 6.308 | 0.342 | 0.112 | 0.620 | 0.417 | 1.687 | 2.411 |
| 2010 | 23.785 | 7.538 | 62.364 | 9.282 | 0.372 | 0.118 | 0.624 | 0.423 | 1.667 | 2.553 |
| 2011 | 24.215 | 7.985 | 89.534 | 13.475 | 0.378 | 0.125 | 0.633 | 0.476 | 1.652 | 2.391 |
| 2012 | 24.215 | 7.892 | 94.828 | 13.759 | 0.378 | 0.123 | 0.639 | 0.468 | 1.654 | 2.501 |
| 2013 | 25.000 | 8.431 | 94.486 | 16.099 | 0.391 | 0.132 | 0.624 | 0.445 | 1.628 | 2.325 |
| 2014 | 25.169 | 8.277 | 90.266 | 17.008 | 0.393 | 0.129 | 0.649 | 0.452 | 1.627 | 2.193 |
| 2015 | 24.138 | 8.215 | 51.607 | 11.554 | 0.377 | 0.128 | 0.644 | 0.463 | 1.656 | 2.279 |
| 2016 | 24.538 | 8.662 | 44.153 | 9.580 | 0.383 | 0.135 | 0.658 | 0.451 | 1.631 | 2.280 |
| 2017 | 25.923 | 8.385 | 57.779 | 11.916 | 0.405 | 0.131 | 0.665 | 0.454 | 1.632 | 2.189 |
| 2018 | 25.446 | 8.538 | 79.165 | 13.037 | 0.398 | 0.133 | 0.672 | 0.457 | 1.617 | 2.270 |

This can be attributed to several factors: firstly, the lower difficulty in the extraction, production, and transportation of oil compared to natural gas, making it easier to engage in large-scale transactions. Additionally, the greater demand for oil in transportation, industrial production, and daily life across countries underscores its dominant role in energy consumption along the Belt and Road region. On the other hand, factors such as geographical conditions, trade patterns, transportation and storage challenges, as well as high investment and maintenance costs, pose greater difficulties for pipeline and liquefied natural gas trade. Despite increasing environmental awareness and policy advancements promoting natural gas trade, there remains a significant gap in traded volumes compared to the oil trade.

Comparison of spatial structural evolution. From 2009 to 2013, the total oil trade volume among the BRI countries was \$2.574 billion. The top 5% of trade relationships (111 links) accounted for \$2.246 billion, representing a high percentage of 87.24%, adhering to the “80/20 rule”. Among these, 50 links of oil export relationships originated from West Asia and North Africa, nearly half of which (10 links) came specifically from Saudi Arabia. Additionally, 21 links of oil export relationships came from Russia. The total oil exports from Saudi Arabia and Russia to the BRI countries amounted to \$0.911 billion, representing 35.39% of the trade network, highlighting them as the two major export centers (Fig. 2). Regarding imports, the top 5% of relationships included 40 links of oil import relationships from China, Singapore, and India, with China having 15 links, Singapore 13 links, and India 12 links. These three countries accounted for \$1.335 billion, or 51.86% of total oil imports, indicating their roles as the three major import centers in the oil trade network. From 2014 to 2018, the total oil trade volume among the BRI countries was \$1.851 billion. The top 5% of trade relationships (113 links) accounted for \$1.603 billion, decreasing to 86.59%, while still adhering to the “80/20 rule”. Among these, 11 links of oil export relationships came from Saudi Arabia and 23 links from Russia, totaling \$0.640 billion, decreasing their share to 34.58%, indicating a weakening of their functions as major export centers. In terms of imports, the top 5% of relationships included 36 links of oil import relationships from China, Singapore, and India, with China having 15 links, Singapore 11 links, and India 10 links. These three countries accounted for \$1.012 billion, or 54.67% of total oil imports, indicating a strengthening of their functions as major import centers.

From 2009 to 2013, the total natural gas trade volume among the BRI countries was \$0.389 billion. The top 5% of trade relationships (43 links) accounted for \$0.326 billion, representing a high percentage of 83.80%, adhering to the “80/20 rule”. Among these, 12 links of natural gas export relationships came from

Russia, which dominated with a total export of \$0.142 billion, representing 36.50% of the natural gas exports in the BRI countries (Fig. 2). However, the distribution of natural gas import relationships within the top 5% was more dispersed, focusing on Southeast Asian countries, Central and Eastern European countries, and China, showing a clear multi-centered characteristic. China’s main natural gas import countries were Russia and Turkmenistan. From 2014 to 2018, the total natural gas trade volume among the BRI countries was \$0.417 billion. The top 5% of trade relationships (44 links) accounted for \$0.351 billion, reaching 84.17%, where the “80/20 rule” became more significant. Among these, 10 links of natural gas export relationships came from Russia and 10 from Qatar. The total natural gas exports from Russia and Qatar to the BRI countries amounted to \$0.177 billion, representing 42.15% and highlighting them as the two major export centers. Qatar’s exports to the BRI countries amounted to \$0.109 billion, surpassing Russia, indicating Qatar’s increasing dominance in the natural gas market among the BRI countries. Regarding imports, the top 5% of relationships included 11 links of natural gas import relationships from China, amounting to \$0.119 billion, or 28.53% of total natural gas imports, making China the major import center in the natural gas trade network among the BRI countries.

Comparing the oil and natural gas trade networks, both adhere to the “80/20 rule”, indicating a clear “rich club” phenomenon where a few countries control the majority of trade. This reflects the non-renewable and regional nature of oil and natural gas. However, there are distinct differences in their spatial structures and evolutionary processes (Fig. 3). The spatial pattern of the oil trade network is stable, forming a distribution characterized by “dual-core exports and tri-core imports,” with exports dominated by Russia and Saudi Arabia, and imports primarily led by China, India, and Singapore. The spatial pattern of the natural gas trade network has seen significant changes, evolving from a distribution characterized by Russian dominance in exports and a dispersed import landscape across multiple countries, to a pattern featuring “dual-core exports and single-core imports,” with Qatar and Russia leading in exports and China taking the lead in imports. As natural gas emerges as a significant cleaner energy source, its trade dynamics are influenced by geopolitical factors such as China’s “Dual Carbon” strategy and uncertainties in Russia’s relations with Western countries, making China a major importer of Russian natural gas.

Comparison of clustered structure evolution. The oil trade network forms four major clusters, with stable spatial distributions (Fig. 4). From 2009 to 2013, Cluster 1 of the oil trade network mainly covered East Asia and West Asia. Cluster 2 covered Southeast Asia. Cluster 3 covered South Asia and West Asia, while Cluster 4

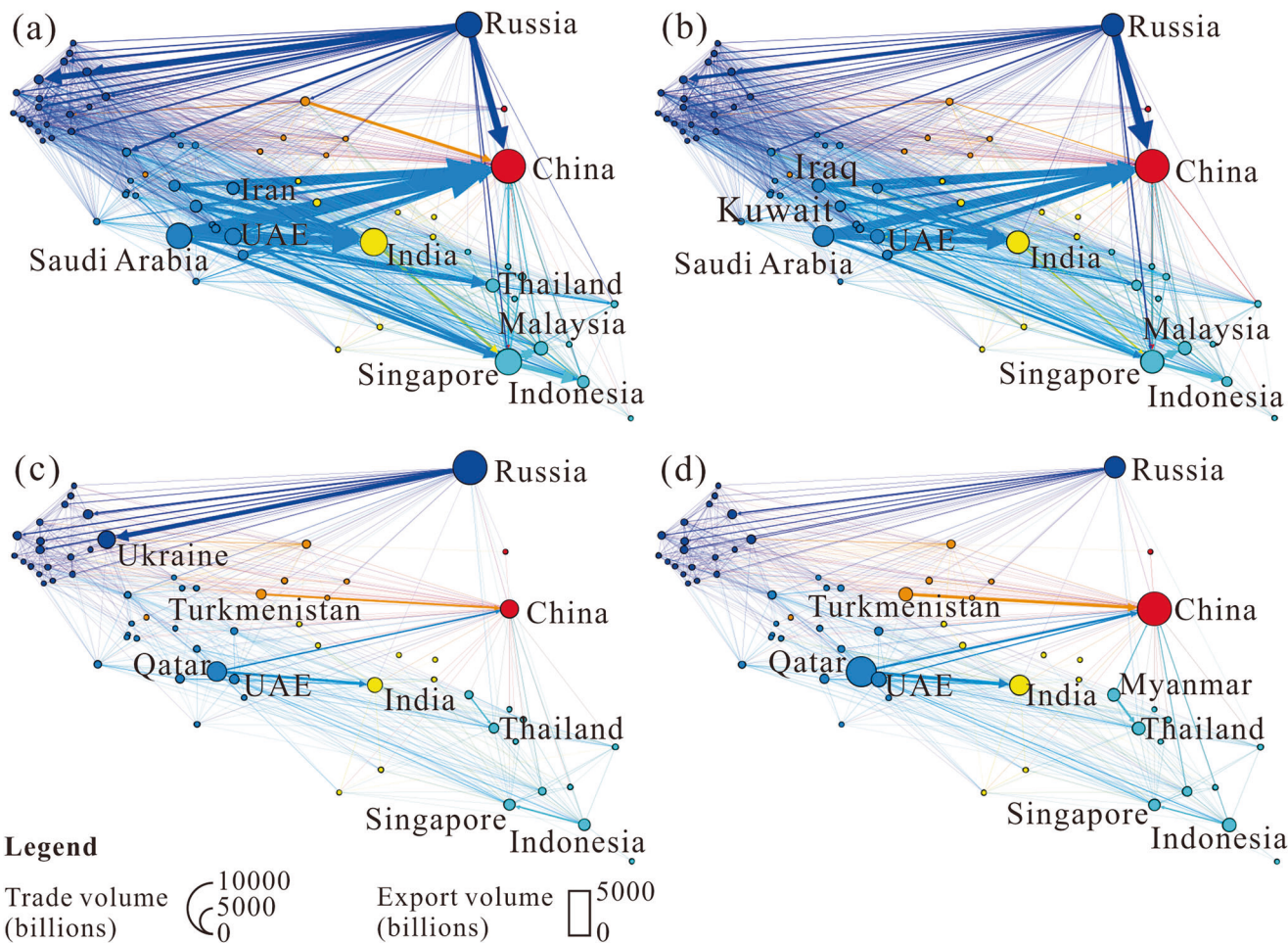


Fig. 2 Evolution of oil and natural gas trade networks among the BRI countries, 2009–2018. **a** Oil trade network (2009–2013); **b** Oil trade network (2014–2018); **c** Natural gas trade network (2009–2013); **d** Natural gas trade network (2014–2018).

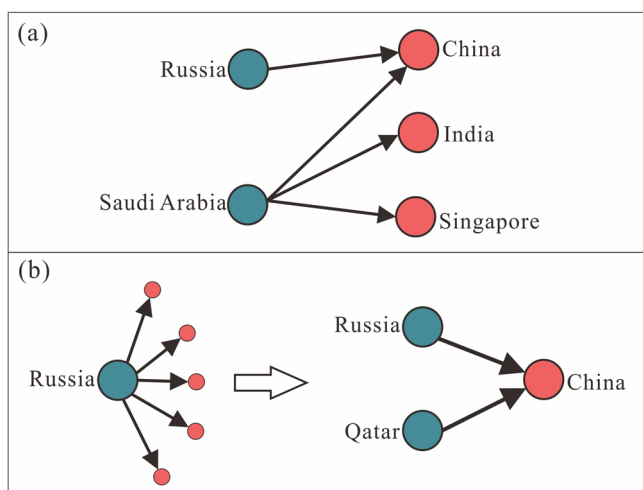


Fig. 3 Schematic representation of the spatial structural evolution in oil and natural gas trade networks among the BRI countries. **a** Oil trade network; **b** Natural gas trade network.

covered Central Asia and Central and Eastern Europe. Overall, there were close oil trade links between East Asia, South Asia, and West Asia, and significant trade relations between Central Eastern Europe and Central Asia. Oil trade among Southeast Asian countries is mainly concentrated within the region. From 2014 to 2018, the oil trade network still maintained four clusters with

overall unchanged coverage areas. Syria moved from Cluster 4 to Cluster 3, and Yemen moved from Cluster 3 to Cluster 1. Syria's shift was influenced by the European Union's imposition of oil sanctions in 2011, leading Syria to cancel its oil exports to Central and Eastern European countries. Yemen's change was due to domestic political unrest and regional conflicts, significantly reducing its oil exports but maintaining relations with China, India, and some Southeast Asian countries, hence entering Cluster 1.

The natural gas trade network forms six major clusters, with varying spatial distributions (Fig. 4). From 2009 to 2013, Cluster 1 of the natural gas trade network covered primarily East Asia and Southeast Asia. Cluster 2 covered Southeast Asia. Cluster 3 covered South Asia. Cluster 4 covered Central Asia and Central Eastern Europe. Cluster 5 covered Central Eastern Europe, and Cluster 6 covered West Asia. Natural gas trade among Southeast Asia, South Asia, and West Asia mainly concentrated within their respective regions, while East Asia had cross-regional trade with Southeast Asia, and Central Eastern Europe had trade interactions with Central Asia. From 2014 to 2018, the natural gas trade network still formed six clusters, but with significant changes in spatial distribution. 25 countries shifted clusters, primarily concentrated in Clusters 1, 2, and 4, while other clusters maintained stable coverage areas. Several countries entered Cluster 1, such as Turkmenistan, Afghanistan, Iraq, Brunei, Pakistan, shifting from other clusters to Cluster 1. The main coverage area of Cluster 1 shifted from East Asia and Southeast Asia to include Central Asia. Some Southeast Asian countries,

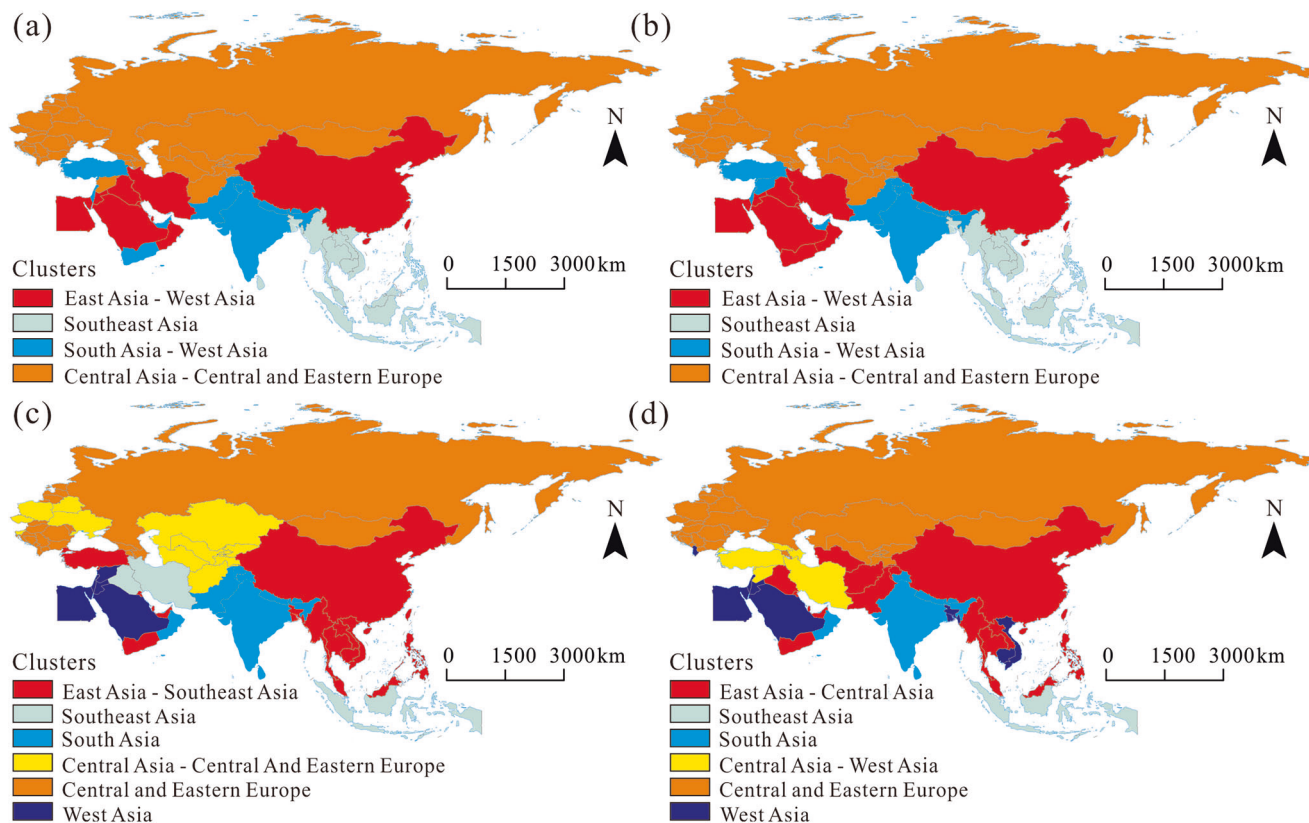


Fig. 4 Cluster structures of oil and natural gas trade networks among the BRI countries, 2009–2018. **a** Oil trade network (2009–2013); **b** Oil trade network (2014–2018); **c** Natural gas trade network (2009–2013); **d** Natural gas trade network (2014–2018). Clusters are ordered in the legend from top to bottom by formation sequence: Group 1, Group 2, Group 3, etc.

such as Cambodia and Vietnam, exited Cluster 1 and entered Cluster 6. Additionally, some countries shifted from Cluster 4 to Cluster 5, such as Poland, Slovakia, Slovenia, Tajikistan, and Ukraine, all mainly from Central Eastern Europe. Hence, the main coverage area of Cluster 4 shifted from Central Asia and Central Eastern Europe to Central Asia and West Asia. These changes indicate a growing number of countries along the BRI with natural gas trade relations with China. It also shows reduced natural gas trade between Central Asian countries and Central Eastern European countries, while intra-regional natural gas trade within Central Eastern Europe continues to strengthen.

Comparison of robustness evolution. Figure 5 shows the changes in the connectivity robustness of oil and natural gas trade networks among the BRI countries under random and targeted attacks. To better observe the impact of node perturbations on the entire network, cumulative attack scenarios involving 10%, 50%, and 80% of nodes are evaluated, following the methodology of Wei et al. (2022b). Under a 10% node attack, both the oil and natural gas trade networks demonstrate strong robustness under both random and targeted attacks. However, network robustness under random attacks is higher than under targeted attacks. Comparing the two networks, the oil trade network exhibits greater resilience than the natural gas trade network. After targeted attacks based on degree, in-degree, and out-degree, the connectivity robustness of the oil trade network remains above 75%, while that of the natural gas trade network drops to approximately 65%. When 50% of nodes are attacked, the connectivity robustness of both networks under random attacks remains at around 25%. The oil trade network is close to collapse under targeted attacks, with its robustness decreasing to about 10% across degree, in-degree, and out-degree attack strategies.

This finding is consistent with the results reported by Wei et al. (2022b). The natural gas trade network collapses under targeted attacks, with connectivity robustness falling to 4.4% (degree), 6.1% (in-degree), and 4.5% (out-degree), respectively. These results indicate that the oil trade network among the BRI countries is more robust than the natural gas trade network. Under an 80% node attack, both the oil and natural gas trade networks collapse completely under targeted attacks, with connectivity robustness dropping to 0.1% and the network structure nearly disintegrated. Only under random attacks does a minimal level of connectivity robustness (around 2%) remain.

Further comparison of the three targeted attack strategies, based on degree, in-degree, and out-degree, reveals differences in network robustness after removing the same number of nodes. For the oil trade network, robustness decreases in the following order: in-degree attack (highest), degree attack, and out-degree attack (lowest). The same pattern is observed in the natural gas trade network. By comparing the slopes of the robustness curves over time under targeted attacks, it is found that the robustness of the BRI oil trade network during 2009–2013 was lower than that during 2014–2018, whereas the robustness of the natural gas trade network during 2009–2013 was higher than in the later period. This suggests that the risk resilience of the BRI oil trade network has been continuously improving, while that of the natural gas trade network has been declining.

To complement the robustness analysis, global network efficiency was employed as an additional metric to evaluate system performance under random and intentional attacks. The results, presented in Fig. 6, demonstrate that both networks maintain higher operational efficiency under random attacks, indicative of inherent robustness, while efficiency under intentional attacks is markedly lower, reflecting structural

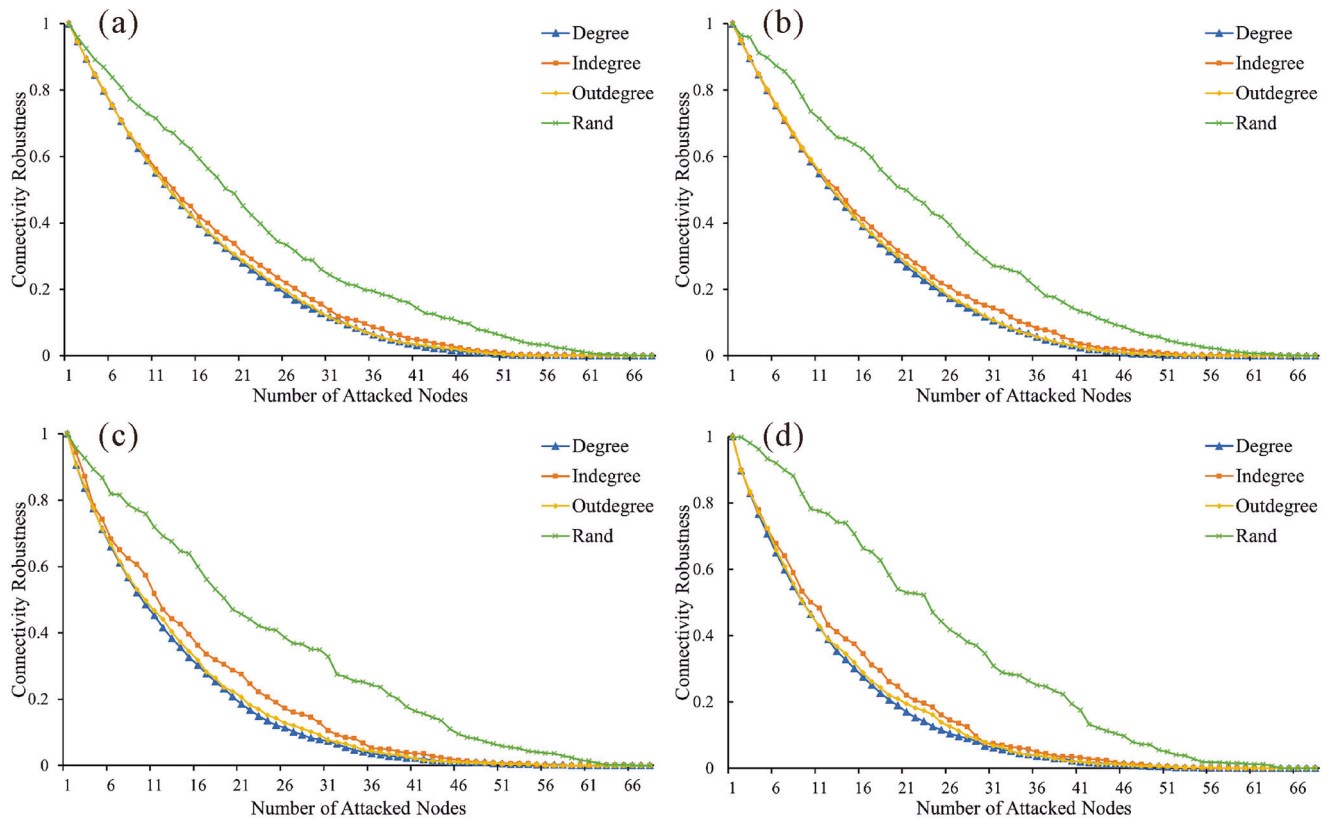


Fig. 5 Connectivity robustness of oil and natural gas trade networks among the BRI countries under intentional and random attacks, 2009-2018. **a** Oil trade network (2009-2013); **b** Oil trade network (2014-2018); **c** Natural gas trade network (2009-2013); **d** Natural gas trade network (2014-2018).

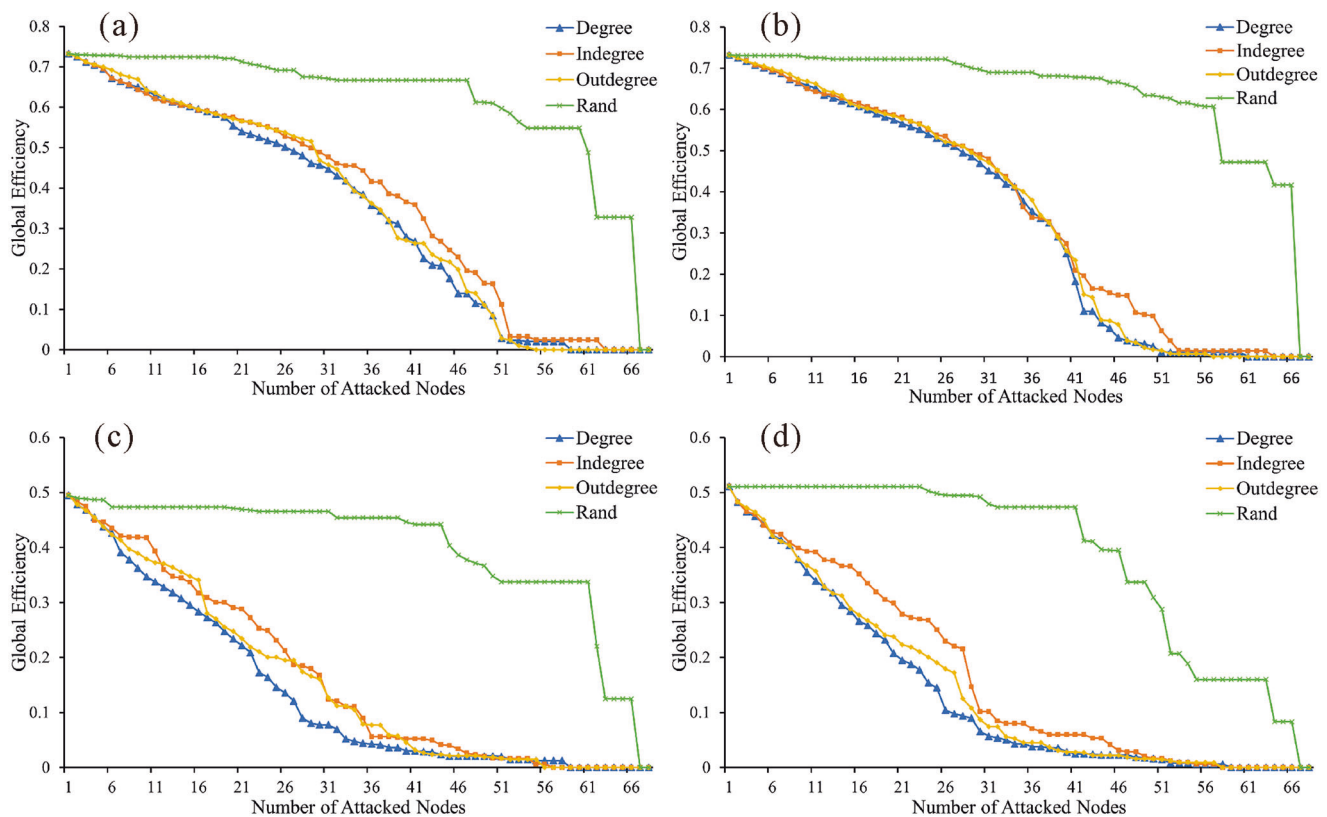


Fig. 6 Global efficiency of oil and natural gas trade networks among the BRI countries under intentional and random attacks, 2009-2018. **a** Oil trade network (2009-2013); **b** Oil trade network (2014-2018); **c** Natural gas trade network (2009-2013); **d** Natural gas trade network (2014-2018).

vulnerability. Comparative analysis of the efficiency curves confirms that the oil trade network is more resilient than the natural gas trade network. This discrepancy is largely attributable to the natural gas network's heavy reliance on pipeline infrastructure, which is highly susceptible to disruption from terrorist incidents or geopolitical conflicts in BRI regions. Such events can lead to physical damage to pipelines, causing critical trade routes to be severed more easily. Accordingly, the natural gas trade network exhibits greater fragility. The prominent roles of energy-importing countries within the networks, as well as the temporal patterns of robustness, further support these conclusions.

Comparison of proximity effects in oil and natural gas trade networks. To study the impact of various factors on the evolution of the oil and gas trade network along the BRI, this paper uses weighted networks as the dependent variable. The UCINET software is employed to import matrix data for Quadratic Assignment Procedure (QAP) regression analysis, obtaining multiple regression results through 2000 matrix permutations. Table 5 displays the regression coefficients and significance test results of the variables, with R^2 and adjusted R^2 indicating the goodness-of-fit of the QAP model. Overall, models (1) to (4) pass the significance tests, suggesting that economic, geographic, cultural, institutional, and organizational factors significantly influence the oil and gas trade networks among the BRI countries. Specifically, the adjusted R^2 for model (1) is 0.789 and 0.878 for model (2), indicating that the explanatory power of these variables for the BRI oil trade network increased from 78.9% in 2009-2013 to 87.8% in 2014-2018. The adjusted R^2 for model (3) is 0.854 and 0.853 for model (4), suggesting relatively stable explanatory power for the BRI gas trade network at 85.4% in 2009-2013 and 85.3% in 2014-2018. The change in explanatory power for the oil network is mainly due to the shift from cooperation to conflict in Sino-U.S. relations, the regionalization, bloc formation, and localization trends in the global economy, and changes in the proximity effect in oil trade.

Regarding oil trade network proximity, from the regression coefficients of models (1) and (2), the $discap_{ij}$ and WGI_{ij} variables have positive coefficients and pass the significance level test. As these are inverse indicators of proximity, it suggests that the BRI oil trade network lacks geographic and institutional proximity, with greater geographic and institutional distances correlating with higher bilateral oil trade volumes between BRI countries. This aligns with Kitamura and Managi's findings that geographic distance and institutional distance, particularly geographic distance, do not inversely correlate with the scale

of oil trade but rather facilitate bilateral oil trade (Kitamura and Managi, 2017). The reason is primarily due to the geographical inertia of oil production and supply, which is more influenced by the geographic distribution of energy resources, with bilateral trade preferences more dependent on the resource volume of oil-exporting countries than on bilateral geographic or institutional distances. These results differ significantly from those of general commodity trade, where geographic proximity typically reduces transportation costs and potential security risks during transport, thereby enhancing trade potential (Borchert and Yotov, 2017; Wu et al., 2020). Additionally, institutional distance can hinder bilateral commodity trade, such as market regulation, protection of private property, and monetary policy (Pan, 2006). The special nature of the oil trade is further indicated by the limitations imposed by the mismatch between production and consumption spaces and the immobility of production. In models (1) and (2), the Eco_{ij} , Cul_{ij} , and Org_{ij} variables have positive coefficients that pass the 1% significance level test, indicating the presence of economic, cultural, and organizational proximity in the BRI oil trade network. Smaller economic, cultural, and organizational distances correlate with higher bilateral trade volumes. The impact of economic proximity on oil trade is different from other regions. For instance, in the High Arctic region, larger economic distances correlate with higher bilateral oil trade volumes (Yang et al., 2022). Comparatively, the BRI's oil supply is concentrated in regions from the Persian Gulf to the Caspian Sea, to the Transcaucasia, and then to Russia's Siberia and other Far Eastern regions, mostly in developing countries, while demand is concentrated in East Asian and Southeast Asian countries, also mostly in developing countries, with relatively smaller economic distances. The results also show a preference for oil trade among countries belonging to the IEA, OPEC, GCC, or having signed the Energy Charter Treaty, as well as countries with a colonial history or sharing an official language. Such similarities reduce asymmetries in strategic trust, communication barriers, and costs associated with legal disputes and information gathering. From the absolute values of the regression coefficients in models (1) and (2), cultural proximity has the greatest impact on the BRI oil trade network, followed by organizational proximity. From the changes in regression coefficients, only $Discap_{ij}$'s coefficient is higher in model (2) than in model (1), indicating a stronger influence of geographic distance on BRI oil trade.

Regarding the natural gas trade network proximity, in model (3), the Eco_{ij} and WGI_{ij} indicators have negative coefficients that pass the significance level test, but in model (4), WGI_{ij} 's coefficient is negative and passes the 1% significance level test, while Eco_{ij} 's coefficient is negative but does not pass the significance level test. This indicates the absence of economic proximity in the BRI gas trade network, with the influence of economic distance weakening over time. Compared to the oil trade network, institutional proximity enhances the tendency towards the BRI gas trade. This is mainly because the natural gas market is more fragmented than the oil market and requires long-term contracts and stable supply-demand relationships. Institutional proximity helps maintain market stability, reducing trade friction and cost increases due to institutional differences, and simplifying pricing mechanisms and settlement methods, lowering transaction costs. For example, the United States became a significant exporter due to the shale gas revolution, while Europe sought diversified supply channels due to factors such as the Ukraine crisis. This requires both parties to reach a consensus on trade systems and contract terms to ensure the stability of natural gas supplies. Model (3) and model (4) both have positive coefficients for $Discap_{ij}$ that pass the significance level test,

Table 5 QAP regression results for oil and natural gas trade-weighted networks among the BRI countries.

| | Model 1 Oil 2009-2013 | Model 2 Oil 2014-2018 | Model 3 Natural Gas 2009-2013 | Model 4 Natural Gas 2014-2018 |
|----------------|--------------------------|--------------------------|----------------------------------|----------------------------------|
| Constant | 0.170 | 0.174 | 0.042 | 0.043 |
| Eco_{ij} | 0.879*** | 0.668*** | -0.477** | -0.024 |
| $Discap_{ij}$ | 0.767*** | 0.917*** | 1.057*** | 0.972*** |
| Cul_{ij} | 3.598*** | 3.267*** | 1.215*** | 1.923*** |
| WGI_{ij} | 0.552** | 0.272** | -1.332*** | -1.050*** |
| Org_{ij} | 1.163*** | 0.703*** | 0.499** | 0.643** |
| R^2 | 0.789 | 0.879 | 0.855 | 0.854 |
| Adjusted R^2 | 0.789 | 0.878 | 0.854 | 0.853 |

***, ** and * indicate 1%, 5%, and 10% significance levels, respectively. Both $discap_{ij}$ and WGI_{ij} are reverse indicators.

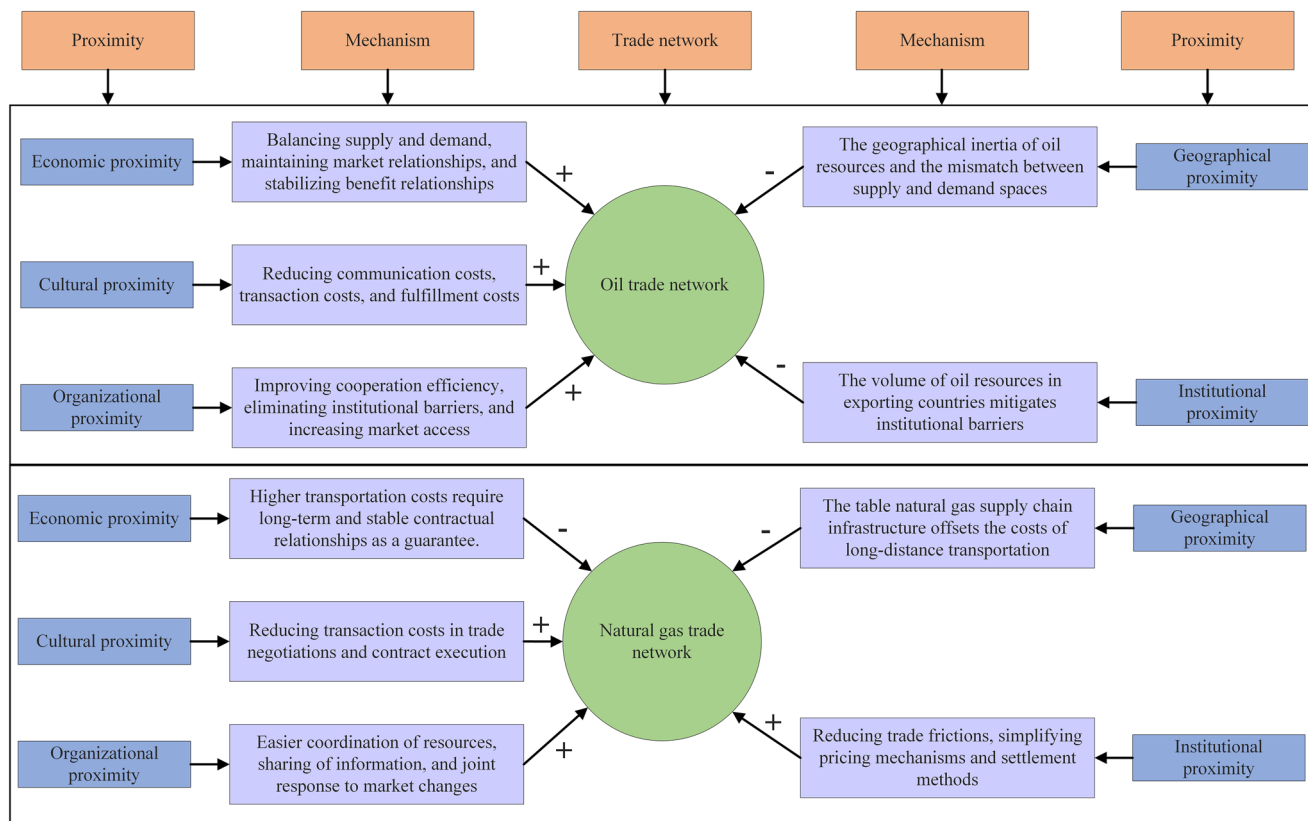


Fig. 7 Schematic illustration of proximity dimensions in oil and natural gas trade networks among the BRI countries. "+" denotes a positive effect, and "-" denotes a negative effect.

indicating that longer geographic distances correlate with higher bilateral gas trade volumes, consistent with the regression results for the oil trade network. The uneven distribution of natural gas resources, primarily in the Middle East and Russia, necessitates long-distance imports for many countries. Moreover, some countries have established efficient natural gas supply chains, including LNG terminals and pipeline networks, enabling them to effectively receive and distribute gas from distant suppliers. Despite the increased costs of long-distance transport, long-term trade contracts, bulk purchases, and favorable price terms may offset these additional costs. This result is also consistent with the research findings on cross-regional cluster spatial patterns proposed in this paper. In models (3) and (4), the Cul_{ij} and Org_{ij} variables have positive coefficients that pass the 1% significance level test, suggesting the presence of cultural and organizational proximity in the BRI gas trade network. Countries with cultural proximity share similar cultural values and social customs, which facilitates the negotiation and fulfillment of trade agreements, reduces transaction risks, and minimizes misunderstandings and conflicts arising from cultural differences. This, in turn, lowers transaction costs related to trade negotiations and contract execution, which is particularly crucial for natural gas trade, given its long-term nature and substantial capital requirements (Zhang et al., 2018). Countries within the same organizational framework can streamline trade processes, enhance cooperation efficiency, and reduce friction costs resulting from organizational differences. They are also better able to coordinate resources, share information, and jointly respond to market changes. From the absolute values of the regression coefficients in models (3) and (4), cultural proximity has the greatest impact on the BRI gas trade network, followed by institutional proximity, indicating the significant role of soft environment convergence in gas trade. This is mainly because

natural gas trade involves higher costs and is more sensitive to issues such as contract fulfillment and trade friction. From the changes in regression coefficients, the coefficients for Cul_{ij} and Org_{ij} are higher in model (4) than in model (3), indicating a strengthening influence of cultural and organizational proximity on BRI gas trade.

The five dimensions of proximity, namely economic, geographic, cultural, institutional, and organizational, have similar and differing impacts on the evolution of the BRI oil and gas trade networks (Fig. 7). Firstly, cultural and organizational proximity are the main drivers of the evolution of both the oil and natural gas trade networks. Cultural proximity effectively reduces communication, transaction, and fulfillment costs for both oil and natural gas trades. Organizational proximity can mitigate trade barriers caused by institutional differences between countries, improve market access for natural gas, and promote trade liberalization and facilitation. Secondly, geographical and institutional proximity do not facilitate oil trade, while economic and geographical proximity do not facilitate natural gas trade. This difference is primarily due to the different physical forms and transportation methods of natural gas compared to oil. Natural gas can be traded in gaseous and liquid forms, and its more dispersed geographical distribution leads to higher transportation costs relative to oil trade. Therefore, natural gas trade is more sensitive to trade risks arising from factors such as institutions, organizations, and culture. Thirdly, the influence of each dimension of proximity on oil and natural gas trade has weakened to varying degrees. This is mainly a result of developments in transportation and pipeline technology. The dominant factor in bilateral oil and natural gas trades is often the resource endowment of energy-exporting countries, which is a natural endowment. Therefore, maintaining stability in the international energy market and

prices largely requires ensuring the security and stability of energy-producing regions.

Discussion and conclusion

Discussion. This study investigates oil and natural gas trade networks among 65 countries along the BRI, aiming to compare their topological, spatial, and cluster structures, and to analyze the significance of network characteristics and models in shaping energy trade dynamics. Using a network robustness framework, we assess the resilience of oil and gas trade networks and examine how geopolitical risks differentially influence the evolution of these two energy systems. Furthermore, integrating proximity theory, we employ the gravity trade model and Quadratic Assignment Procedure (QAP) analysis to uncover variations in trade preferences within oil and natural gas networks. Based on our findings, we offer the following discussion.

Firstly, the oil trade network is more developed than the natural gas trade network, despite both exhibiting a trend toward densification. Our analysis of topological structure reveals that oil and natural gas trade relationships among the BRI countries have become increasingly interconnected, with both networks trending toward greater completeness. However, the oil trade network demonstrates superior development in terms of national participation, network density, and trade accessibility. This disparity stems largely from the physical and logistical differences between oil and natural gas. Natural gas transportation entails higher complexity and cost due to its physical state: liquefied natural gas (LNG) requires energy-intensive liquefaction, ultra-low temperature storage, and a fragile global supply chain, while pipeline gas depends heavily on fixed infrastructure, limiting transport distance and increasing unit costs. Research indicates that the cost of delivering equivalent thermal energy via natural gas is nearly six times higher than that of crude oil (Xi et al., 2016). Although advancements in clean energy technologies and rising demand for low-carbon fuels have boosted natural gas trade volumes, this growth has not fundamentally altered the dominance of oil in the regional energy mix. Oil remains the primary energy source for most BRI countries. To align with global clean energy transitions, BRI nations should strengthen cooperation in natural gas trade and infrastructure development.

Secondly, both oil and natural gas trade networks exhibit spatial polarization, with a few key countries dominating energy flows. Spatial analysis reveals a “rich-club” phenomenon in both networks, where a small number of countries exert disproportionate influence over trade dynamics. However, the spatial evolution patterns differ significantly. The oil trade network is evolving toward a “dual-export, triple-import” structure, with the Middle East and North Africa maintaining their dominance as primary export hubs. In contrast, the natural gas trade network is developing three major export centers, with Qatar’s network centrality steadily increasing. Major energy importers have gained substantial control over both networks, reflecting their growing influence in regional energy governance. These findings align with Zhang and Li et al., who observe that large energy-consuming countries are increasingly shaping the regional energy trade landscape by directing resource allocation and flow patterns (Li et al., 2021; Zhang et al., 2019). They also support Niu et al.’s conclusion that global energy power is gradually shifting from producers to consumers (Niu et al., 2023).

Thirdly, the oil and natural gas trade networks display strong regional clustering, but the natural gas network is more fragmented and dynamic. Cluster analysis shows that both networks exhibit significant regionalization, grouping, and fragmentation, consistent with global energy trade patterns (Ji et al., 2014; Zhong et al., 2017). However, differences exist in

cluster stability and evolution. The oil trade network has formed four relatively stable clusters, with minimal membership changes over time. Notable exceptions include Syria and Yemen, whose reclassification was driven by external shocks: EU-imposed economic sanctions in 2011 led to a 50% drop in Syria’s daily crude oil production and a 90% decline in exports to Europe, while Yemen’s political instability and regional conflict disrupted its trade integration (Suliman et al., 2023). In contrast, the natural gas trade network comprises six clusters and exhibits greater temporal volatility in country membership. This dynamism is primarily driven by China’s strategic economic transformation toward a green, low-carbon development model, which has increased natural gas consumption and strengthened import ties with Central Asian suppliers, thereby expanding the East Asia–West Asia cluster.

Fourthly, both networks are robust to random disruptions but vulnerable to targeted attacks, highlighting systemic fragility under geopolitical stress. Network robustness analysis indicates that both oil and natural gas trade systems are resilient to random node failures but highly susceptible to deliberate attacks on key economies. Targeted disruptions, such as those caused by political instability, economic sanctions, armed conflicts, or terrorism, can significantly degrade network connectivity and global efficiency. If such shocks exceed a critical threshold, cascading failures may lead to systemic collapse. While our evaluation methodology differs from that of Huang and Wei et al., our conclusions are broadly consistent: extreme events in the international oil trade can propagate through trade linkages, potentially destabilizing the entire network (Huang et al., 2023; Wei et al., 2022b). Recent developments, such as the shift of the global energy trade center to the Asia-Pacific, Europe’s reduced reliance on Russian energy, the Russia–Ukraine war, and the Israel–Palestine conflict, have all disrupted energy flows along the BRI, underscoring the need for enhanced network stability. Identifying and safeguarding strategically critical nodes, ensuring supply chain resilience, and mitigating trade security risks are essential for national energy strategies. As Cappelli notes, major energy importers must reduce overreliance on key suppliers to enhance energy security (Cappelli and Carnazza, 2023). Moreover, our comparison shows that the oil trade network exhibits greater resilience than the natural gas network, a finding consistent with Sun et al. (Sun et al., 2023). This suggests that the resilience of the natural gas network requires urgent strengthening through diversification and structural complexity.

Finally, proximity effects shape the evolution of both networks, but with divergent mechanisms across energy types. Our proximity analysis reveals that cultural and organizational proximity positively influence both oil and natural gas trade, consistent with theoretical expectations and prior empirical findings (Cappelli et al., 2023; Kitamura and Managi, 2017). Shared language, cultural affinity, and similar institutional frameworks reduce communication, transaction, and enforcement costs, facilitating trade cooperation. Economic proximity significantly promotes oil trade, aligning with conventional gravity model predictions. However, its effect on the natural gas trade is weaker, a deviation from global oil trade patterns (Sevencan and Uslu, 2022). This may reflect the economic homogeneity among many BRI countries, which are predominantly developing economies with limited complementary advantages. Institutional proximity, measured by shared memberships in international organizations, positively affects natural gas trade but not oil trade. This divergence likely arises from the higher sensitivity of natural gas trade to institutional risks due to its complex production, storage, transportation, and contractual arrangements. Surprisingly, geographical proximity acts as a negative factor in both networks: greater bilateral distance

correlates with higher trade volumes. This contradicts the typical gravity model assumption and differs from Zhang et al.'s findings (Clark, 2007; Zhang et al., 2019). We attribute this counter-intuitive result to the geopolitical nature of energy trade. Oil and natural gas are strategic commodities whose trade is driven more by resource availability and political alliances than by physical proximity. Importing countries prioritize access to abundant reserves over transport distance, and energy trade is often embedded in long-term geopolitical and security considerations.

In sum, while oil and natural gas trade networks share structural similarities, their developmental trajectories, resilience, and driving forces differ significantly. Policymakers should design differentiated strategies that account for the unique characteristics and vulnerabilities of each network to enhance energy security and sustainable cooperation within the BRI framework.

Conclusion. This study examines the evolutionary differences between oil and natural gas trade networks among the BRI countries across four dimensions: topological structure, spatial configuration, community structure, and network robustness. To identify the determinants influencing the formation of bilateral oil and natural gas trade relationships, we employ the Quadratic Assignment Procedure (QAP) model. Our findings reveal that both oil and natural gas trade networks among the BRI countries have become increasingly interconnected over time, exhibiting more cohesive and structurally complete architectures. However, cooperation in the oil market is more active, and the topological structure of the oil trade network is more highly developed compared to that of the natural gas network. Oil-exporting countries show a trend toward spatial dispersion, indicating a gradual erosion of energy dominance by traditional export hubs. In contrast, natural gas-importing countries display a pattern of spatial agglomeration, suggesting a shift in energy leverage toward importing nations. Both networks exhibit clear group formation, characterized by distinct blocs or community structures. Nevertheless, the spatial and community structures of the oil trade network are more stable than those of the natural gas network, demonstrating stronger temporal inertia. Both the oil and natural gas trade networks feature chain-like structural configurations and are vulnerable to targeted attacks. The entire system collapses abruptly once the number of removed nodes exceeds a critical threshold. However, the oil trade network demonstrates greater robustness under intentional attack scenarios than the natural gas network. Furthermore, network robustness varies significantly under different attack strategies based on degree, in-degree, and out-degree. Countries with high out-degree, such as Russia, the United Arab Emirates, Ukraine, and Kazakhstan, are identified as key nodes whose disruption would critically undermine network integrity. Importantly, we investigate the role of proximity in shaping oil and natural gas trade patterns, uncovering distinct energy trade preferences among the BRI countries. Our results show that cultural proximity and shared membership in international organizations significantly promote both oil and natural gas trade. In contrast, geographic proximity, measured by capital distance, does not significantly enhance trade propensity. Notably, economic and institutional proximity exert divergent effects across the two energy sectors. Countries with similar levels of economic development are more likely to engage in oil trade, whereas institutional proximity does not strengthen oil trade ties. Conversely, institutional proximity positively influences natural gas trade, while economic proximity has no significant effect.

Based on these insights, we propose a “DURC” policy framework (Diversification, Unionisation, Regulation, and Connectivity) to strengthen the resilience and sustainability of oil and gas trade relations within the BRI. Our policy recommendations

are as follows: (1) **Diversification:** Energy-importing countries should optimize their energy strategies to diversify sources of supply and modes of consumption. To safeguard against systemic disruptions caused by “black swan” events, major importers such as China, India, Indonesia, and Malaysia should not only maintain strong ties with established producers such as Iran, Saudi Arabia, and Russia, but also deepen energy partnerships with Central Asian nations such as Kazakhstan and Turkmenistan. Moreover, they should expand engagement with non-BRI energy suppliers in Africa and Latin America, actively participating in global energy markets, adhering to competitive rules, and leveraging market mechanisms to hedge risks. Such diversification enhances import system resilience and long-term trade stability, reducing strategic dependence on a limited number of suppliers and thereby mitigating systemic network risks. (2) **Unionisation:** A coordinated energy cooperation alliance should be established under the BRI framework to strengthen policy alignment and collective action among energy consumers and between producers and consumers. Institutional collaboration should be prioritized among BRI importers with convergent energy strategies, similar economic profiles, and compatible regulatory environments. This includes establishing permanent dialogue platforms, co-developing contingency plans, and instituting risk-sharing mechanisms to respond to market volatility and geopolitical shocks. Regional institutions such as ASEAN and APEC can serve as institutional anchors to consolidate a unified energy bloc. By pooling bargaining power, this coalition can negotiate favorable pricing and secure long-term supply contracts, improving leverage vis-à-vis exporting countries. Furthermore, strategic partnerships spanning the entire energy value chain, including upstream exploration and production, midstream transportation and storage, and downstream distribution, should be cultivated to ensure stable, predictable, and mutually beneficial energy supply arrangements. (3) **Regulation:** A multilayered, systematic, and legally binding regulatory framework should be developed to harmonize energy trade policies across communities. Within blocs, standardized trading protocols and contract templates should be adopted, incorporating indexed pricing in long-term contracts, risk-allocation clauses for extreme market fluctuations, and uniform quality and delivery standards. Such standardization would minimize transaction costs and reduce compliance burdens. Between blocs, mechanisms for policy coordination and mutual recognition of regulations should be institutionalized through regular consultations on tariffs, transit rules, and infrastructure access standards. This would prevent regulatory fragmentation and eliminate de facto trade barriers, thereby enabling more efficient cross-border energy flows. Critically, a binding dispute prevention and resolution mechanism must be established to provide legal certainty and institutional stability for inter-bloc oil and gas trade, fostering deeper integration. (4) **Connectivity:** BRI countries should jointly invest in cross-border energy infrastructure and establish shared strategic reserves to build a fully connected, highly resilient trade network. Strategic co-investment should support the development of critical energy corridors, including transnational oil and gas pipelines, regionally shared liquefied natural gas (LNG) terminals and storage facilities, and modern refining and distribution networks serving major demand centers. Enhanced physical connectivity reduces transportation costs and lead times, while shared infrastructure investment aligns national energy security interests and mitigates vulnerability to unilateral actions. Additionally, strategic reserve systems should be interconnected through regional or sub-regional cooperation, with pre-agreed protocols for joint draw-down, redistribution, and replenishment to enable collective management of supply shocks.

Limitations. While this study contributes to understanding the evolutionary divergence between oil and natural gas trade networks, several limitations warrant acknowledgment. First, due to its focus on structural and institutional drivers of network evolution, the analysis does not comprehensively assess the impact of geopolitical risks, such as armed conflicts, public health emergencies, or economic sanctions, on network vulnerability. The mechanisms through which such shocks propagate through trade networks remain underexplored. Second, energy trade networks, as complex adaptive systems, are shaped not only by external factors but also by internal structural dynamics. However, due to model constraints, this study emphasizes exogenous determinants and does not fully capture endogenous network properties, such as reciprocity, transitivity, triadic closure, and node interdependence, whose roles in shaping network evolution may be significant. As a result, the potential influence of self-organizing processes on network development is not fully accounted for. Future research will integrate geopolitical risk assessment and critical node identification into the analytical framework, examining the impacts of major global disruptions, including the COVID-19 pandemic, the Russia–Ukraine war, and the Israel–Palestine conflict, on energy trade resilience. Furthermore, we aim to extend the analysis to dynamic network modeling, incorporating internal structural mechanisms to better understand the endogenous drivers of energy trade network evolution.

Data availability

The data used in this study to construct the oil and natural gas trade networks among Belt and Road Initiative countries and to analyze their determinants were obtained from various public databases, such as the Chatham House Resource Trade database (<https://resourcetrade.earth/?year=2018&category=1&units=value>), the World Bank Open Data portal (<https://data.worldbank.org.cn/indicator?tab=all>), and the CEPII database (https://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele.asp). All data processing and analytical procedures have been fully described in the manuscript. If researchers need to use the processed dataset from this study, please contact the corresponding author to obtain it.

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Author contributions

Conceptualization: WY, WS; Data curation: WY; Formal analysis: WY, WS; Methodology: WY, WS and WG; Resources: WY; Software: WY and WG; Writing – original draft: WY, WS; Writing – review & editing: WY, WS and WG.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

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