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Energy Consumption and Export Growth Decoupling in Post-WTO China

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Abstract

This study examines the dynamic decoupling relationship between energy consumption and export growth in China since its accession to the World Trade Organization (WTO) (2002–2018) by combining the noncompetitive input–output model, Tapio decoupling model, and the Logarithmic Mean Divisia Index (LMDI) model. The results reveal the substantial energy consumption generated by China's export trade, emphasizing the urgency of reducing energy consumption in export trade for energy conservation and emissions reduction. Since its WTO accession, China has experienced sustained improvement in the energy decoupling effect during the growth of export trade, entering a period of strong decoupling from 2014 to 2018. The expanded export scale remains a major obstacle to decoupling export trade growth from energy consumption, while decreased energy intensity in exports is a significant driving force for energy decoupling, with relatively minor impact from changes in the export trade structure. By integrating non-competitive input–output modeling, Tapio decoupling analysis, and LMDI decomposition, this study develops a novel framework to investigate the structural drivers of energy–export decoupling in China from 2002 to 2018. Bridging methods from energy systems, trade economics, and policy modeling, it contributes to the field of multi-disciplinary sustainability by offering sector-level insights and decomposition-based evidence to support more efficient, equitable, and sustainable trade transitions.

Keywords: Tapio decoupling model; input–output modeling; LMDI decomposition; trade energy intensity; industrial energy efficiency; energy policy; multi-disciplinary sustainability

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1. Introduction

China's energy research has substantial global significance, given its position as the most populous nation and the world's second-largest economy, as highlighted by data from the World Bank (http://www.worldbank.org) and the United Nations (https://www.un.org/en/library/page/databases (accessed on 1 July 2025)). Effectively addressing China's energy challenges will enhance global energy security, support sustainability, and advance climate mitigation efforts, fostering international collaboration and pioneering solutions for a sustainable future [1–3].

Energy is a crucial element of China's national economy [4,5]. Since the 18th National Congress, China has significantly advanced energy conservation, focusing on stringent control over total energy consumption, effective policy enforcement, and comprehensive

conservation strategies during the nation's economic and social development. The 14th Five-Year Plan emphasized green development and an energy strategy to reduce energy consumption per unit of GDP by 13.5% and carbon dioxide emissions by 18%, to propel socioeconomic advancement. Furthermore, the National Development and Reform Commission established dual-control targets for China's energy consumption and intensity until 2035, while the 20th National Congress has been proactive in striving to meet peak carbon emissions and achieve carbon neutrality, which necessitates optimizing China's energy resources, accelerating the energy revolution, and hastening the planning and construction of new energy systems [6,7].

Since the start of economic reforms, China's energy consumption has surged. In 1978, energy use was 570 million tons of standard coal, which jumped to 3.61 billion tons by 2010, making China the world's largest energy consumer, and rose to 5.24 billion tons by 2021 (https://www.stats.gov.cn/ (accessed on 1 July 2025)). This relentless increase has pressured the domestic energy supply and increased dependence on energy imports, amplifying China's energy security risks [8]. The nation's reliance on coal, oil, and natural gas contributes to substantial carbon emissions and pollutants such as sulfur dioxide, complicating the achievement of the dual-carbon objectives and air quality improvement. In response, the State Council released the Notice on the Action Plan for Peaking Carbon Dioxide Emissions before 2030, emphasizing the urgent need to build an energy-efficient economy.

The ongoing COVID-19 pandemic and geopolitical tensions from the Russia–Ukraine conflict have compounded economic pressures [9]. At the Central Political Bureau meeting on 29 April 2022, stabilizing economic growth was deemed crucial. As the leading global ex-porter, China's export sector is pivotal in spurring domestic economic growth, yet it requires considerable energy consumption that impacts energy conservation, carbon reduction, and pollution control efforts. The nexus between carbon emissions, atmospheric pollutants, and energy consumption mandates a reduction in energy use to fulfill carbon and pollution reduction goals and ecological expansion [10]. It is essential to decouple energy consumption from export growth, in line with the 20th National Congress's directive to promote carbon reduction, pollution control, ecological expansion, and economic growth simultaneously.

Energy conservation and consumption reduction are vital for meeting national energy-saving targets as well as reducing carbon dioxide and PM2.5 emissions, advancing China's dual-carbon objectives, and improving air quality [11]. Exports have driven China's economic growth, but require significant energy, which impedes objectives related to energy conservation, consumption reduction, and carbon/pollution reduction. It is imperative to regulate total energy consumption and intensity in exports to achieve carbon neutrality. The current priority in-volves developing sophisticated theories and policies that concurrently promote export growth and energy-efficient emissions reduction within a dual-circulation framework.

Previous studies have primarily focused on the decoupling between energy consumption and overall economic growth, while the relationship between energy consumption and export growth has received less attention [12]. Understanding the decoupling dynamics within the context of export trade is of paramount importance for developing effective strategies for energy conservation and emissions reduction in China's ever-changing economic landscape. This approach aligns harmoniously with the objectives of the United Nations Sustainable Development Goal (SDG) 12–Ensure sustainable consumption and production patterns and SDG 7–Ensure access to affordable, reliable, sustainable, and modern energy for all, which underscore the significance of sustainable consumption, production, and access to affordable and modern energy. By effectively addressing these goals, China can assume a leadership role in advancing sustainable trade practices, enhanc-

ing energy efficiency, and propelling the global transition toward a more sustainable and inclusive future.

The remainder of this paper is organized as follows. Section 2 reviews related literature. Section 3 introduces the methodology and data. Section 4 presents the empirical results. Section 5 offers discussion, and Section 6 concludes with policy implications.

2. Literature Review

The term decoupling was initially coined by the Organization for Economic Co-operation and Development (OECD) in 2001 referring to reducing environmental pressure amid economic growth [13]. This notion, which is fundamental in environmental economics, distinguishes between "relative decoupling," where economic growth outpaces environmental degradation, and "absolute decoupling," characterized by economic expansion alongside stable or declining environmental impact [14,15]. These classifications underscore potential nuanced strategies for mitigating environmental stress while fostering economic resilience.

Research deploying Tapio's elasticity analysis method has enriched our understanding of the global decoupling phenomenon. In Japan and the UK, studies have examined the effectiveness of decoupling in contexts such as national economic growth and specific sectors like road transport [16]. Similarly, extensive investigations into China's energy and economic dynamics have revealed varied success in achieving decoupling, particularly high-lighting challenges faced by developing nations from rapid industrial expansion and corresponding energy demands [17–19].

China's burgeoning export sector, which is a substantial energy consumer, involves a complex scenario in which economic benefits are often offset by environmental and energy costs [20,21]. Notably, from 2002 to 2004, the energy consumption attributed to export activities rose from 21% to 27% of the nation's total, underscoring exports as a critical driver of China's energy usage [22]. Furthermore, previous research has demonstrated a direct correlation between China's export sector growth and increased domestic energy consumption, with significant environmental implications [23–25].

Recent advancements in decoupling research have introduced innovative models and analytical frameworks to assess the relationship between economic growth and environmental impact [26–28]. One notable development is the integration of the Logarithmic Mean Divisia Index (LMDI) decomposition method with decoupling analysis [29,30]. This approach enables a more granular examination of the factors influencing decoupling, such as energy intensity, economic structure, and technological progress. For instance, a study by Liu et al. (2024) applied the LMDI method to China's industrial sectors, identifying key drivers of carbon emissions and assessing the effectiveness of decoupling strategies [31].

Additionally, the adoption of system dynamics models has provided a dynamic perspective on decoupling processes [32–34]. These models simulate complex interactions between economic activities and environmental pressures over time, offering insights into potential future scenarios. Alkemade & de Coninck (2021) utilized a system dynamics approach to evaluate the long-term impacts of policy interventions on decoupling in emerging economies, highlighting the importance of adaptive strategies in achieving sustainable development [35].

In recent years, research on decoupling in export-oriented economies has intensified, focusing on the relationship between economic growth and environmental impact. Jimenez and Razmi (2013) examined ex-port-led growth strategies in Asian countries, discovering a strong correlation between the proportion of manufactured exports destined for industrialized nations and economic growth, while high-lighting that South–South trade may not effectively substitute for South–North trade [36].

Shahbaz et al. (2013) investigated the dynamic relationships among energy consumption, economic growth, financial development, and trade in China, finding that energy use positively influences economic growth, with a unidirectional causal relationship from energy consumption to economic growth [37]. Ünal et al. (2023) utilized input–output analysis to assess CO_2 emissions embodied in China's bilateral trade, identifying that export goods, particularly intermediate products, significantly contribute to emission increases [38]. Baccaro and Benassi (2017) explored the evolution of German industrial relations, noting a shift from a growth model driven by both net exports and consumption to one almost exclusively reliant on export-led growth [39]. Collectively, these studies underscore the necessity for export-oriented economies to prioritize environmental protection and sustainable resource utilization while pursuing economic growth, thereby exploring effective pathways for decoupling economic expansion from environmental degradation.

Market-based financial and allocation mechanisms have recently gained attention in decoupling studies. Cao et al. (2023) demonstrated that expanding green credit significantly curbs industrial carbon emissions and facilitates strong decoupling [40]. Similarly, Du et al. (2025) showed that energy quota trading (EQT) enhances energy efficiency and produces positive spatial spillovers in pilot regions [41]. While these studies emphasize institutional and market-driven effects, our research complements them by focusing on structural sector-level decoupling in export-oriented industries, offering a distinct yet synergistic perspective on China's energy transition.

While substantial progress has been made in understanding the relationship between economic growth and environmental impact in export-oriented economies, significant limitations remain: (1) Limited Sectoral Coverage. Research predominantly focuses on isolated sectors, such as manufacturing or services, lacking comprehensive analyses across all economic sectors, thereby restricting broader applicability. (2) Short-Term Focus. Existing studies often emphasize short-term trends, neglecting the deeper understanding of long-term decoupling dynamics and their implications for sustainability. (3) Methodological Fragmentation. Although advanced methods like LMDI and system dynamics models have been applied, their lack of integration undermines the capacity to fully capture the multifaceted nature of decoupling processes. While these methodologies enhance analytical precision, addressing these gaps through innovative and integrative frameworks is imperative for devising effective strategies to reconcile economic growth with environmental sustainability.

Despite the progress in decoupling research, this study addresses critical sectoral, temporal, and methodological shortcomings through three key innovations:

(1) Integration of Contemporary Input–Output Data. By utilizing the latest noncompetitive in-put–output tables from China's National Bureau of Statistics and the WIOD, this study refines de-coupling analyses by distinguishing domestic from imported inputs. Spanning data from 2002 to 2018, it provides a nuanced assessment of the distinct impacts of domestic production and import-ed intermediate goods on China's energy consumption.

(2) Advanced Analytical Framework. Integrating noncompetitive input–output models, system dynamics, and LMDI decomposition, this research reveals the complex relationship between export growth and energy consumption. It also explores how transitions to energy-efficient and high-tech industries reshape energy use patterns, delivering insights that surpass conventional analyses.

(3) Policy-Oriented Strategies for Multi-disciplinary Sustainability. The findings underscore the importance of targeted interventions to drive technological innovation and enhance energy efficiency in pivotal export-oriented industries. Aligning economic

strategies with environmental sustainability objectives not only strengthens China's decoupling efforts but also contributes to global environmental preservation.

By bridging critical gaps in existing literature, this study equips policymakers with practical tools to balance economic growth with environmental stewardship in the context of global trade and industrialization.

3. Methodology

To enhance clarity for non-specialist readers, Figure 1 presents a schematic overview of the logical integration among the three core models employed in this study. First, the non-competitive input–output model distinguishes between the energy consumption of domestically produced and imported intermediate goods, forming the foundation for calculating energy consumption specifically attributable to export activities. This serves as the data input layer. Second, the Tapio decoupling model utilizes the derived energy consumption data and export volume growth to assess the elasticity relationship, thereby identifying decoupling states across different time periods and sectors—this constitutes the indicator analysis layer. Third, to interpret the drivers of observed decoupling dynamics, the LMDI decomposition model disaggregates changes in export-related energy consumption into three components: scale, structure, and intensity effects. This provides a deeper analytical lens on how export expansion, trade restructuring, and energy efficiency, respectively, contribute to decoupling outcomes. Together, these models form a closed-loop methodological chain—linking physical accounting, policy-relevant indicators, and decomposition-based diagnostics—to ensure consistent, multi-layered interpretation.

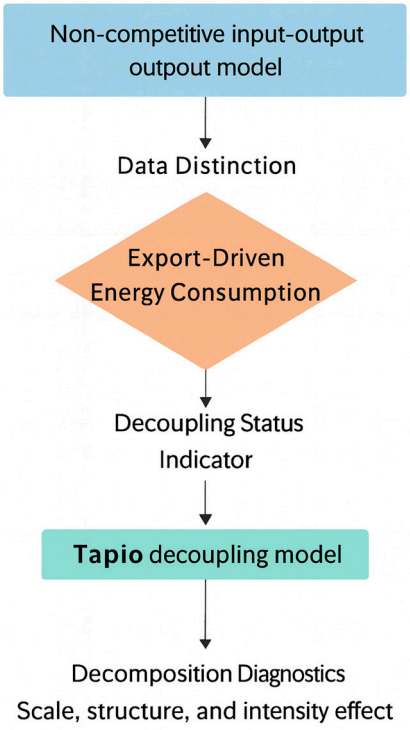


Figure 1. Methodological Framework: Model Integration Logic.

3.1. System Dynamics Diagram

The pentagram system dynamics diagram in Figure 2 is an indispensable tool for analyzing the intricate interdependencies among key variables shaping energy decoupling in China's export-driven economy. By providing a visual representation of these relationships, the diagram facilitates a nuanced understanding of how interconnected factors collectively influence decoupling dynamics.

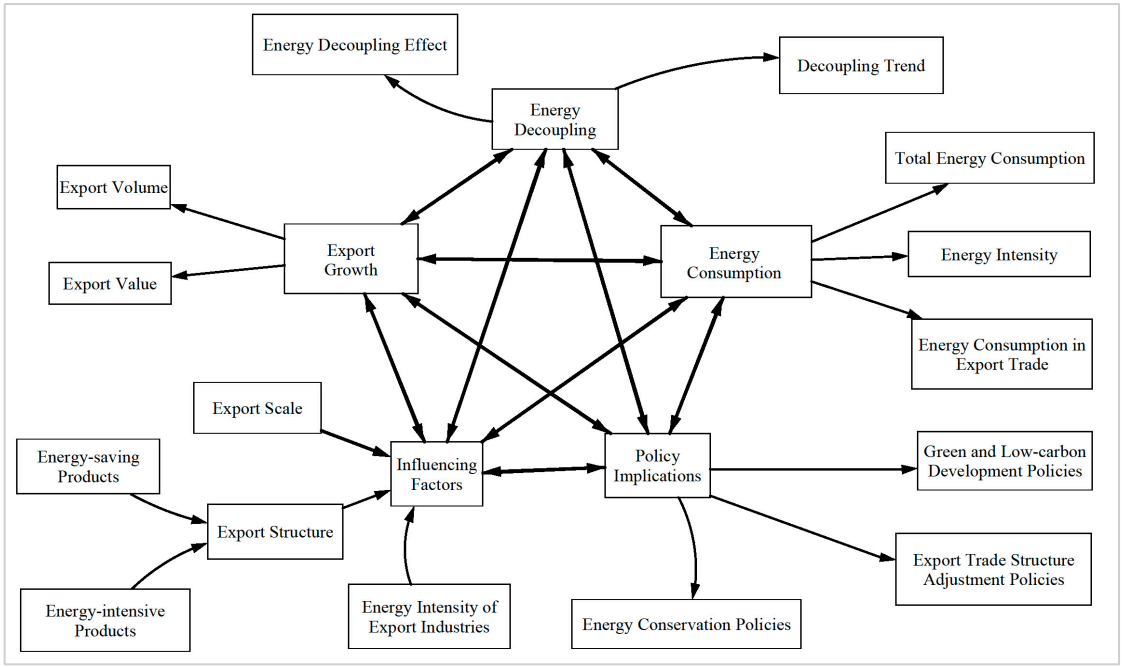


Figure 2. System dynamics diagram depicting the interdependencies among critical nodes. Note: This diagram provides an overview of the critical components and their interdependencies within the context of enhancing energy decoupling in China's export growth. This is a simplified representation, and the actual system may involve many additional factors and complexities.

At its core, the diagram highlights the pivotal role of export growth—an essential driver of economic development—and its inherent linkage to energy consumption. It illustrates the critical impact of export structure, sector-specific energy intensity, and technological advancements on decoupling efficiency. By emphasizing the transition toward energy-efficient and high-tech export sectors, the diagram underscores how strategic shifts can reduce energy consumption while sustaining or enhancing export value.

Furthermore, it reveals the feedback loops between export structure optimization and energy-saving innovations, illustrating their combined potential to drive sustainable growth. The diagram also demonstrates the importance of policy measures designed to enhance energy efficiency and foster green technologies, aligning economic objectives with environmental sustainability.

Through its comprehensive depiction of these dynamic interactions, the pentagram system dynamics diagram provides a robust framework for crafting effective strategies. It offers actionable insights for optimizing export composition, advancing energy efficiency, and achieving a sustainable export-driven economy.

3.2. Noncompetitive Input–Output Table

The structure of a single-region, multisector open economy input–output table is depicted in Table 1. The country consists of n sectors that are classified according to the same criteria. We use X_{ij} to represent the amount of intermediate input provided by country i to country j. V represents the value-added vector matrix, Y represents the total output vector matrix, A represents the intermediate consumption coefficient matrix, and F represents the final product consumption matrix across countries. The columns in the table are divided into intermediate and final usage categories, encompassing investment (I), consumption (C), and exports (EX), while the rows are divided into intermediate and initial input (labor (L) and capital (K)), forming four quadrants in the input–output table. The table's rightmost column represents total output (Y), which is the sum of the intermediate

usage columns and the final usage columns across sectors. The bottom row of the table represents total input, which is the sum of the middle usage rows and the initial input rows across sectors. Total input (X) is equal to total output (Y).

Table 1. Single-region, multisector open economy noncompetitive input–output table.

Input \ *Output*		*Intermediate Use*	*Finally Use*				*Import*	*Total Output*
		Sector (1, 2, . . ., n)	*Consumption*	*Investment*	*Export*	*Sum-Up*		
Intermediate input products	*Domestic*	X_{ij}^{DD}	C_i^{DD}	I_i^{DD}	EX_i^{DD}	X_i^{DD}	-	Y_i
	Imported	X_{ij}^{FD}	C_i^{FD}	I_i^{FD}	EX_i^{FD}	X_i^{FD}	IM_i^{FD}	*0*
Value added	*L&K*	V_j						
Total input		Y_j						

The intermediate and final usage data are further differentiated into domestic products (denoted by superscript *DD*) and foreign products (indicated by superscript *FD*). Here, superscript *DD* means exports from the domestic country to foreign countries, while *FD* represents imports from foreign countries to the domestic country. *FDF*, represents re-export trade, which refers to importing goods from foreign countries and subsequently re-exporting them to other foreign countries.

Since exports inherently include re-export trade, the associated energy consumption and carbon emissions from import trade must be excluded when calculating net exports. To ensure accuracy in this study, re-export trade has been removed from import trade calculations, thereby avoiding double counting of energy consumption and carbon emissions in China's carbon reduction estimates.

The matrix representation of the input–output balance equation is $AX + F = Y$. By rearranging the equation, we obtain $\boldsymbol{X} = (I - A)^{-1} F$, where the Leontief inverse matrix $\boldsymbol{B} = (I - A)^{-1}$ represents the complete consumption coefficient matrix. The element B_{ij} in matrix B, located in the i-th row and j-th column, indicates an output increase in country i resulting from a unit increase in final product demand from country j.

In the matrix structure of the noncompetitive input–output table, the export vector includes both exports of domestically produced goods and re-exports (denoted as FDF). These re-exported goods are imported into the country and then exported again without undergoing significant domestic processing. To ensure that the calculated energy consumption reflects only the domestic value-added in export trade, it is essential to subtract the FDF component. Operationally, this adjustment is made by excluding the energy embedded in imported inputs from the total export-driven energy consumption calculation.

Mathematically, the energy consumption attributed to exports $E^{\exp}$ is computed as:

$$E^{\exp} = \mathbf{e} \cdot \mathbf{B} \cdot \left(\mathbf{EX}^{DD}\right)$$

where $\mathbf{e}$ is the direct energy intensity vector for domestic sectors; $\mathbf{B} = \left(I - A\right)^{-1}$ is the Leontief inverse matrix for domestic production; $\mathbf{EX}^{DD}$ is the final demand vector for exports of domestic products only.

In this study, $\mathbf{EX}^{DD}$ is derived by subtracting the re-export trade component FDF from the total export vector in the input–output table, such that

$$\mathbf{EX}^{DD} = \mathbf{EX}^{Total} - \mathbf{FDF}$$

For the WIOD datasets, the energy use is already aligned with the domestic production boundary. For the Chinese IO tables, we utilized supplementary data from the National Bureau of Statistics that disaggregates the export structure and allows identification of re-export volumes based on the share of imported intermediate inputs used in processing trade.

3.3. Constructing the Analytical Model

3.3.1. Export Trade–Energy Consumption Measurement Model

(1) Measuring export trade–energy consumption intensity

We obtain the energy consumption intensity matrix of export trade for each industry based on the input–output relationship between the domestic and international economic activity processes of each sector in China's noncompetitive input–output table.

$$E = E^Z \left(I - A^h \right)^{-1} \tag{1}$$

where E represents a matrix of export trade–energy consumption intensity in China by sector, E^Z is a matrix of direct energy consumption intensity of traded goods generated by each sector, A^h is a matrix of consumption coefficients of domestically produced intermediate inputs in sector j per unit of output of sector i in China domestic products (i.e., a matrix of direct consumption coefficients of domestically produced intermediate inputs).

(2) Measuring export trade–energy consumption

Each export sector's energy consumption is obtained by multiplying sectors' energy consumption intensity of by its export trade volume.

$$E_i^{EX} = e_i \times EX_i^h (i = 1, 2, \ldots, n) \tag{2}$$

where E_i^{EX} represents the export trade–energy consumption in the domestic sector i, e_i represents the energy intensity of each export sector, and EX_i^h represents the amount of domestic exports in that sector.

The energy consumption of each sector's export trade is summed up to obtain the values for Equation (3) to calculate the total energy consumption of China's export trade.

$$E^{EX} = \sum_{i=1}^{n} E_i^{EX} = \sum_{i}^{n} e_i \times EX_i^h \quad (i = 1, 2, \ldots, n) \tag{3}$$

3.3.2. Export Trade Growth and Energy Consumption Decoupling Evaluation Model

Referencing Tapio's (2005) elasticity analysis method [42], we construct the following model to measure the decoupling index (DI) between China's export growth and energy consumption, where a smaller DI indicates less impact from export growth on increased energy consumption, and a more significant degree of decoupling between the export trade growth and energy consumption. Conversely, a higher energy consumption growth rate attributable to export growth indicates that the extent of decoupling between export trade growth and energy consumption is minimal and the two subjects might even be advancing toward negative decoupling.

$$DI = \frac{\left(E_t^{EX} - E_0^{EX} \right) / E_0^{EX}}{\left(EX_t - EX_0 \right) / EX_0} = \frac{\Delta E^{EX} / E_0^{EX}}{\Delta EX / EX_0} \tag{4}$$

where DI represents the $(T_0 - T_t)$ period of China's export growth and energy consumption DI, E_0^{EX} and E_t^{EX} represents China's export trade–energy consumption in the base period and the reporting period, respectively, EX_0 and EX_t denote China's total exports

in the base period and the reporting period, respectively, and ΔE^{EX} and ΔEX refer to the amount of change in export trade–energy consumption and the amount of change in export size, respectively.

Building upon the classification methods outlined by Sun and Song (2024), Sun et al. (2024) and Sun et al. (2025), and following Tapio's (2005) elasticity criteria, this study categorizes the decoupling between export trade growth and energy consumption into positive, linking, and negative decoupling types, as detailed in Figure 3 [42–45]. Positive decoupling, which is the most desirable state, occurs when export growth exceeds energy consumption increases. In contrast, negative decoupling reflects increased energy consumption outpacing export growth, where strong negative decoupling is the least favorable scenario.

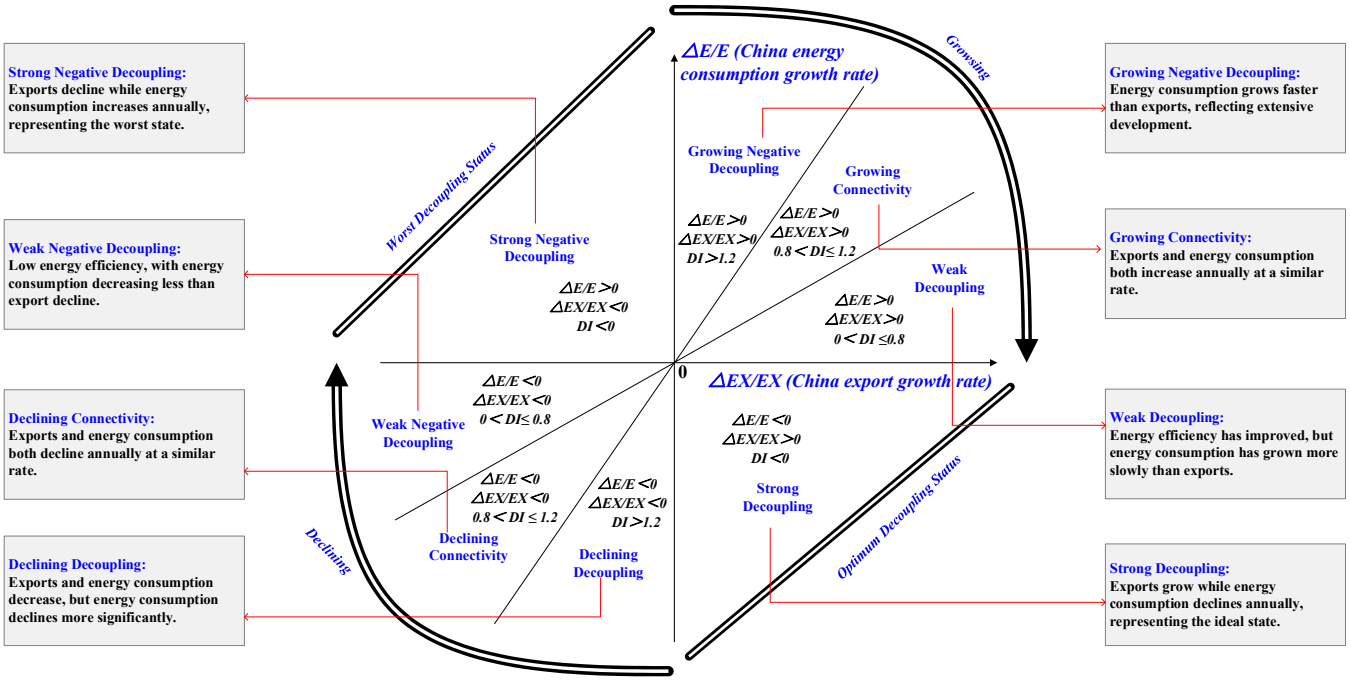


Figure 3. Types of Decoupling States and Their Characteristic Values.

3.3.3. Model Construction of Factors Influencing Export Growth and Energy Consumption Decoupling

To determine the influencing factors that affect the decoupling relationship between export growth and energy consumption, we use the following factor decomposition method to construct an analysis model of the desired influencing factors.

Let θ_i be the share of China's exports from sector i in China's total exports, and obtain Equation (5) from Equation (3).

$$E^{EX} = \sum_{i=1}^{n} E_i^{EX} = \sum_{i=1}^{n} EX_i \times e_i = \sum_{i=1}^{n} (EX_i \times \theta_i) \times e_i \tag{5}$$

In Equation (5), the amount of exports, the structure of export trade, and the energy intensity of the export sector determine the energy consumption of China's export trade.

Let the energy consumption of China's export trade in the base period and the reporting period be E_0^{EX} and E_t^{EX}, respectively. The difference between export trade–energy consumption in the base period and the reporting period can then be expressed as an additive form of export size, export trade structure, and export trade–energy consumption intensity effects as shown in Equation (6).

$$\Delta E^{EX} = E_t^{EX} - E_0^{EX} = \Delta E_G^{EX} + \Delta E_S^{EX} + \Delta E_T^{EX} \tag{6}$$

The Logarithmic Mean Divisia Index decomposition method (LMDI method) is an appropriate approach as it does not generate decomposition residuals (Ang, 2005 [46]). Therefore, this study applies this method to obtain the decomposition equations to determine the effects of changes in export trade size, trade structure, and energy intensity on China's export trade–energy consumption in Equations (7)–(9).

$$\Delta E_S^{EX} = \sum_{i=1}^{n} \frac{E_t^{EX_i} - E_0^{EX_i}}{ln\left(E_t^{EX_i}/E_0^{EX_i}\right)} \times ln\,\frac{\theta_i^t}{\theta_0^t} \tag{7}$$

$$\Delta E_G^{EX} = \sum_{i=1}^{n} \frac{E_t^{EX_i} - E_0^{EX_i}}{ln\left(E_t^{EX_i}/E_0^{EX_i}\right)} \times ln\,\frac{EX_t}{EX_0} \tag{8}$$

$$\Delta E_T^{EX} = \sum_{i=1}^{n} \frac{E_t^{EX_i} - E_0^{EX_i}}{ln\left(E_t^{EX_i}/E_0^{EX_i}\right)} \times ln\,\frac{e_i^t}{e_0^t} \tag{9}$$

In Equations (7)–(9), ΔE_S^{EX}, ΔE_G^{EX}, and ΔE_T^{EX} have the same interpretation as in Equation (6); $E_t^{EX_i}$ and $E_0^{EX_i}$ refer to the energy consumption of export sector i in the reporting and base periods, respectively; θ_i^t and θ_0^t represent the share of sector i's exports in China's total exports in reporting and base periods, respectively; EX_t and EX_0 denote China's total exports in reporting and base periods, respectively; and e_i^t and e_0^t represent the energy consumption intensity of export sector i in reporting and base periods, respectively.

According to Equations (4) and (6), the model for measuring the DI of export growth and energy consumption can be expressed in Equation (10).

$$DI = \frac{\Delta E^{EX}/E_0^{EX}}{\Delta EX/EX_0} = \frac{\Delta E^{EX}}{E_0^{EX} \times (\Delta EX/EX_0)} = \frac{\Delta E_S^{EX} + \Delta E_G^{EX} + \Delta E_T^{EX}}{E_0^{EX} \times (\Delta EX/EX_0)} \tag{10}$$

Let $DI_G = \frac{\Delta E_G^{EX}/E_0^{EX}}{\Delta EX/EX_0}$, $DI_S = \frac{\Delta E_S^{EX}/E_0^{EX}}{\Delta EX/EX_0}$, $DI_T = \frac{\Delta E_T^{EX}/E_0^{EX}}{\Delta EX/EX_0}$, then Equation (10) can be written as Equation (11).

$$DI = DI_G + DI_S + DI_T \tag{11}$$

where DI_G, DI_S, and DI_T represent the decoupling subindices of export growth and energy consumption generated by export size, export trade structure, and energy consumption intensity effects, respectively. These decoupling subindices can reveal the impact of changes in export size, export trade structure, and energy intensity on the decoupling of export growth and energy consumption in China.

3.4. Data Sources

This study uses the 2018 National Noncompetitive Input–Output Tables issued by the National Bureau of Statistics of China, marking a pivotal update from the predominantly competitive tables that were previously produced. The primary objective of this research is to assess the decoupling of China's export trade growth from energy consumption following its accession to the World Trade Organization (WTO). This analysis spans from 2002 to 2018; a period that is strategically selected to encapsulate significant policy shifts and economic activities post-WTO accession, and to allow for the evaluation of long-term trends using data in five-year intervals. This periodization ensures a robust examination of the patterns emerging from China's integration into the global economy and subsequent environmental policy responses.

This study also incorporates noncompetitive input–output tables for 2002, 2006, 2010, and 2014 from the World Input-Output Database (WIOD) (available at https://www.rug.nl/ggdc/valuechain/wiod/wiod-2016-release (accessed 1 July 2025)). These tables,

originally denominated in USD, were converted to CNY using average annual exchange rates to ensure consistency with the 2018 Chinese tables, which are denominated in CNY. The average exchange rates (CNY per USD) for the respective years were 8.2770 in 2002, 7.9718 in 2006, 6.7695 in 2010, and 6.1428 in 2014. Sourced from the People's Bank of China, these rates ensure accurate currency conversion and provide a reliable foundation for comparative analysis across different years.

Since the China Input–Output Tables published by the WIOD are denominated in USD, while the 2018 National Noncompetitive Input–Output Tables are in CNY, the WIOD data for the four specified years were converted into CNY millions using the average annual USD-to-CNY exchange rates for each respective year. The alignment between the Chinese government's input–output tables and the WIOD is highly robust. Erumban et al. (2011) designed the WIOD to integrate national supply and international trade statistics seamlessly, facilitating comprehensive analysis of globalization's effects on socioeconomic and environmental dynamics [47]. Together, the contributions strongly affirm the credibility and consistency of the alignment between the two input–output frameworks.

We simplify the energy consumption data across 21 defined sectors to S1–S21, which are integrated from these diverse sources to provide a nuanced understanding of the influencing factors on the decoupling process within China's export sector in Table 2. The harmonization of sectoral classifications between the WIOD (ISIC Rev.4, 56 sectors) and the Chinese 2018 input–output tables (GB/T4754-2017 [48], 21 sectors) followed an aggregation mapping process summarized. WIOD sectors with similar production and energy-use characteristics were merged to align with the 21-sector Chinese classification. For example, "Manufacture of textiles, wearing apparel and leather products" (WIOD sector 6) corresponds to "Textiles, clothing and leather products" (S4) in the Chinese system, while multiple WIOD service sectors (37–56) were aggregated into "Other services" (S21). This concordance ensures both structural comparability and analytical consistency across all five benchmark years (2002, 2006, 2010, 2014, 2018).

Table 2. Chinese export sector's numbers and details.

No.	Sectors Breakdown Details	No.	Sectors Breakdown Details
S1	Agriculture, forestry, animal husbandry and fisheries	S12	General and special purpose machinery and equipment manufacturing
S2	Coal, oil, gas, metal, and non-metal mining	S13	Transport equipment manufacturing
S3	Food and tobacco manufacturing	S14	Electrical machinery and equipment manufacturing
S4	Textiles, clothing and leather products	S15	Communications equipment, computers and other electronic equipment, instruments and meters
S5	Woodworking products and furniture industry	S16	Waste utilization and other manufacturing industries
S6	Paper, printing and educational and sporting goods manufacturing	S17	Electricity, heat, gas and water production and supply
S7	Petroleum, coking products and nuclear fuel processing	S18	Building and Construction
S8	Chemicals manufacturing	S19	Transportation, storage and postal services
S9	Non-metallic mineral products	S20	Wholesale and retail trade and accommodation and catering
S10	Metal smelting and rolling processing	S21	Other services
S11	Metal products industry	Avg.	Average level

4. Results

4.1. Analysis of Energy Intensity and Energy Consumption of China's Export Trade

4.1.1. China's Export Trade–Energy Consumption Intensity and Its Changes

This analysis quantifies the energy consumption intensity of China's export trade from 2002 to 2018 across various sectors using Equation (1), which is detailed in Figures 4 and 5. Energy intensity per CNY 10,000 of export trade decreased progressively from 2.49 TCE in 2002 to 0.71 TCE in 2018. This corresponds to reductions of 23.69%, 40%, 20.9%, and 14.74% for the intervals 2002–2006, 2006–2010, 2010–2014, and 2014–2018, respectively, culminating in an overall decrease of 69.17%. These reductions underscore the substantial gains in energy efficiency in China's export sector since its WTO accession, which were significantly influenced by the continuous energy conservation efforts initiated in 2003 and integrated into the nation's economic development strategies.

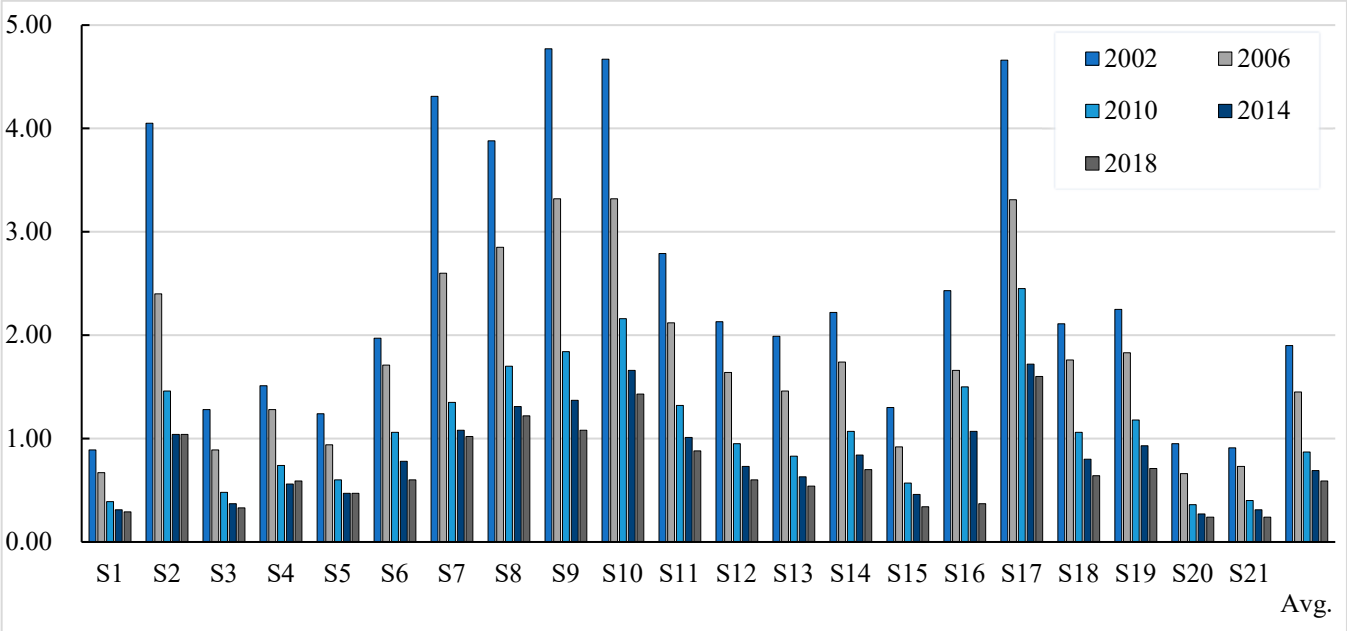


Figure 4. Energy intensity of China's export trade by sector during 2002–2018 (TCE/CNY 10,000).

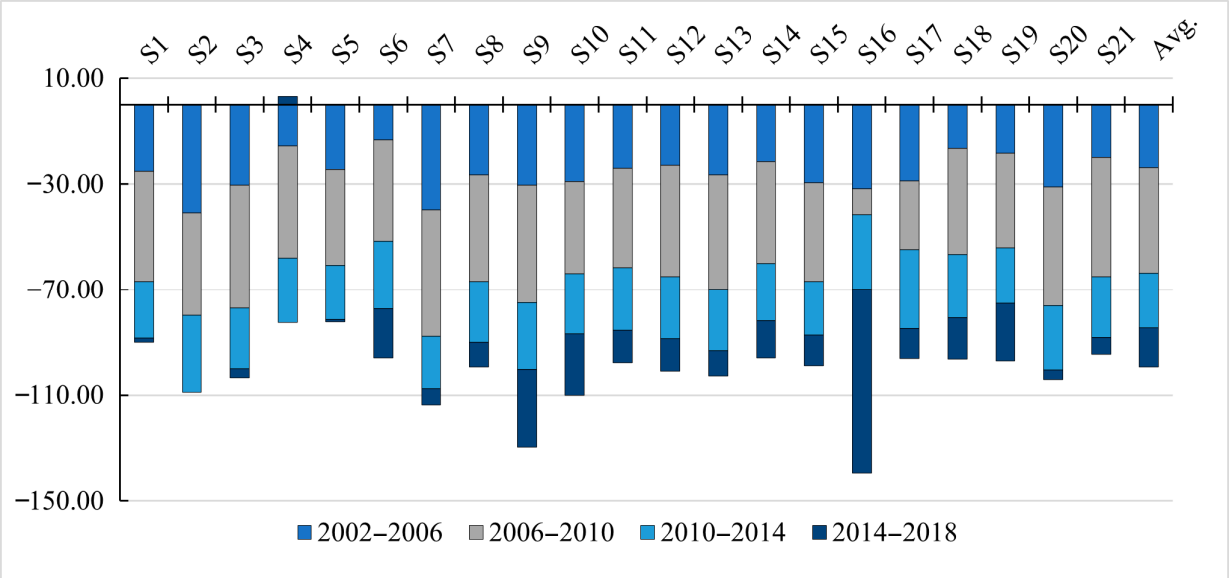


Figure 5. Change in energy intensity of China's export trade by sector during 2002–2018 (%).

Sector-specific data reveal disparities in energy intensity. High consumption sectors include coal, oil, and gas; metal and nonmetal mining (S2); petroleum and coking products; nuclear fuel processing (S7); chemical manufacturing (S8); nonmetallic mineral products (S9); metal smelting and rolling processing (S10); metal products (S11); and water, electricity, gas, and heat supply (S17). In contrast, sectors like agriculture, forestry, animal husbandry, and fishery (S1); food and tobacco manufacturing (S3); woodworking products and furniture (S5); communication equipment, computers, and electronics (S15); and waste utilization and other manufacturing (S16). In addition, wholesale and retail trade, accommodation, and catering (S20) and other services (S21) sectors also show lower energy intensities. These insights highlight critical areas for targeted energy efficiency enhancements and policy interventions.

Our analysis of energy consumption intensity trends from 2002 to 2018 reveals consistent decreases in most of China's export sectors initially, with significant reductions from 2002 to 2006 and continued progress from 2006 to 2010. However, the pace of reduction decelerated during the 2010–2014 period. In the latest interval (2014–2018) the overall decrease in energy intensity slowed even further, with notable exceptions in textiles, clothing, and leather products (S4) and coal, oil, gas, metal, and nonmetal mining (S2) sectors, both of which registered increases in energy consumption intensity. This trend underscores the need to develop strategically targeted interventions to address sectors in which energy efficiency gains are stagnating or reversing.

4.1.2. Energy Consumption in China's Export Trade and Its Changes

This study also quantified energy consumption in China's export trade from 2002 to 2018 using Equations (2) and (3), as depicted in Figure 6. The total energy consumption of China's export trade demonstrated significant figures, at 432,883,500 TCE in 2002, 983,913,100 TCE in 2006, 973,842,000 TCE in 2010, 1,079,977,500 TCE in 2014, and 1,013,747,200 TCE in 2018. These figures reveal substantial energy usage in China's export sector. In comparison, China's overall energy consumption during these years was 1695.77 million TCE, 2864.67 million TCE, 3606.48 million TCE, 4283.34 million TCE, and 4719.25 million TCE, respectively. The energy consumed by the export trade sector represented a significant proportion of the national total, ranging from 25.5% in 2002 to 21.5% in 2018. Despite a slight decline, this proportion consistently exceeded 20%, emphasizing persistent demand on China's energy resources and underscoring the need for robust energy conservation and emissions reduction strategies in the export sector.

Sector-specific analysis reveals that key industries such as textiles and garments, leather products (S4); chemical manufacturing (S8); metal smelting and rolling processing (S10); metal products (S11), various machinery manufacturing (S12, S13); electrical and communication equipment (S14, S15); and transport, storage, and related services (S19, S20) collectively accounted for approximately 85% of the export trade's energy consumption. This concentration indicates the dominant energy demand within these sectors, which is crucial for informing targeted energy efficiency and sustainable practices in China post-WTO accession.

4.2. Analysis of Decoupling and Influencing Factors

4.2.1. Comprehensive Analysis of Export Trade Growth and Energy Consumption Decoupling

The DIs quantifying the relationship between China's export growth and energy consumption from 2002 to 2018 are calculated using Equation (4) and presented in Figure 6. During the initial period of 2002–2006, China's export trade surged by 197.85%, while energy consumption increased by 127.29%, with a DI of 0.64, which indicates a weak decoupling state that is still considered favorable, as illustrated in Figure 7.

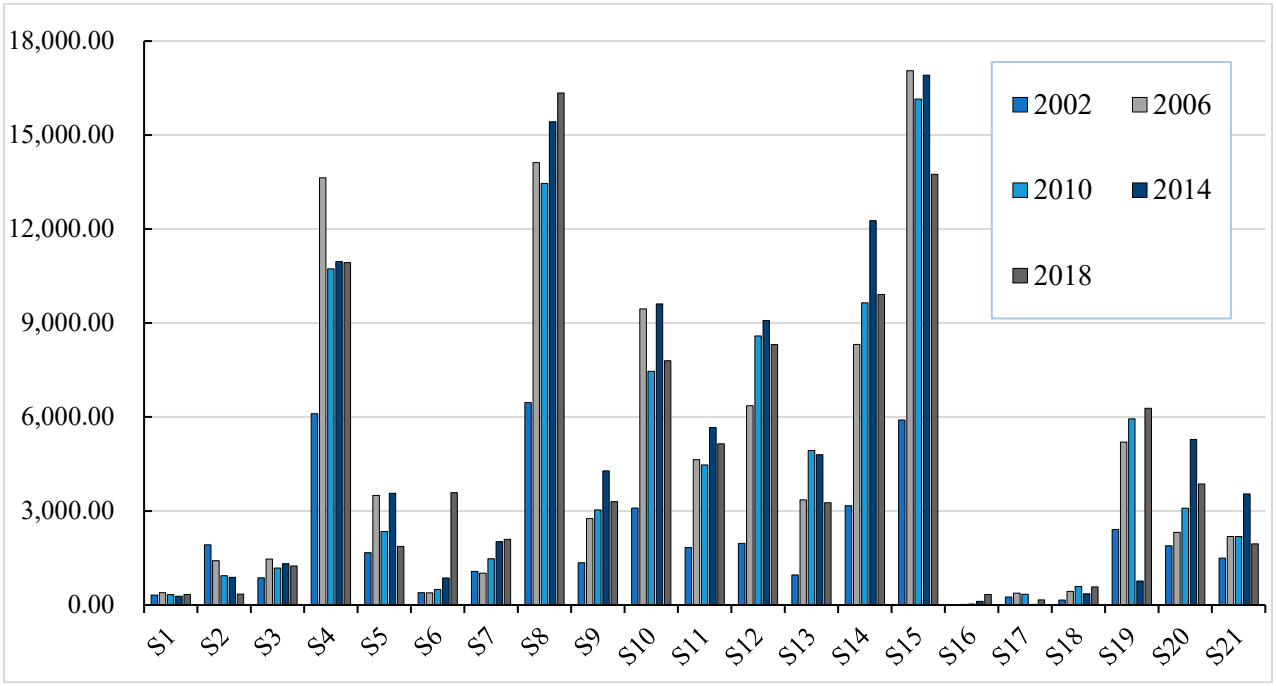


Figure 6. China's exports by sector and their energy consumption during 2002–2018 (million TCE).

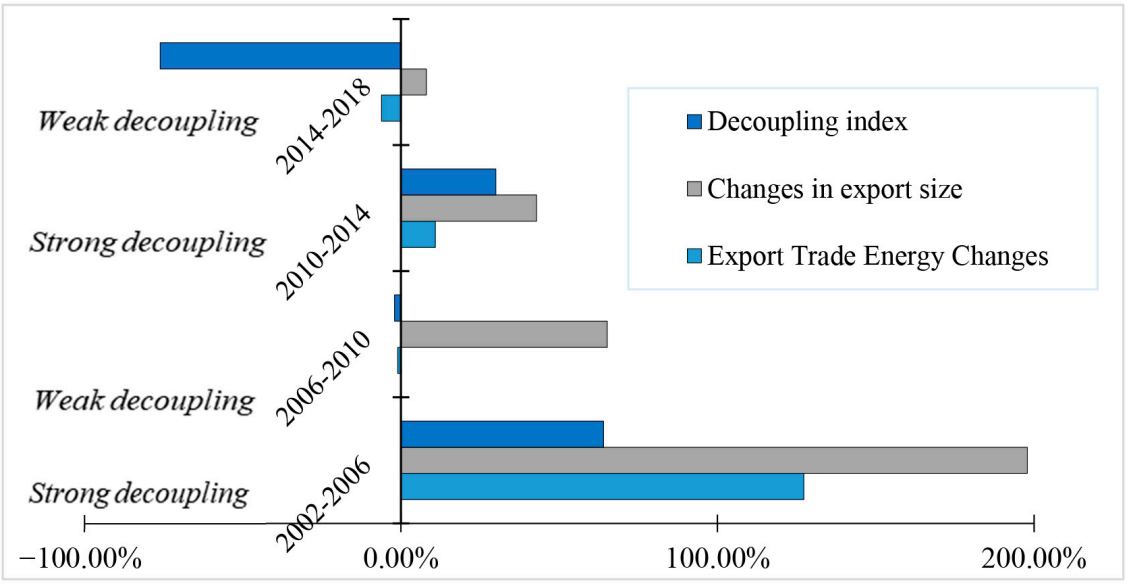


Figure 7. Indices and status of decoupling of export growth and energy consumption in China.

In the subsequent 2006–2010 period, exports expanded by 65.21%, but energy consumption slightly declined by 1.02%. This resulted in a DI of −0.02, representing a strong decoupling state that demonstrated an ideal scenario in which export growth is accompanied by a reduction in energy consumption. From 2010 to 2014, export growth was 42.86%, while the increase in energy consumption was comparatively lower at 13.01%, resulting in a DI of 0.30, once again indicating a weak decoupling state. In the final period of 2014–2018, a modest export increase of 8.05% occurred, which was paralleled by a 7.89% decrease in energy consumption, with a DI of −0.98. This strongly negative value signifies substantial decoupling.

Overall, the analysis across these periods reveals that the 2002–2006 and 2010–2014 phases exhibited weak decoupling, whereas the 2006–2010 and 2014–2018 periods showed strong decoupling. This pattern can be interpreted in light of real-world economic and

policy dynamics: During 2002–2006 and 2010–2014, China's export growth was heavily driven by energy-intensive industries such as heavy manufacturing and raw material processing, which limited improvements in energy efficiency. In contrast, the 2006–2010 period coincided with intensified efforts in industrial upgrading and the global financial crisis, which led to efficiency gains and export restructuring. Similarly, between 2014 and 2018, China accelerated its transition toward high-tech and high-value-added exports under policies such as "Made in China 2025," while energy consumption grew more slowly due to stricter environmental regulations and technological adoption, resulting in strong decoupling. Notably, the 2014–2018 period had the most significant decoupling among all periods, highlighting an effective disassociation between export growth and energy consumption that reflects robust energy efficiency and policy effectiveness in China's export sectors.

4.2.2. Industry Heterogeneity Analysis of Export Trade Growth and Energy Consumption Decoupling

Figure 8 provides a detailed overview of sector-specific trends in energy decoupling within China's export growth from 2002 to 2018, segmented into the four distinct periods examined in this study.

The first stage (2002–2006): Initial analysis reveals that sectors like coal, petroleum, natural gas, and metal mining exhibited positive export growth alongside a decrease in energy consumption, illustrating robust decoupling with negative indices. Conversely, the majority of the 18 other industries demonstrated slower growth in energy consumption relative to exports, classified within a weak decoupling range (0, 0.8).

The second stage (2006–2010): This period experienced an increase to ten sectors' strong decoupling, encompassing diverse industries from agriculture to high-tech manufacturing. These sectors successfully reduced energy consumption against rising export volumes, achieving strong decoupling. The remaining 12 sectors maintained weaker decoupling, with energy consumption growth significantly lagging behind export expansion.

The third stage (2010–2014): The trend toward strong decoupling diminished, with only three sectors—coal, petroleum and natural gas, and metal mining—continuing to exhibit strong decoupling and reduced energy usage despite growing exports. Other sectors presented only weak decoupling, narrowing the gap between export growth and energy consumption.

The fourth stage (2014–2018): This period presented varied decoupling dynamics. (1) Strong Decoupling: Sectors like food and tobacco manufacturing, machinery, and other services exhibited decreases in energy consumption against the backdrop of growing exports. (2) Weak Decoupling: A significant proportion of sectors, including agriculture and chemical manufacturing, displayed moderate decoupling with indices between 0.36 and 0.77. (3) Recession Decoupling: Sectors such as electrical machinery and transport equipment experienced simultaneous export and energy consumption declines, with indices exceeding 1.2, indicating energy savings presumably due to reduced export volume. (4) Recession Connection: Sectors like wood processing and mining also experienced declines in exports and energy use, with DIs around 100%, indicating proportionate reductions.

Overall, these insights reveal the complex interplay between export activities and energy consumption in China's export sectors, with varying degrees of success in achieving decoupling across different periods and sectors [49,50]. The analysis underscores the need for targeted strategies to enhance energy efficiency, particularly in sectors struggling to decouple effectively [51,52].

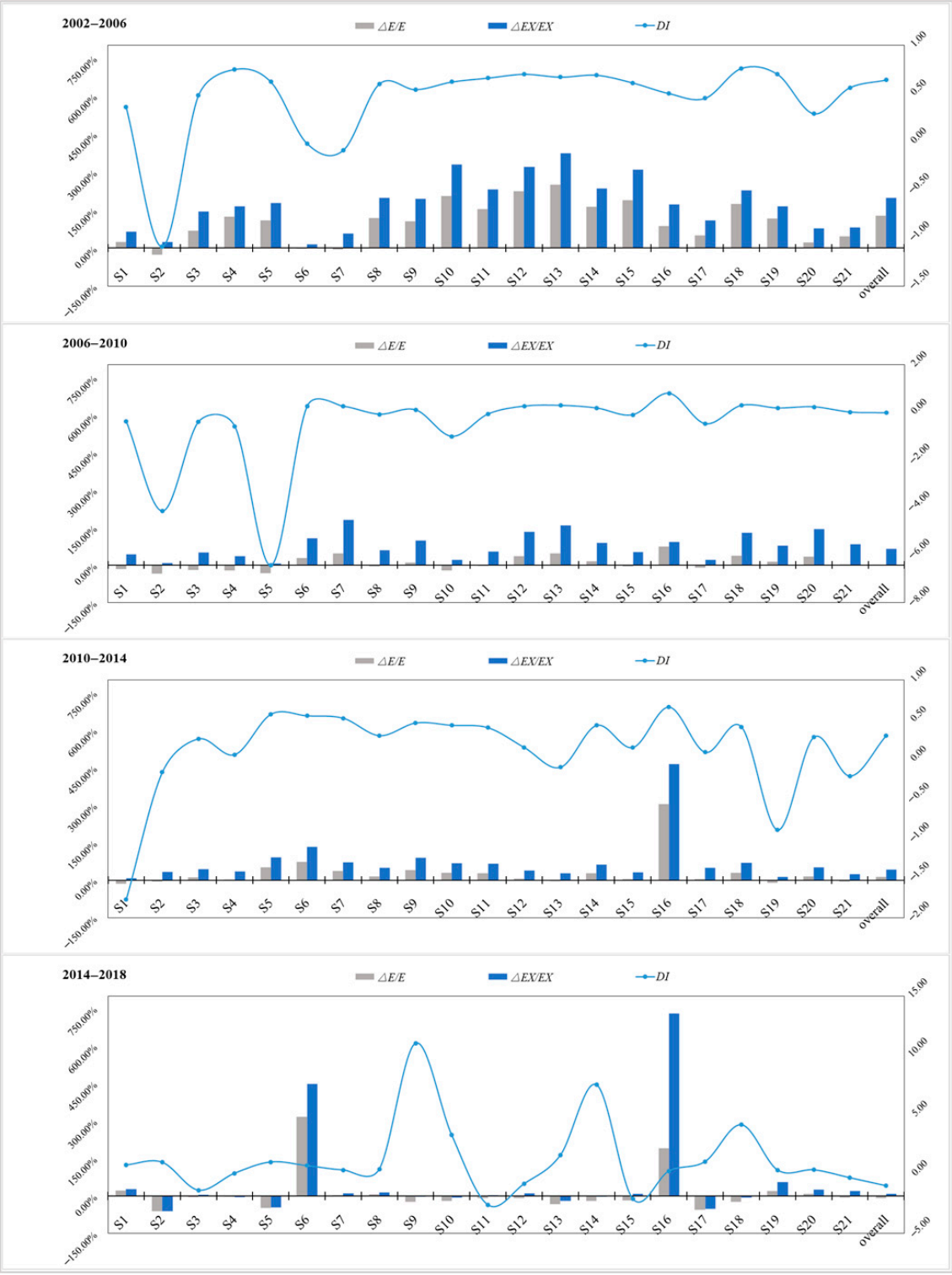


Figure 8. The decoupling state of four sectors in the four periods.

To further deepen the heterogeneity analysis, two representative cases merit particular attention. First, the textiles, clothing, and leather products sector (S4) exhibited a rebound in energy intensity during 2014–2018 despite overall national decoupling progress. This may be attributed to rising raw material costs, stagnation in technological upgrading, and short-term overcapacity driven by export demand volatility. A closer inspection of sector-level R&D intensity and energy-saving retrofitting investments is necessary to validate this hypothesis. Second, the strong decoupling observed in the high-tech manufacturing sector

(S15) reflects the synergistic effect of advanced digitalization, lower energy intensity of output, and sustained government support for innovation. For example, China's "Made in China 2025" and "Strategic Emerging Industries" policies have provided substantial subsidies and fiscal incentives, which have accelerated the sector's shift toward clean and efficient production [53,54]. Future studies could incorporate segmented indicators—such as industry-specific R&D intensity, government support indices, or technological adoption rates—to offer a more nuanced understanding of the drivers behind inter-industry decoupling disparities.

4.2.3. Quantifying Energy Consumption and Decoupling Subindices

The changes in energy consumption (△EG, △ES, and △ET) resulting from changes in the scale of China's export trade, trade structure, and energy consumption intensity for 2002–2006, 2006–2010, 2010–2014, and 2014–2018 are presented in Figure 9a, using Equations (7)–(9). The energy consumption decoupling subindices (DI_G, DI_S, and DI_T) resulting from changes in the scale of China's export trade, the structure of China's export trade and energy consumption intensity are presented in Figure 9b. using Equations (10) and (11). This section analyzes the impact of changes in export volume, trade structure, and energy intensity on decoupling China's export growth from energy consumption based on these decoupling subindices.

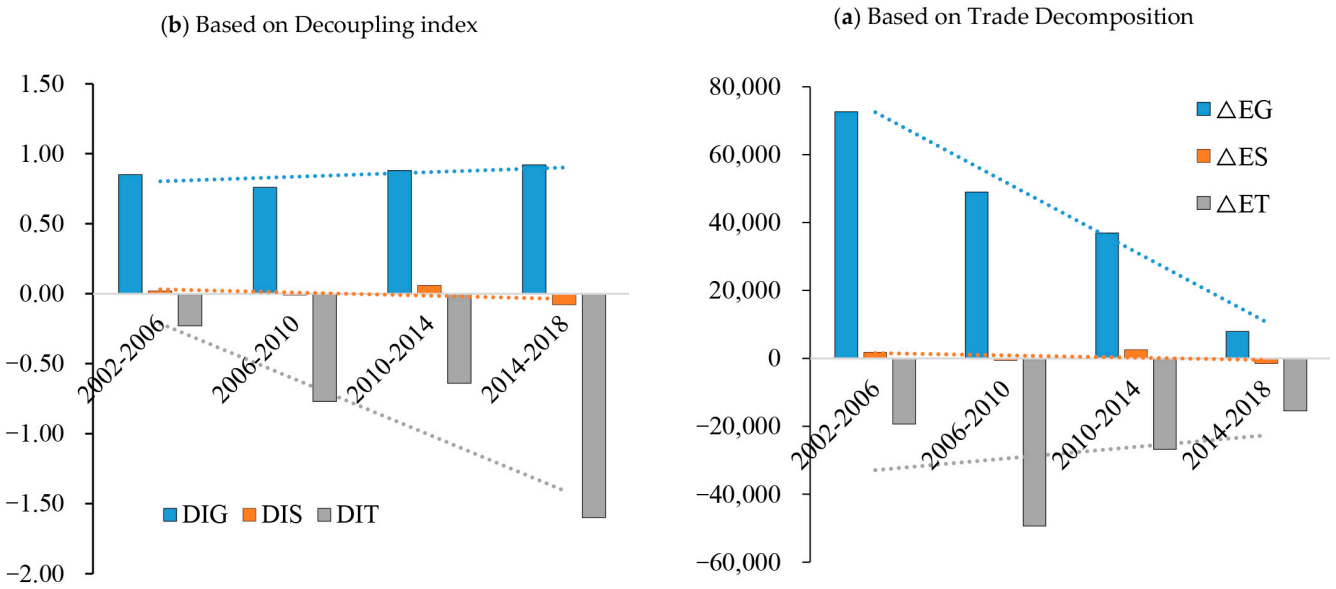


Figure 9. Breakdown of the influencing factors in China by specific periods.

In Figure 8, the variables G, S, and T represent the trade volume impact, structural impact, and energy intensity impact, respectively. Correspondingly, △EG, △ES, and △ET denote the changes in energy consumption in export trade resulting from variations in the scale of China's export trade, adjustments in trade structure, and shifts in energy consumption intensity. Additionally, DIG, DIS, and DIT signify the decoupling subindices of export growth and energy consumption in export trade, attributed to changes in trade volume, trade structure, and energy consumption intensity, respectively.

In the first stage (2002–2006), China's energy consumption in the export sector increased by 726,288,800 TCE and 18,308,000 TCE due to changes in export volume, trade structure, and energy intensity, resulting in corresponding positive decoupling subindices (DI_G and DI_S) of 0.85 and 0.02, respectively. Conversely, energy intensity changes in export trade during the period resulted in a decrease of 193,567,200 TCE in energy consumption, yielding a negative subindex (DI_T) of −0.23. These findings indicate that changes in the

scale and structure of China's exports contribute to increased energy consumption, hindering the decoupling of export growth from energy consumption. In contrast, the reduction in energy intensity facilitated the decoupling process. Among the three factors analyzed, the expansion in the export scale had the most significant influence on decoupling, followed by changes in energy consumption intensity and export trade structure.

In the second stage (2006–2010), changes in export scale increased China's energy consumption in the export sector by 489,754,900 TCE, resulting in a decoupling subindex (DI_G) of 0.76. Conversely, changes in the structure and energy intensity of export trade reduced energy consumption by 6,045,100 TCE and 493,780,900 TCE, respectively, resulting in negative decoupling subindices (DI_S and DI_T) of -0.01 and -0.80, respectively. This suggests that changes in export volume during this period impeded export growth from energy consumption, while changes in export trade structure and energy intensity promoted decoupling. The influence of changes in export trade–energy intensity had the most significant impact in this period, followed by export growth and trade structure.

In the third stage (2010–2014), changes in export scale and trade structure increased China's energy consumption in the export sector by 368,959,800 TCE and 25,750,100 TCE, respectively, resulting in positive decoupling subindices (DI_G and DI_S) of 0.88 and 0.06, respectively. Conversely, changes in export trade–energy intensity reduced energy consumption by 268,020,700 TCE, resulting in a negative subindex (DI_T) of -0.64. These results indicate that changes in the scale and structure of China's exports in this stage did not advance the decoupling of export growth from energy consumption, while changes in energy intensity facilitated the decoupling process. The influence of export scale growth was the most critical factor in this period, followed by changes in energy consumption intensity and export trade structure.

In the fourth stage (2014–2018), changes in export scale increased China's export sector's energy consumption by 79,670,300 TCE, resulting in a decoupling subindex (DI_G) of 0.92. Conversely, changes in export trade structure and energy intensity reduced energy consumption by 15,227,800 TCE and 154,392,000 TCE, respectively, resulting in negative decoupling subindices (DI_S and DI_T) of -0.08 and -1.60, respectively. These findings indicate that the influence of changes in export trade–energy intensity on China's export growth and energy consumption decoupling during this period were significantly greater than the resistance posed by export scale expansion. Moreover, changes in export trade structure also contributed to the decoupling process.

In comparative terms, the four stages exhibit distinct decoupling dynamics. The 2002–2006 and 2010–2014 periods reflect weaker decoupling due to continued reliance on energy-intensive sectors and relatively modest policy interventions. By contrast, 2006–2010 demonstrates an early shift towards efficiency gains, partially influenced by the 2008 financial crisis and domestic energy-saving campaigns. The strongest decoupling is observed during 2014–2018, when industrial upgrading, structural optimization, and stricter environmental regulations jointly drove down energy consumption even amid sustained export growth. These differences suggest that both external shocks and internal policy orientation played vital roles in shaping decoupling performance across time.

In summary, the evolution of China's export–energy relationship, as reflected by the decoupling subindices (DI_G, DI_S, and DI_T), shows that different drivers dominated at different stages (Figure 9b). The overall decoupling index (DI) gradually shifted from weak to strong decoupling, particularly after 2010, when technological innovation and energy-efficiency policies became more effective [55]. Specifically, the DIG index confirms that the expansion of export scale consistently acted as the main constraint on decoupling, while the DI_T index highlights the decisive role of declining energy intensity in promoting it—especially during 2014–2018, when cleaner technologies and industrial upgrading

reduced energy use even under sustained export growth. The DIS index, though relatively small in magnitude, increased over time as high-value-added sectors such as S14 (electrical machinery) and S15 (electronic equipment) expanded their export shares. These findings emphasize that efficiency improvements and structural upgrading, rather than trade volume growth, are the core pathways to sustaining strong decoupling in China's export sector.

4.2.4. Analyzing the Factors Impacting Export Growth–Energy Consumption Decoupling

We obtain the DIs of China's export growth and energy consumption for the four periods based on the same calculation method. Additionally, the subindices of export growth and energy consumption decoupling are once again decomposed into export scale, export trade structure, and energy intensity effects. This section explores the impact of export scale, export trade structure, and energy intensity changes on the decoupling between China's export growth and energy consumption.

The impact of export scale on the subindices of export growth and energy consumption decoupling (DI_G) is evident in the 2002–2006, 2006–2010, 2010–2014, and 2014–2018 periods, with values expansion of 0.85, 0.76, 0.88, and 0.92, respectively. These values indicate that the export scale after 2002 has continuously driven increased DIs between China's export growth and energy consumption. The expanding trend of China's export trade volume in these periods has increased decoupling resistance between export trade and energy consumption.

In terms of the impact of trade structure, during the 2002–2006 and 2010–2014 periods, the subindices of export growth and energy consumption decoupling (DI_S) were positive, indicating that export trade structure changes during these periods were unfavorable for decoupling. Conversely, for the 2006–2010 and 2014–2018 periods, the subindices of export trade and energy consumption decoupling were negative, suggesting that the export trade structure changes during these periods facilitated decoupling between China's export growth and energy consumption. Overall, since 2002, the subindices of export growth and energy consumption decoupling due to the trade structure effect have demonstrated a fluctuating downward trend. This indicates that the changes in export trade structure since joining the WTO have predominantly promoted China's export trade and energy consumption decoupling.

Regarding the impact of energy intensity, for the 2002–2006, 2006–2010, 2010–2014, and 2014–2018 periods, the subindices of export growth and energy consumption decoupling (DI_T) resulting from changes in export trade–energy intensity are all negative, exhibiting an overall decreasing trend. The above analysis demonstrates that the export sector's continuous reduction in energy intensity is a crucial factor driving China's export growth and energy consumption decoupling.

4.2.5. Analysis of Factors in Various Sectors

Figure 10 illustrates that, for the 2002–2006, 2006–2010, and 2010–2014 periods, the decoupling subindices (DI_G) resulting from the export trade scale effect in various sectors were positive, indicating that the of export scale expansion was unfavorable for decoupling. However, in the same periods, the decoupling subindices (DI_T) resulting from changes in energy intensity in these sectors were negative, indicating that reduced energy intensity propelled decoupling.

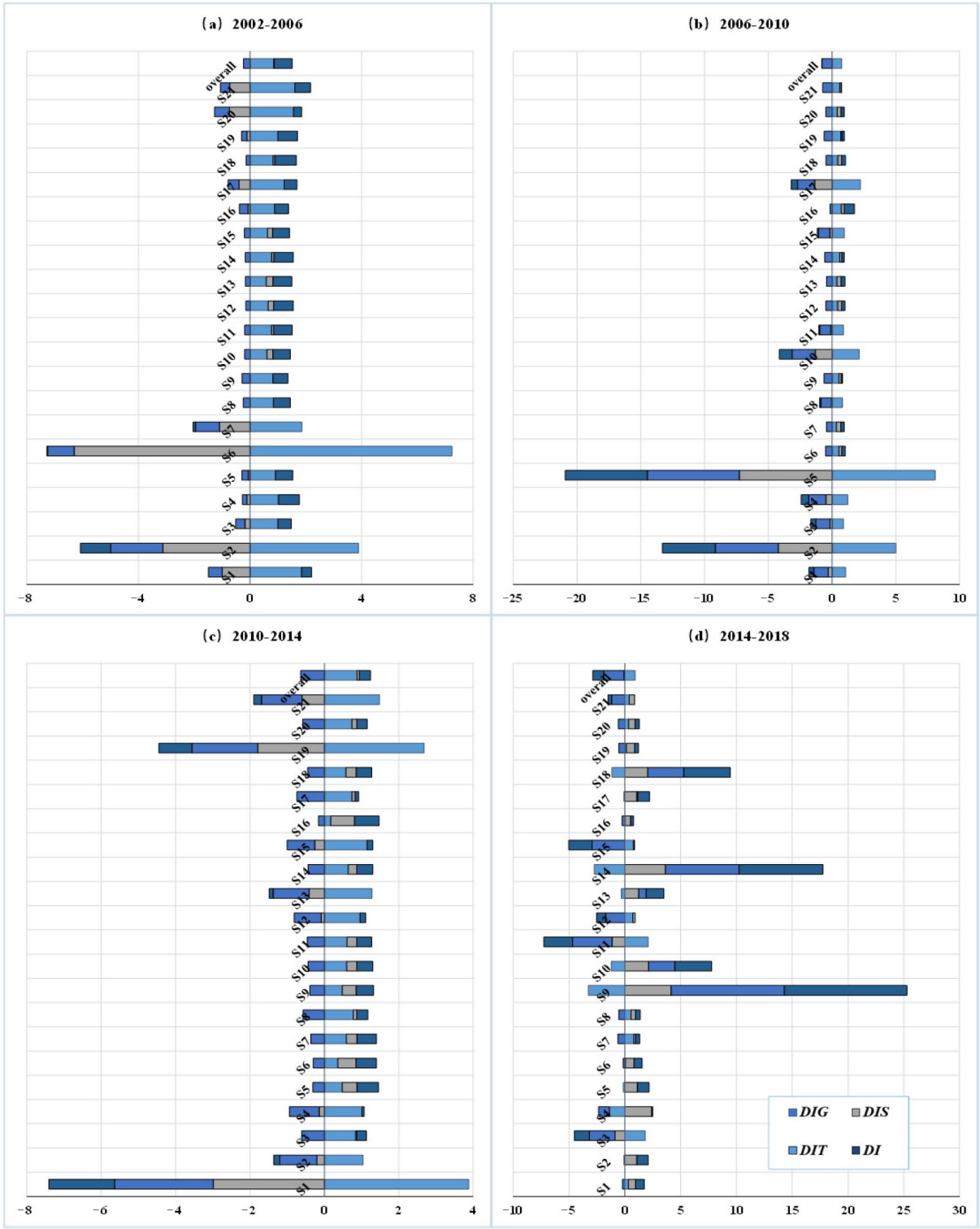


Figure 10. Factor decomposition of the decoupling index between export growth and energy consumption in China.

In the three periods noted above, the decoupling subindices (DI_S) resulting from the export trade structure effect varied between positive and negative values; however, the absolute values of DI_S for the majority of sectors were much smaller than those of DI_G and significantly smaller than the absolute values of DI_T. This indicates that the impact of export trade structure changes on export growth and energy consumption decoupling in most sectors during these three periods was relatively minor. However, there are some

notable exceptions. In the three periods noted, paper printing and educational and sports goods manufacturing; coal, oil, and natural gas; and metal and nonmetal mining and quarrying sectors exhibited relatively large decoupling subindices (DI_S) resulting from the export trade structure effect. These sectors' export trade structure changes have significantly impacted the decoupling of their export growth and energy consumption.

In contrast to the previous three periods, during the 2014–2018 period, nearly half of the sectors experienced negative decoupling subindices (DI_G) resulting from the export trade scale effect. Seven export sectors demonstrated positive decoupling subindices (DI_T) resulting from changes in energy intensity, indicating a differentiation in the impact of export scale and energy intensity changes on the decoupling status of various sectors' export growth and energy consumption. During this period, except for the metal products, food, and tobacco manufacturing sectors, for which the decoupling subindices (DI_S) resulting from export trade structure effect were negative, the decoupling subindices for most sectors resulting from export trade structure effect were positive.

Moreover, these decoupling subindices have significantly increased compared with the previous three periods. However, the majority of decoupling subindices resulting from the export trade structure effect were notably smaller than those from export scale and energy intensity effects, indicating that the impact of export structure changes on decoupling is less significant for most sectors than the effects of export scale and energy intensity.

During the 2014–2018 period, seven sectors exhibited positive values for the decoupling subindex related to energy intensity (DIT), indicating that rising energy consumption per unit of export in these sectors hindered the overall decoupling process. These sectors include textiles, clothing and leather products (S4), non-metallic mineral products (S9), metal smelting and rolling processing (S10), metal products (S11), woodworking and furniture (S5), food and tobacco manufacturing (S3), and other services (S21). Several underlying factors contributed to this deterioration in energy efficiency. In traditional manufacturing sectors such as S4, S5, and S10, the shift toward lower-margin, energy-intensive orders amid global trade uncertainty may have resulted in reduced incentive or capacity for upgrading energy-efficient equipment. S9 and S11 were simultaneously affected by overcapacity and policy lag in energy retrofitting, especially in smaller private enterprises that lagged in technological modernization. In the case of S3 and S21, increasing domestic demand and a lack of strict energy efficiency benchmarks for service-related activities may have led to operational inefficiencies. These sector-specific trends highlight the importance of aligning industrial policy with energy upgrading incentives, especially in sectors traditionally considered less responsive to environmental performance metrics.

Notably, during the 2014–2018 period, nearly half of the sectors exhibit a negative ΔEG, indicating that the scale effect—normally associated with export expansion—contributed to reductions in energy consumption. This phenomenon warrants further explanation. A negative ΔEG reflects that the total export volume of these sectors contracted in absolute terms, rather than merely growing more slowly. This is consistent with China's broader trade transition during this period, which involved: (1) the phasing out of low-end, energy-intensive exports (e.g., certain raw materials and basic manufacturing goods), (2) supply side structural reforms aimed at cutting overcapacity in heavy industry sectors (e.g., S9, S10), (3) and a deceleration of global trade demand following the aftermath of the global financial crisis and rising trade frictions. For example, the metal smelting and rolling sector (S10) and non-metallic minerals (S9) both saw negative ΔEG, aligning with government-led capacity reduction policies in the steel and cement industries. Similarly, some light manufacturing sectors such as S4 (textiles) were impacted by rising labor costs and global value chain reconfiguration, leading to a dip in export competitiveness and volume. Therefore, the negative ΔEG values do not merely represent a relative shift in decoupling dynamics, but a

real contraction in export volume for specific sectors. This highlights the effectiveness of industrial restructuring policies and the shifting landscape of China's export composition during the late 2010s.

5. Discussion

Based on the preceding analysis, we present Figure 11 as the focal point of our subsequent analysis. China's accession to the WTO has had a substantial influence on the nation's contribution to global trade [56], fostering enhanced trade openness and active participation in the global economy [57].

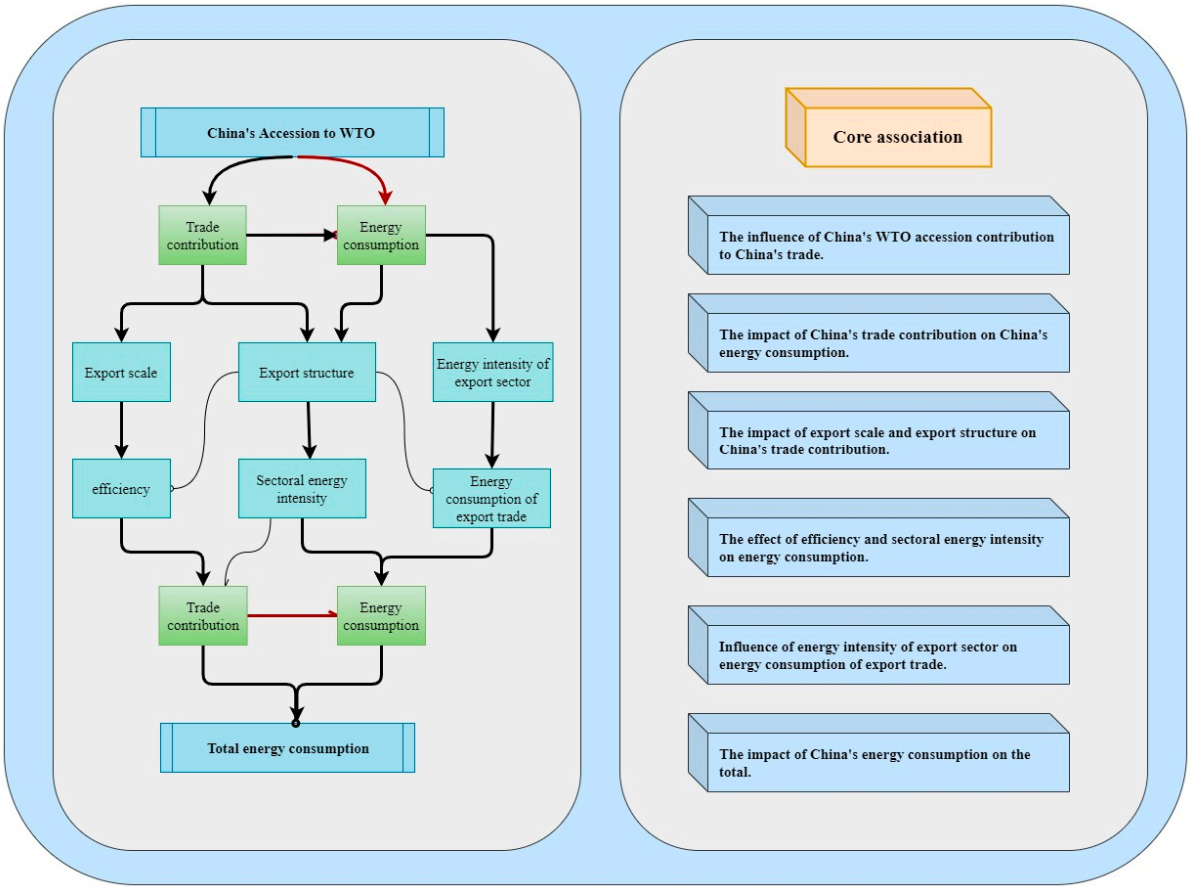


Figure 11. Impact of China's WTO accession on energy consumption, trade, and contributing factors.

WTO accession has expanded China's market access, diminished trade barriers, and demonstrated a commitment to adhering to international trade regulations and standards. These measures have elevated Chinese enterprises' competitiveness, attracting an increased influx of foreign companies and investors into the Chinese market [58,59]. Consequently, China's trade volume has expanded, resulting in a corresponding rise in export trade.

The growth of China's trade volume has significantly impacted its energy consumption. As trade volume increases, so do economic activities, resulting in a corresponding effect on energy consumption [60,61]. The upsurge in China's trade activities has indeed exerted a substantial influence on its energy consumption. Research has demonstrated that trade openness has promoted increased use of nonrenewable energy sources, emphasizing heavy reliance on fossil fuel for production and exports [62].

Additionally, both domestic and foreign trades have had an influence on reshaping the energy landscape in China, notably reducing interprovincial disparities in energy use [63]. Foreign trade, particularly imports, has been found to enhance China's overall energy effi-

ciency, benefiting local regions as well as neighboring provinces through spatial spillover effects. As one of the world's largest energy-consuming nations, China's energy consumption is a crucial support for its trade contribution, necessitating strategic policy interventions to strike a balance between energy consumption and sustainable development.

Concurrently, escalation in China's energy consumption may result in a corresponding rise in energy use linked to export trade [25,64]. As economic development progresses and export volumes expand, energy consumption associated with export trade will likewise increase. The energy-intensive sectors' exportation can have a substantial influence on energy consumption related to export trade. Previous research has shown that companies heavily engaged in exporting tend to exhibit higher levels of energy intensity, particularly industries with higher energy consumption needs [65]. Moreover, trade openness has significantly contributed to the consumption of nonrenewable energy, signifying a reliance on such sources in production and export activities [66]. Notably, long-term analysis has suggested that an upsurge in exports per capita can bolster clean energy use, underscoring the pivotal role of exports in enhancing a nation's clean energy development and consumption [67].

Sectoral variations in energy intensity have had a pivotal role in shaping China's energy consumption landscape. The levels of energy intensity observed in different sectors have significantly influenced overall energy consumption patterns [68]. Sectors such as oil processing and coking; manufacturing; nonmetal products manufacturing; metal smelting and rolling processes; and electricity, gas, water, sewage treatment, waste, and remediation, have been recognized as key contributors to carbon intensity in China [69]. Furthermore, the embodied energy of China's information and communications technology sectors was substantial in 2018, with communications equipment emerging as the primary consumer [70].

The aggregate energy consumption and energy efficiency have notable implications for China's overall energy consumption. Scholarly investigations have revealed regional disparities in energy consumption in China, where factors influencing energy consumption remain consistent across regions but exhibit varying impacts attributable to geographical and stress-related variations [56]. Per capita GDP has been identified as the principal catalyst for heightened energy consumption, whereas advancements in energy-efficient technologies can promote substantial energy conservation [71,72]. Furthermore, examinations of urban energy efficiency have demonstrated that technological advancements predominantly drive improved energy efficiency, while declines in technical efficiency impede progress in different cities [53].

Export scale, structure, and composition significantly impact China's trade volume and energy consumption. Expanding markets, improving export quality and competitiveness, and focusing on intermediate products can enhance trade and influence energy use [25,73,74].

Although this study focuses on the period from 2002 to 2018, which captures the pivotal phase of China's post-WTO trade expansion, it does not include structural transformations that emerged after 2019. This subsequent period witnessed two major disruptions: intensified U.S.–China trade tensions and the COVID-19 pandemic, which reshaped global supply chains and industrial allocation [56,57]. In parallel, the enforcement of "dual-carbon" policies accelerated the adoption of renewable energy and transformed domestic energy consumption patterns [33]. These post-2019 developments likely altered the decoupling dynamics between export growth and energy use. Future research should incorporate updated data (e.g., 2019–2022) or employ scenario simulations to capture emerging decoupling trends under evolving geopolitical and policy environments. Such efforts would

enhance the timeliness, policy relevance, and strategic foresight of the analysis, ensuring stronger alignment with contemporary foreign trade and energy governance needs [54,75].

Additionally, China's commitment to carbon neutrality by 2060 suggests a gradual transition towards renewable energy sources, which will likely alter the energy intensity of export activities [76]. Comparing these projections with historical data underscores the necessity for continuous monitoring and adaptive strategies to balance economic development with environmental sustainability.

In summary, China's accession to the WTO has had a multifaceted impact on its trade contributions. Market expansion, trade barrier reduction, and adherence to international trade rules have fostered China's trade development, which has facilitated the growth of export scale, promoted export restructuring, and influenced energy consumption and energy-related trade. Furthermore, sectoral energy intensity, overall energy consumption, and energy efficiency are crucial determinants that shape China's energy consumption and trade contributions.

6. Conclusions and Policy Implications

6.1. Conclusions

(1) The findings of this study demonstrate the substantial energy consumption associated with China's export trade, despite its decreasing proportion compared with total domestic energy consumption. Energy consumption figures for China's export trade have remained significant over the years, accounting for a considerable proportion of total domestic energy consumption (consistently over 20%). These results emphasize the substantial energy demand generated by China's export trade, placing significant pressure on domestic energy conservation and emissions reduction efforts.

(2) Furthermore, a clear decoupling trend between export growth and energy consumption emerged following China's accession to the WTO. The decoupling relationship varied during different time periods, with weak decoupling observed from 2002 to 2006, strong decoupling from 2006 to 2010, weakened decoupling from 2010 to 2014, and a return to strong decoupling from 2014 to 2018. The shifting DIs indicate that the highest decoupling level was achieved from 2014 to 2018.

(3) The impact of changes in export trade scale, trade structure, and energy consumption intensity on China's export growth and energy consumption decoupling has been significant and diverse. The increasing scale of exports has generally hindered the decoupling process, while decreased energy consumption intensity was identified as the primary driver of China's export trade–energy consumption decoupling, whereas structural changes in export trade have had a relatively minor impact on the decoupling relationship.

China's experience highlights the significance of addressing energy demands in export trade and implementing effectively targeted policies to decouple export growth from energy consumption. It also offers valuable lessons for global policymakers, emphasizing the importance of sustainable economic development and improved energy consumption intensity within the export sector.

6.2. Policy Implications

6.2.1. Promoting Energy Efficiency Through Green Export Technologies

Given that export-related industries remain major contributors to national energy use, policies should prioritize sector-wide adoption of energy-efficient technologies and green production practices. Governments can establish export-oriented "Green Process Catalogues" to guide the transition toward low-carbon manufacturing, particularly in energy-intensive sectors such as textiles, petrochemicals, and metallurgy. Financial

incentives—such as tax rebates, green credit lines, or carbon labeling benefits—can be offered to exporting firms that meet advanced efficiency benchmarks. These efforts will not only align with national carbon neutrality goals but also enhance export competitiveness in a climate-sensitive global market.

6.2.2. Institutionalizing Decoupling Indicators into Policy Evaluation

To enhance accountability and steer policy effectiveness, decoupling indicators (e.g., DI, DI_G, DI_S, and DI_T) should be integrated into official performance assessment systems at both regional and enterprise levels. For example, in regions with high export-dependence, these indices can complement existing energy dual-control (total volume and intensity) frameworks. Similarly, large exporters can be required to disclose decoupling metrics in annual ESG or sustainability reports. Embedding these indicators in monitoring mechanisms will ensure more targeted governance and encourage long-term decarbonization commitments.

6.2.3. Tailoring Sector-Specific Decoupling Strategies

Sectoral heterogeneity in decoupling performance calls for differentiated policy strategies. In sectors where energy intensity has worsened—such as garments, basic chemicals, and non-metallic minerals—regulations should include mandatory energy audits, industry-specific efficiency standards, and support for energy retrofit programs. In contrast, sectors with strong decoupling performance, such as electronics and ICT manufacturing, should receive enhanced trade and R&D support to scale their low-carbon models. These strategies can create a "demonstration effect", accelerating the diffusion of best practices across export-oriented value chains. Furthermore, decoupling indicators (DI_G, DI_S, DI_T) should be incorporated into the performance evaluation metrics of provincial governments and major export enterprises, enabling periodic assessment and policy feedback loops.

6.2.4. Developing Adaptive Mechanisms for Periodic Decoupling Assessment

Considering that decoupling patterns vary significantly across time periods and external shocks, a robust monitoring and response mechanism is essential. Governments should establish decoupling dashboards that provide real-time updates on sectoral trends, enabling policymakers to quickly respond to emerging energy-export misalignments. Policy instruments—such as carbon pricing, green trade agreements, or export credit guidelines—can be dynamically adjusted based on the observed decoupling status. Such adaptive governance models can help countries reconcile trade growth with energy sustainability, especially in the context of volatile global supply chains and climate uncertainty.

6.3. Outlook

Despite its contributions, this study faces several limitations. The reliance on input–output data from only five discrete years (2002, 2006, 2010, 2014, and 2018) constrains the ability to capture short-term fluctuations, transitional shocks, and non-linear policy effects. Additionally, the LMDI decomposition approach, while widely used, is sensitive to data quality and assumes a stable technological structure over time. These constraints suggest the need for methodological triangulation and higher temporal resolution in future studies.

Future research should expand the analytical scope in several directions. First, applying panel data methods or constructing time-series input–output datasets would enable dynamic decoupling trajectory analysis, enhancing policy relevance. Second, comparative studies across export-driven economies—especially emerging markets in Asia, Africa, and Latin America—could identify heterogeneous drivers of export–energy decoupling and yield more generalizable conclusions. Third, incorporating advanced methods such as Computable General Equilibrium (CGE) models, dynamic panel regressions, or PVAR

frameworks would provide causal insights into how trade policy, energy regulation, or technological diffusion affect decoupling patterns.

Furthermore, translating academic insights into actionable policy strategies is crucial. Future studies should evaluate the alignment between decoupling metrics and national climate goals (e.g., China's 2060 carbon neutrality target), as well as their potential integration into energy and trade governance frameworks. This includes embedding sectoral decoupling indices (e.g., DI_G, DI_S, DI_T) into environmental performance assessments of regional governments or major exporters. Additionally, the analytical framework presented in this study can be extended to other countries or sectors seeking to balance export expansion with sustainable energy use [41,61].

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