Chinese Journal of Population, Resources and Environment

Decoupling economic growth from industrial SO$_2$ emissions in China: A two-stage decomposition approach

Yuanna Tian[ab], Yizhong Wang[bc], Ye Hang[ab], Dequn Zhou[ab], Xiurong Hu[ab*], Qunwei Wang[ab*]

[a] College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China
[b] Research Centre for Soft Energy Science, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China
[c] School of Politics & Public Administration, Soochow University, Suzhou 215006, China

A B S T R A C T

Exploring the factors driving the decoupling of China's sulfur dioxide (SO$_2$) emissions from economic growth (DEI) is crucial for achieving sustainable development. By analyzing the decoupling indicators and driving factors at both the generation and treatment stages of SO$_2$, more effective targeted mitigation strategies can be developed. We employ the Tapio decoupling model and propose a two-stage method to examine the decoupling issues related to SO$_2$. Our findings indicate that: ① DEI shows a steady and significant improvement, with SO$_2$ emission intensity identified as the primary driver. ② for the decoupling of economic growth and SO$_2$ generation, energy scale serves as the largest stimulator, while the effect of energy intensity changes from negative to positive, and pollution intensity is first positive and then negative. ③ For the decoupling of SO$_2$ generation and SO$_2$ removal, treatment efficiency leads as the largest promoter, followed by treatment intensity. Based on these results, this study recommends that China focuses more on enhancing clean energy utilization and the effectiveness of treatment processes.

1. Introduction

As the largest developing country in the world, China boasts a strong economy, with its gross domestic product (GDP) soaring from 0.8 trillion in 1985 to 101 trillion in 2020 (Zhang et al., 2021a). Simultaneously, the gross industrial output value increased from 0.5 trillion in 1980 to 90 trillion in 2020, contributing 40% to overall GDP growth (Wang and Qiu, 2021). However, industrial exhaust emissions have also risen alongside economic growth, positioning China as the third-largest emitter of sulfur dioxide (SO$_2$) globally (Liu et al., 2019). In 2007, China's total SO$_2$ emission load was 8.75 million tonnes (Mt), with industrial emissions contributing 7.35 Mt, or 84% of the total (Qian et al., 2020). That year, over seven thousand industrial parks in China produced SO$_2$ pollution, and only about 25% of the emissions met official environmental standards (Cai and Hu, 2022). By 2018, annual anthropogenic SO$_2$ emissions in China had reached nearly 2.7 Mt, accounting for 9% of global emissions (Xu et al., 2021). Almost 85% of overall SO$_2$ emissions originate from the industrial sector (MEE, 2019).

SO$_2$ is an invisible noxious gas that poses significant risks to human health, particularly the respiratory system. Research has shown that SO$_2$ exposure can lead to irreversible lung diseases (Xu et al., 2021). Additionally, SO$_2$ contributes to the formation of acid rain, resulting in acidified soil and reduced farmland productivity (Wei et al., 2014). Unbalanced industrial structures, low energy efficiency, stagnant technological innovation, and ineffective governance have all contributed to severe SO$_2$ pollution in China. Additionally, owing to varying resource endowments and geographic positions, different provinces have experienced significant disparities in SO$_2$ emissions. For instance, the top ten provinces in China account for half of the total SO$_2$ emissions (Peng et al., 2021). To address these challenges, China must continue to improve the decoupling of economic growth from emission pollution to promote comprehensive, balanced, and sustainable development.

The Chinese government has consistently sought to decouple economic growth from air pollution. In 1987, the *Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution* was enacted with the aim of controlling air pollution (Liu and Wang, 2017). Since then, China has implemented policies and measures to enhance environmental quality alongside economic growth. However, as economic development has traditionally taken precedence over environmental protection, local governments and enterprises have fo-

---

* Corresponding authors.

E-mail address: huxr@pku.edu.cn (X. Hu), wqw0305@126.com (Q. Wang).

cused primarily on end-of-pipe treatment measures.

From a pollution control perspective, production activities in the industrial sector consist of two stages: the generation stage and the treatment stage (Shao et al., 2016). As illustrated in Figure 1, in the generation stage, industrial producers use inputs to achieve desired outputs while generating undesired SO_2 emissions. In the treatment stage, producers purify the generated SO_2 using treatment inputs, resulting in the removal of SO_2 as the desired output, while the emissions remain the undesired output. According to Wang et al. (2019a), the amount of generated SO_2 can be reduced in the generation stage by improving raw materials, process design, and production technology. During the treatment stage, greater SO_2 removal can be achieved by introducing purification facilities.

Given the significant increase in pollution, efforts are needed in both the generation and treatment stages to enhance emission control. In the generation stage, adjustments to industrial structures and reductions in energy intensity can help lower emissions. In the treatment stage, effective measures such as advancing treatment technologies and increasing treatment intensity should be prioritized. In 2012, the State Council of China released the *Twelfth Five-Year Plan on Air Pollution Prevention and Control in Key Regions*, which outlined goals for air quality improvements in thirteen pilot areas from 2011 to 2015 (Liu et al., 2022). Subsequently, the government aimed to increase the percentage of clean energy in total energy consumption by 2020 (Liu and Wang, 2013). To further address air quality concerns, the *Clean Generation Promotion Law of the People's Republic of China* was enacted in 2012 to implement generation-stage measures, including industrial structure transformation and pollution-control technologies. Additionally, in 2015, the *Environmental Protection Law of China* was revised to establish principles for prevention-oriented pollution control (Cao et al., 2021; Hang et al., 2019). To achieve cleaner production and more effective treatment, pollution control should be improved at both the source and throughout each stage of production.

To effectively modify the full treatment process, studying the decoupling states individually at both the generation and treatment stages is essential. Based on the Tapio model, we developed a two-stage approach that includes a two-stage decoupling model and a two-stage decomposition model. This study first assesses the decoupling states of SO_2 emissions from economic growth (DEI), SO_2 generation relative to economic growth (DIG), and the relationship between SO_2 removal and SO_2 generation (DIT) at both provincial and national levels. Utilizing the Logarithmic Mean Divisia Index (LMDI) method, we decompose the driving factors of DEI, DIG, and DIT. Additionally, we conduct an empirical analysis of the decoupling status of SO_2 emissions and economic development in China from 2000 to 2020 using the proposed methodology. The results can assist policymakers in making more effective decisions that promote economic development while ensuring sustainable environmental practices.

This study constructs novel decoupling and decomposition models from a two-stage perspective, addressing gaps in previous research that focused solely on decoupling or decomposition from a holistic perspective. Our study is distinct from other research in two ways: first, unlike previous studies that examined driving forces across the entire stage, we develop a decoupling model specifically for economic

growth and SO_2 generation, as well as separate models for DIG and DIT; second, we further decompose the driving forces from the two stages, providing more precise measures based on the two-stage decomposition results to address SO_2 emission reduction in China.

The remainder of this paper is organized as follows: Section 2 reviews relevant literature; Section 3 outlines the study's methodology; Section 4 presents the empirical results along with an analysis of decoupling and decomposition; and Section 5 provides conclusions, implications, and policy recommendations.

2. Literature review

2.1. Origin and development of decoupling measurement

The decoupling concept, proposed by the Organization for Economic Cooperation and Development (OECD) in 2002, was initially used to analyze the relationship between economic development and environmental impacts (OECD, 2002). Following the signing of the *Paris Agreement*, decoupling emissions from economic growth became crucial for enhancing energy efficiency and reducing pollution (Shao et al., 2016; Wang et al., 2019b). However, the OECD's indicators were found to be limited, as they presented a broad view of the decoupling relationship without distinguishing between cases of simultaneous increases and decreases.

To address this, Tapio (2005) enhanced the elastic coefficient method by introducing a decoupling index. This index was used to analyze the decoupling of CO_2 emissions and economic development in the transportation sectors of 15 European countries from 1970 to 2001. The Tapio decoupling model reduces uncertainty related to selecting base periods, improves the accuracy of decoupling measures, and incorporates a set of intermediate quantities to refine decoupling indicators (Dong et al., 2020). Subsequently, researchers adapted the Tapio model to meet specific needs. For instance, Song et al. (2020) developed the Tapio-Z decoupling model, a bi-dimensional approach, to assess the decoupling of CO_2 emissions in China.

Owing to its effectiveness in calculating decoupling indicators and classifying states, the Tapio model is widely used globally. Lundquist (2021) examined factors influencing the decoupling of emissions and economic development in 35 OECD countries from 1994 to 2016, finding that countries with green technologies could facilitate decoupling. Similarly, Zhang et al. (2021b) and Kong et al. (2021) applied the Tapio theory to investigate water consumption decoupling, identifying that water-saving technology, urbanization rates, and population size are vital for decoupling water use from economic growth. Zhang et al. (2020b) also studied the decoupling of thermal energy use in the construction sector, concluding that while heating energy intensity can enhance decoupling, district and demographic factors may impede it.

2.2. Combination of decoupling and decomposition

Diakoulaki and Mandaraka (2007) argued that research focused solely on decoupling cannot adequately clarify the impact of environmental externalities or provide actionable policy recommendations. To address these limitations, researchers have begun incorporating de-
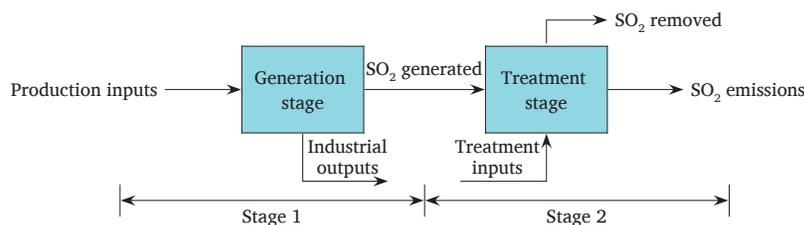

Figure 1. Two substages of industrial activities and relevant impact pathways

coupling indicators with decomposition analysis, creating specific road maps for enhancing decoupling activities globally. One extensively used method is the LMDI, which facilitates analysis across various sectors (Du et al., 2022; Miao et al., 2020).

For instance, Jia et al. (2018) examined the drivers of industrial SO_2 emissions in China using the LMDI model. Their findings revealed that the output effect increased SO_2 emissions, while pollution abatement and clean production technologies effectively reduced them. Gao et al. (2021) combined the Tapio method with the LMDI model, discovering that capital investment and total factor productivity were major contributors to the weak decoupling (WD) state between emission pollution and economic development. Similarly, Song et al. (2021) employed both models to investigate the relationship between industrial CO_2 emissions and the industrial economy, finding that decoupling elasticity decreased in the central and southwestern provinces due to a strong decoupling (SD) state. They identified energy intensity and industrial structure as the primary inhibitors of industrial CO_2 emissions in China. Shan et al. (2021) used the Tapio method and LMDI to analyze the decoupling states of CO_2 emissions from economic development across 294 Chinese cities from 2005 to 2015. Their study indicated that demographic factors, energy efficiency, industrial structure, and economic level influenced emissions, while emission intensity, economic growth, and economic transformation affected decoupling. Dong et al. (2020) also adopted the Tapio and LMDI methods to explore the factors influencing the decoupling of $PM_{2.5}$ emissions from economic development. They found that the emissions coefficient was a significant negative factor, whereas per capita GDP was a major positive driver. Lastly, Wang et al. (2019a) investigated the decoupling of economic growth from energy depletion in China and India by combining the LMDI with the Cobb-Douglas (C-D) function. Their results showed a stronger decoupling effect in China than in India, with energy efficiency being the main driver in China and technological advancement being the key contributor in India.

To promote a green and circular economy, an increasing number of researchers are focusing on decoupling air pollution from economic growth. For instance, Liu et al. (2023) utilized the Tapio and LMDI models to investigate the decoupling relationships between CO_2 emissions and economic development, as well as the driving factors for CO_2 emissions resulting from China's agricultural land use. Their study revealed a shift in the decoupling of CO_2 emissions from a WD state to an SD state. They found that the agricultural economic level significantly stimulated the increase in CO_2 emissions, while CO_2 emission intensity, agricultural structure, and labor force had a mitigating effect. Qian et al. (2020) also applied the Tapio and LMDI methods to analyze the drivers of decoupling states between SO_2 emissions in the industrial sector and economic growth. They demonstrated that the intensity of SO_2 generation and SO_2 reduction were the main drivers of decoupling, while economic activity was the primary inhibitor. In a different approach, Dong et al. (2021) developed a new decoupling model to address the shortcomings of the original version and identified influencing factors using the C-D-Kaya equation. They found that energy structure, energy intensity, and technological advancement significantly impacted the decoupling states between haze emissions and economic prosperity. Yang et al. (2020) used the Tapio and LMDI methods to study variations in residential energy-related CO_2 emissions between urban and rural areas. Their findings indicated that, in terms of emissions, per capita consumption expenditure was the major stimulatory factor, while energy prices were the largest inhibitor. The urban areas experienced a WD state, while the rural areas remained in an expansive negative decoupling (END) state.

Yu and Fang (2021) developed a new decoupling indicator to examine the relationship between $PM_{2.5}$ pollution and economic development. They found that technical factors facilitated decoupling states, while non-technical factors acted as hindrances. In a related study, Fang and Yu (2021) explored the driving factors and decou-

pling effects of industrial $PM_{2.5}$ pollution using a refined Laspeyres index method combined with the LMDI method. Their findings indicated that the $PM_{2.5}$-coal consumption effect and the energy consumption-economic growth effect were the primary drivers of the decoupling indicators. Zhang et al. (2020a) evaluated the decoupling state between $PM_{2.5}$ pollution and economic development in China. They identified that the scale of investment was a major driver, while the structure of investment had a more nuanced impact on facilitating decoupling states. Although these studies made significant contributions by integrating both decoupling and decomposition methods, they did not analyze the driving factors from a two-stage perspective.

2.3. Two-stage decomposition

Following the stage-specific classification of environmental pollution, the volume of SO_2 emissions is defined as the SO_2 generated minus the SO_2 removed (MEE, 2013). This indicates that industrial production activities can be divided into two stages from a pollution control perspective: generation and treatment. Consequently, two pathways exist to alter SO_2 emissions in industrial production: by changing the scale of SO_2 generated or by adjusting the scale of SO_2 removed. Clean production serves as the primary approach to reduce pollution during the generation stage, while end-of-pipe treatment is the main strategy employed during the treatment stage (Wang et al., 2021a). Identifying the key factors that influence both SO_2 generation and removal is crucial, as this understanding can inform the effectiveness of clean production and end-of-pipe treatment strategies.

Hang et al. (2019) identified six drivers of industrial SO_2 emissions by employing a holistic treatment process. Their findings indicated that treatment, followed by process control, was the primary factor in reducing emissions within the industrial sector. Using a two-stage production-theoretical decomposition analysis (PDA), Tian et al. (2022) examined the driving factors of industrial SO_2 emissions in relation to both the generation and treatment stages from the perspectives of technology and efficiency. Wang et al. (2021a) applied a modified two-stage method to assess the effects of generation and treatment on reducing SO_2 emissions in China. They concluded that clean production had emerged as the predominant approach for mitigating SO_2 pollution. By considering different factors at each stage, the accuracy of the results could be improved, leading to more effective and targeted strategies for emissions reduction. Additionally, Wang et al. (2019b) categorized the entire SO_2 emission process into cleaner production and end-of-pipe treatment stages to analyze variations. During the cleaner production stage, SO_2 generation can be reduced by enhancing raw materials, process design, and production technology. In the end-of-pipe treatment stage, further SO_2 removal can be achieved through the implementation of purification facilities.

While these studies address the decoupling and decomposition of environmental emissions, they have several shortcomings. First, the traditional methods used do not differentiate between the decoupling states of the production and treatment processes, specifically DIG and DIT. This lack of distinction hinders the identification of phased decoupling states and presents challenges in focusing on vulnerable stages that could facilitate economic development while reducing pollution emissions. Second, these studies fail to account for the differing impact pathways of factors at various stages. This oversight can lead to biased estimations, potentially misleading decision-makers. Furthermore, the Report of the 19th National Congress emphasizes the need for government policies such as raising pollution discharge standards, enhancing the accountability of polluters, improving environmental credit evaluations, and ensuring mandatory information disclosure. Implementing these policies requires coordinated efforts across both production and treatment processes. Thus, conducting research on decoupling and decomposition in stages is both necessary and urgent, providing more targeted recommendations for policymakers.

To address the limitations of traditional methods, this study in-

vestigates the factors driving the decoupling of industrial SO_2 emissions from economic development. The analysis is conducted in two phases: first, generally, and then focusing on both the generation and treatment stages. This is accomplished by integrating the Tapio decoupling method with the LMDI method, using relevant data from 30 Chinese provinces spanning 2000 to 2020. This study contributes to the literature in two significant ways. First, it introduces a two-stage decoupling measurement model that clarifies the decoupling states of both the generation and treatment stages. This model addresses the shortcomings of traditional methods in examining substage decoupling states, facilitating the implementation of targeted decoupling policies. Second, from this two-stage perspective, this study develops a new decoupling decomposition model. This model incorporates the driving forces from both treatment and generation stages into a unified analytical framework, offering more detailed insights into various decoupling states. These advancements may aid in identifying the reasons behind differing decoupling states at each stage and provide a theoretical foundation for policymakers seeking to enhance the decoupling of SO_2 emissions from economic growth.

3. Methodology

3.1. Overall decoupling and decomposition model

Based on Tapio (2005), we first develop an overall decoupling indicator for SO_2 pollution ($DI^{overall}$) at both the national and regional levels, as represented in Equation (1). This indicator assesses the decoupling relationship between SO_2 emissions and economic development.

$$\text{DI}_{(s,t)}^{overall} = \frac{\left(P_t^e - P_s^e\right)/P_s^e}{\left(Y_t - Y_s\right)/Y_s} = \frac{\Delta P_{(s,t)}^e/P_s^e}{\Delta Y_{(s,t)}/Y_s} \tag{1a}$$

$$\text{DI}_{i(s,t)}^{overall} = \frac{\left(P_{it}^e - P_{is}^e\right)/P_{is}^e}{\left(Y_{it} - Y_{is}\right)/Y_{is}} = \frac{\Delta P_{i(s,t)}^e/P_{is}^e}{\Delta Y_{i(s,t)}/Y_{is}} \tag{1b}$$

In Equation (1), P^e and Y represent SO_2 emissions and GDP, respectively. The variables s and t denote the two different periods, while i ($i = 1,...,n$) indicates different regions. Table 1 displays the classification of the decoupling indicators' status.

Table 1
The status classification of the overall decoupling indicator

Status		Standard		
		$\Delta Y_{(s,t)}$	$\Delta P_{(s,t)}^e$	$DI^{overall}$
Decoupling	Strong decoupling (SD)	> 0	< 0	$DI^{overall} < 0$
	Weak decoupling (WD)	> 0	> 0	$0 < DI^{overall} < 1$
	Recessive decoupling (RD)	< 0	< 0	$DI^{overall} > 1$
Negative decoupling	Strong negative decoupling (SND)	< 0	> 0	$DI^{overall} < 0$
	Weak negative decoupling (WND)	< 0	< 0	$0 < DI^{overall} < 1$
	Expansive negative decoupling (END)	> 0	> 0	$DI^{overall} > 1$

Next, the LMDI method is applied to identify the drivers of the overall decoupling indicator. Equation (2) and Equation (3) illustrate that the national-level overall decoupling indicator can be divided into three factors: SO_2 emission intensity (*SEI*), energy intensity (*EI*), and economic scale (*ES*).

$$\begin{aligned}
\Delta P_{(s,t)}^e &= \sum_{i=1}^{n} P_{it}^e - \sum_{i=1}^{n} P_{is}^e = \sum_{i=1}^{n} \frac{P_{it}^e}{E_{it}} \times \frac{E_{it}}{Y_{it}} \times Y_{it} - \sum_{i=1}^{n} \frac{P_{is}^e}{E_{is}} \times \frac{E_{is}}{Y_{is}} \times Y_{is} \\
&= \sum_{i=1}^{n} \text{SEI}_{it} \times \text{EI}_{it} \times \text{ES}_{it} - \sum_{i=1}^{n} \text{SEI}_{is} \times \text{EI}_{is} \times \text{ES}_{is} \\
&= \Delta\text{SEI}_{(s,t)} + \Delta\text{EI}_{(s,t)} + \Delta\text{ES}_{(s,t)}
\end{aligned} \tag{2}$$

$$\begin{aligned}
\text{DI}_{(s,t)}^{overall} &= \frac{\Delta P_{(s,t)}^e/P_s^e}{\Delta Y_{(s,t)}/Y_s} = \delta \times \Delta P_{(s,t)}^e \\
&= \delta \times \Delta\text{SEI}_{(s,t)} + \delta \times \Delta\text{EI}_{(s,t)} + \delta \times \Delta\text{ES}_{(s,t)} \\
&= \Delta\text{SEI}_{(s,t)}^* + \Delta\text{EI}_{(s,t)}^* + \Delta\text{ES}_{(s,t)}^*
\end{aligned} \tag{3}$$

In Equation (3), E_i represents the energy consumption of each region. The parameter δ is defined as the scaling factor, equal to $Y_s/\left(\Delta Y_{(s,t)} \times P_s^e\right)$. The LMDI method is then applied to calculate the effect of each driving factor, as expressed in Equation (4).

$$\Delta\text{SEI}_{(s,t)}^* = \delta \times \sum_{i=1}^{n} \frac{P_{it}^e - P_{is}^e}{\ln\left(P_{it}^e/P_{is}^e\right)} \times \ln\left(\frac{\text{SEI}_{it}}{\text{SEI}_{is}}\right) \tag{4a}$$

$$\Delta\text{EI}_{(s,t)}^* = \delta \times \sum_{i=1}^{n} \frac{P_{it}^e - P_{is}^e}{\ln\left(P_{it}^e/P_{is}^e\right)} \times \ln\left(\frac{\text{EI}_{it}}{\text{EI}_{is}}\right) \tag{4b}$$

$$\Delta\text{ES}_{(s,t)}^* = \delta \times \sum_{i=1}^{n} \frac{P_{it}^e - P_{is}^e}{\ln\left(P_{it}^e/P_{is}^e\right)} \times \ln\left(\frac{\text{ES}_{it}}{\text{ES}_{is}}\right) \tag{4c}$$

At the regional level, Equation (5) is used to calculate the effects of each driving factor.

$$\Delta\text{SEI}_{i(s,t)}^* = \delta_i \times \frac{P_{it}^e - P_{is}^e}{\ln\left(P_{it}^e/P_{is}^e\right)} \times \ln\left(\frac{\text{SEI}_{it}}{\text{SEI}_{is}}\right) \tag{5a}$$

$$\Delta\text{EI}_{i(s,t)}^* = \delta_i \times \frac{P_{it}^e - P_{is}^e}{\ln\left(P_{it}^e/P_{is}^e\right)} \times \ln\left(\frac{\text{EI}_{it}}{\text{EI}_{is}}\right) \tag{5b}$$

$$\Delta\text{ES}_{i(s,t)}^* = \delta_i \times \frac{P_{it}^e - P_{is}^e}{\ln\left(P_{it}^e/P_{is}^e\right)} \times \ln\left(\frac{\text{ES}_{it}}{\text{ES}_{is}}\right) \tag{5c}$$

When the economy is growing (or in a recession), if the effect of one factor on the overall decoupling indicator is less than zero, the factor contributes to (or hinders) DEI. If the effect of one factor on the overall decoupling indicator is equal to zero, the factor does not influence DEI. If the effect of one factor on the overall decoupling indicator is greater than zero, the factor hinders (or contributes to) DEI.

3.2. Generation-stage decoupling and decomposition model

The results of traditional decoupling and decomposition methods may be biased because they fail to account for the differences in impact pathways of factors at various stages (Wang et al., 2021a). For instance, EI influences the generation volume of industrial SO_2 but does not affect its emission volume. Directly decomposing the factors of DEI into EI may lead to biased estimations, potentially misleading decision-makers. Additionally, previous studies have not explored the subdivision factors within these two stages. Traditional methods can only assess the impact of a single factor on pollution emissions during the treatment stage. However, the effectiveness of treatment in reducing pollution emissions is influenced by various factors, including the efficiency and strength of the treatment processes. Consequently, traditional methods cannot provide a targeted direction for improving DIG and DIT.

To address these shortcomings and further investigate the decoupling status and decomposition factors of SO_2 pollution, we construct two substage decoupling indicators. In the generation stage, the substage decoupling indicators at the national and regional levels are defined in Equation (6), which reflects the decoupling status between the generated SO_2 pollution and economic development.

$$\text{DI}_{(s,t)}^{generation} = \frac{\left(P_t^g - P_s^g\right)/P_s^g}{\left(Y_t - Y_s\right)/Y_s} = \frac{\Delta P_{(s,t)}^g/P_s^g}{\Delta Y_{(s,t)}/Y_s} \tag{6a}$$

$$\mathrm{DI}_{i(s,t)}^{generation} = \frac{\left(P_{it}^g - P_{is}^g\right)/P_{is}^g}{\left(Y_{it} - Y_{is}\right)/Y_{is}} = \frac{\Delta P_{i(s,t)}^g/P_{is}^g}{\Delta Y_{i(s,t)}/Y_{is}} \tag{6b}$$

In Equation (6), P^g represents SO$_2$ generation, rather than the final SO$_2$ emissions. The classification of the decoupling indicators in the generation stage is similar to that of the overall decoupling indicators (Table 2).

Table 2
The status classification of the decoupling indicators in the generation stage

Status		Standard		
		$\Delta Y_{(s,t)}$	$\Delta P_{(s,t)}^g$	DI^{generation}
Decoupling	SD	>0	<0	DI$^{production} < 0$
	WD	>0	>0	$0 < DI^{production} < 1$
	RD	<0	<0	DI$^{production} > 1$
Negative decoupling	SND	<0	>0	DI$^{production} < 0$
	WND	<0	<0	$0 < DI^{production} < 1$
	END	>0	>0	DI$^{production} > 1$

To identify the drivers of the decoupling indicators in the generation stage, Equation (7) and Equation (8) illustrate that the national-level decoupling indicator for the generation stage can be decomposed into three factors: pollution intensity (PI), EI, and ES.

$$\Delta P_{(s,t)}^g = \sum_{i=1}^n P_{it}^g - \sum_{i=1}^n P_{is}^g = \sum_{i=1}^n \frac{P_{it}^g}{E_{it}} \times \frac{E_{it}}{Y_{it}} \times Y_{it} - \sum_{i=1}^n \frac{P_{is}^g}{E_{is}} \times \frac{E_{is}}{Y_{is}} \times Y_{is}$$
$$= \sum_{i=1}^n \mathrm{PI}_{it} \times \mathrm{EI}_{it} \times \mathrm{ES}_{it} - \sum_{i=1}^n \mathrm{PI}_{is} \times \mathrm{EI}_{is} \times \mathrm{ES}_{is} \tag{7}$$
$$= \Delta\mathrm{PI}_{(s,t)} + \Delta\mathrm{EI}_{(s,t)} + \Delta\mathrm{ES}_{(s,t)}$$

$$\mathrm{DI}_{(s,t)}^{generation} = \frac{\Delta P_{(s,t)}^g/P_s^g}{\Delta Y_{(s,t)}/Y_s} = \alpha \times \Delta P_{(s,t)}^g$$
$$= \alpha \times \Delta\mathrm{PI}_{(s,t)} + \alpha \times \Delta\mathrm{EI}_{(s,t)} + \alpha \times \Delta\mathrm{ES}_{(s,t)} \tag{8}$$
$$= \Delta\mathrm{PI}_{(s,t)}^* + \Delta\mathrm{EI}_{(s,t)}^* + \Delta\mathrm{ES}_{(s,t)}^*$$

In Equation (8), the parameter α is defined as the scaling factor, equal to $Y_s/\left(\Delta Y_{(s,t)} \times P_s^g\right)$. The calculation of weight coefficients for the generation stage is detailed in the Supplementary Materials.

3.3. Treatment-stage decoupling and decomposition model

For the treatment stage, this study focuses on the decoupling status of SO$_2$ removal and SO$_2$ generation rather than economic development. This focus is due to the close relationship between end-of-pipe treatment and SO$_2$ generation. The decoupling indicators in the treatment stage at the national and regional levels are defined in Equation (9), where P^r represents the SO$_2$ removed from the treatment facility. Table 3 presents the classification of the decoupling indicators in the treatment stage.

$$\mathrm{DI}_{(s,t)}^{treatment} = \frac{\left(P_t^r - P_s^r\right)/P_s^r}{\left(P_t^g - P_s^g\right)/P_s^g} = \frac{\Delta P_{(s,t)}^r/P_s^r}{\Delta P_{(s,t)}^g/P_s^g} \tag{9a}$$

$$\mathrm{DI}_{i(s,t)}^{treatment} = \frac{\left(P_{it}^r - P_{is}^r\right)/P_{is}^r}{\left(P_{it}^g - P_{is}^g\right)/P_{is}^g} = \frac{\Delta P_{i(s,t)}^r/P_{is}^r}{\Delta P_{i(s,t)}^g/P_{is}^g} \tag{9b}$$

Equation (10) and Equation (11) illustrate that the national-level decoupling indicator in the treatment stage can be decomposed into three factors: treatment efficiency (TE), treatment intensity (TI), and pollution generation scale (PS).

Table 3
The status classification of the decoupling indicator in the treatment stage

Status		Standard		
		$\Delta P_{(s,t)}^r$	$\Delta P_{(s,t)}^g$	DI^{treatment}
Negative decoupling	SND	<0	>0	DI$^{treatment} < 0$
	WND	>0	>0	$0 < DI^{treatment} < 1$
	Recessive negative decoupling (RND)	<0	<0	DI$^{treatment} > 1$
Decoupling	SD	>0	<0	DI$^{treatment} < 0$
	WD	<0	<0	$0 < DI^{treatment} < 1$
	Expansive decoupling (ED)	>0	>0	DI$^{treatment} > 1$

$$\Delta P_{(s,t)}^r = \sum_{i=1}^n P_{it}^r - \sum_{i=1}^n P_{is}^r = \sum_{i=1}^n \frac{P_{it}^r}{T_{it}} \times \frac{T_{it}}{P_{it}^g} \times P_{it}^g - \sum_{i=1}^n \frac{P_{is}^r}{T_{is}} \times \frac{T_{is}}{P_{is}^g} \times P_{is}^g$$
$$= \sum_{i=1}^n \mathrm{TE}_{it} \times \mathrm{TI}_{it} \times \mathrm{PS}_{it} - \sum_{i=1}^n \mathrm{TE}_{is} \times \mathrm{TI}_{is} \times \mathrm{PS}_{is} \tag{10}$$
$$= \Delta\mathrm{TE}_{(s,t)} + \Delta\mathrm{TI}_{(s,t)} + \Delta\mathrm{PS}_{(s,t)}$$

$$\mathrm{DI}_{(s,t)}^{treatment} = \frac{\Delta P_{(s,t)}^r/P_s^r}{\Delta P_{(s,t)}^g/P_s^g} = \beta \times \Delta P_{(s,t)}^r$$
$$= \beta \times \Delta\mathrm{TE}_{(s,t)} + \beta \times \Delta\mathrm{TI}_{(s,t)} + \beta \times \Delta\mathrm{PS}_{(s,t)} \tag{11}$$
$$= \Delta\mathrm{TE}_{(s,t)}^* + \Delta\mathrm{TI}_{(s,t)}^* + \Delta\mathrm{PS}_{(s,t)}^*$$

In Equation (12), T_i represents the treatment facilities in each region. The parameter β is a scaling factor, which is equal to $P_s^g/\left(\Delta P_{(s,t)}^g \times P_s^r\right)$ in Equation (11). To save space, the detailed calculation process is provided in the Supplementary Materials.

3.4. Data sources

This study investigates the state of decoupling and the drivers of SO$_2$ pollution from 2000 to 2020. The input-output indicators include SO$_2$ emissions in the industrial sector, SO$_2$ generated in the industrial sector, SO$_2$ removed in the industrial sector, GDP, energy expenditure, and treatment facilities. The GDP data were sourced from the *China Statistics Yearbook*, while data on SO$_2$ pollution levels and treatment facilities were obtained from the *China Environment Statistics Yearbook* and the *China Environment Yearbook*. Energy consumption data were estimated based on the *China Energy Statistics Yearbook*. GDP was converted to 2000 constant prices. Descriptive statistics for the samples are presented in Table 4. Data for the three indicators—SO$_2$ generated, SO$_2$ removed, and treatment equipment—in 2020 are missing, as official statistical agencies no longer disclose these figures. This limitation should be noted. The minimum values for SO$_2$ removal and treatment equipment are both zero because Qinghai Province did not implement end-of-pipe treatment of industrial SO$_2$ before 2005.

4. Results and discussion

4.1. Overall decoupling analysis

4.1.1. National-level overall decoupling and decomposition analysis

Figure 2 shows DEI in China from 2000 to 2020. Overall, DEI at the national level transitioned from a WD status during the 10th Five-Year Plan (FYP) to an SD status in the 11th FYP, maintaining stability during the 12th FYP. Subsequently, it experienced a sharp decline during the 13th FYP, with the decoupling index decreasing by four times. This decline aligns with significant efforts made to reduce pollution in sectors such as thermal power, iron and steel, non-ferrous metals, cement, paper making, chemicals, brewing, and printing and dyeing (Hang et al., 2021).

From the perspective of driving factors (Figure 3), the index expe-

Table 4
Descriptive statistics of input-output indicators

Indicators	Number	Unit	Min	Max	Mean	Std.
SO_2 generated	120	ton	23 233	7 075 696	1 403 028	1 151 854
SO_2 removed	120	ton	0	5 854 759	812 000.1	954 176.3
SO_2 emission	150	ton	988	1 715 000	489 664.6	392 884.4
Treatment equipment	120	set	0	4 123	799.308 3	835.997
GDP	150	10^8 yuan	300.95	64 570.98	11 650.81	12 441.79
Energy	150	10^4 ton	207.82	35 242.6	8 080.977	6 732.171
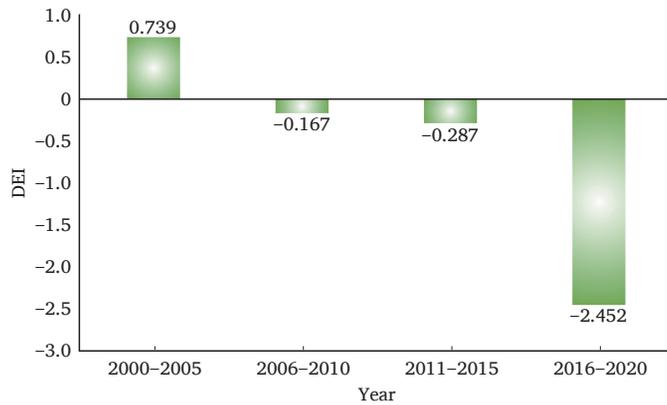
Figure 2. Status of DEI at the national level from 2000 to 2020
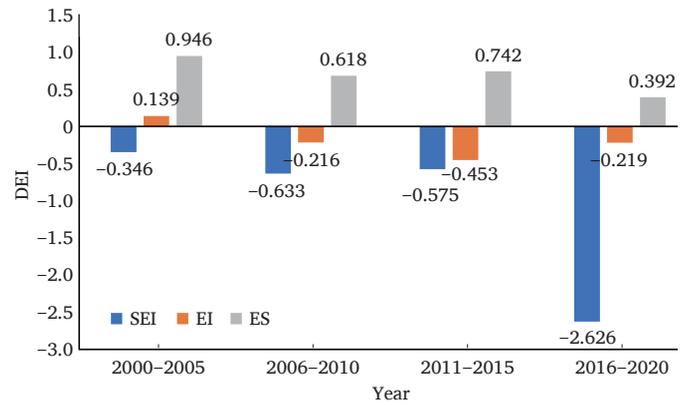
Figure 3. Driving factors of DEI at the national level from 2000 to 2020
*Notes*: SEI = SO_2 emission intensity; EI = energy intensity; ES = economic scale.

rienced a sharp decline during the 13th FYP, while ES consistently hindered progress throughout the years. This trend aligns with China's sustained rapid economic growth. According to the China Statistical Yearbook, China's GDP rose from 10.03 trillion yuan in 2000 to 101.36 trillion yuan in 2020, reflecting an average growth rate of 45.5%. The primary factor improving DEI was SEI, which triggered decoupling in the 10th FYP with an index value of −0.346.By the end of 2020, this index had decreased six-fold, reflecting an annual decline rate of 32.9%. Initially, EI impeded decoupling with an index of 0.139 in the 10th FYP, but it began to accelerate decoupling from 2005 onward, although its positive impact diminished during the 13th FYP. This pattern is consistent with findings from Wu and Zeng (2013), Yang et al. (2016), and Chang et al. (2018), who noted that EI initially increased SO_2 emissions between 2000 and 2005 before contributing to emission reductions with a declining trend. One reason for this may be the influx of low-quality coal in China's coal market in recent years (Wang et al., 2021b). For instance, by 2015, low-quality lignite coal accounted for a quarter of all coal imports into China (Cai and Hu, 2022).

4.1.2. Provincial-level overall decoupling and decomposition analysis

To further investigate the decoupling states among provinces, this study classifies the 30 provinces into three groups[②]: 17 provinces in the WD group, 12 provinces in the END group, and Beijing in the SD group. Figure 4 illustrates that after the 10th FYP period, Beijing led all provinces in terms of the SD state of DEI. Subsequently, the SD state of DEI continued to strengthen, with indicators consistently decreasing. This trend is linked to Beijing's unique political and economic status, which benefits from strong policy and resource support, enhancing its economic development and pollution management. As a result, Beijing has taken the lead in decoupling SO_2 emissions from economic growth. Other provinces also experienced improvements in their decoupling states; however, differences in economic growth lev-

els, SO_2 emissions, and treatment capacities led to varied decoupling states across the provinces.

As shown in Figure 4, for provinces in the WD group from 2000 to 2020, DEI initially remained in the WD state. After entering the 11th FYP, nearly all provinces transitioned to the SD state, with the exception of Hainan (0.33). During the 12th FYP, the decoupling indices showed no significant changes. However, in the 13th FYP, the decoupling indices experienced a sharp decline, resulting in significant improvements in the SD state. Notably, Hainan, which had previously remained in the WD state, also entered the SD group with an index of −0.245.
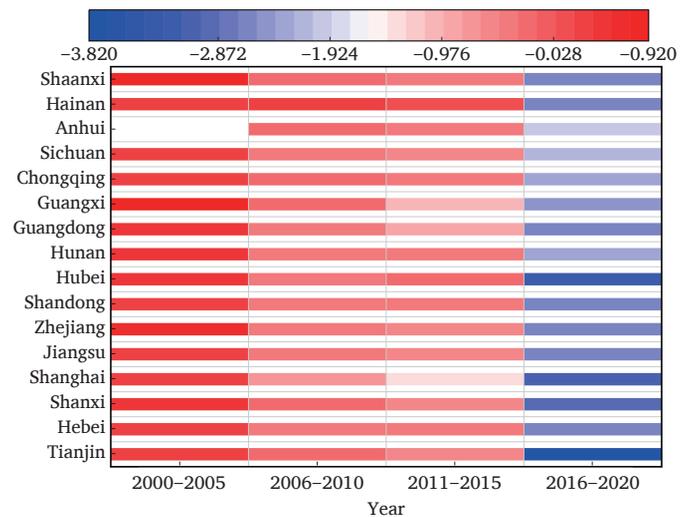
Figure 4. Provincial DEI values in the WD group between 2000 and 2020

---

②SD group: Beijing; WD group: Tianjin, Hebei, Shanxi, Shanghai, Jiangsu, Zhejiang, Shandong, Hubei, Hunan, Guangdong, Guangxi, Chongqing, Sichuan, Anhui, Hainan, Guizhou, Shaanxi; END group: Inner Mongolia, Liaoning, Jilin, Heilongjiang, Fujian, Jiangxi, Henan, Yunnan, Gansu, Ningxia, Xinjiang, Qinghai.

When examining the driving factors behind the improvement in decoupling states, SEI consistently served as a strengthening stimulator. As shown in Table 5, during the 10th FYP, SEI had a positive impact across most provinces, except in Anhui. Shaanxi and Hebei experienced the largest positive effects, with values of −1.61 and −1.04, respectively. In the 11th FYP, SEI values declined in nine provinces, particularly in Shanghai, Guangxi, and Chongqing. During the 12th FYP, SEI values remained stable. However, in the 13th FYP, these values sharply declined to one-third of those in the 12th FYP, exerting a more significant positive effect on DEI. Regarding EI, it initially hindered decoupling in ten provinces during the 10th FYP. In the 11th FYP, EI began to positively influence decoupling in nearly all provinces, except for Hainan (0.04). During the 12th FYP, EI values continued to decline, with Hunan, Guangdong, and Hubei leading this trend. However, in the 13th FYP, the overall declining trend stagnated, and 13 provinces, including Hebei, Shanxi, Zhejiang, and Shandong, experienced slight increases in their EI values. As for ES, it initially had a negative effect on DEI, with an average value of nearly 1 in the 10th FYP. During the 11th and 12th FYPs, the average values were 0.67 and 0.69, respectively. In the 13th FYP, the average value declined to 0.37, indicating a weakened negative effect on DEI. Overall, although the positive effects of EI on DEI diminished, SEI remained dominant, and the negative impact of ES lessened, collectively promoting DEI toward a stronger SD state.

As shown in Figure 5, for provinces in the END group from 2000 to 2020, DEI initially remained in the END state. In the 11th FYP, the decoupling states improved (9SD + 3WD); in the 12th FYP, decoupling indices increased, with 7 provinces transitioning to the WD state. However, in the 13th FYP, the decoupling indices experienced a sharp drop, leading to significant improvement, as all provinces entered the SD state.

As shown in Table 6, SEI initially acted as an inhibitor in the 10th FYP. Its values fell below zero starting in the 11th FYP, and during the 12th FYP, its positive effect on DEI weakened, with two provinces—Jilin and Yunnan—experiencing a negative effect. In the 13th FYP, SEI values dropped sharply. Regarding EI, it initially hindered decoupling, as approximately nine provinces had elastic values above 0 in the 10th FYP. By the 11th FYP, EI began to positively influence decoupling in nearly all provinces, except for Qinghai (0.17). In the 12th FYP, EI values continued to decline, led by Jilin, Liaoning, and Henan. However, in the 13th FYP, the overall declining trend stagnated, with 13 provinces, including Inner Mongolia, Liaon-

ing, and Ningxia, showing a slight increase in EI values. As for ES, it initially had a strong negative effect on DEI, with an average value of 1.18 in the 10th FYP. During the 11th and 12th FYPs, the average values remained at 0.72 and 0.77, respectively. In the 13th FYP, the average value declined to 0.43, indicating a weakened negative effect on DEI.

4.2. Generation-stage decoupling and decomposition

4.2.1. National-level generation decoupling and decomposition analysis

Since the status of DEI is influenced by both DIG and DIT, this study analyzes the decoupling status and relevant drivers from both the generation and treatment stages to identify pathways for decoupling SO_2 pollution emissions from economic growth.

According to Equation (2), decoupling states are calculated during the generation stage. As shown in Figure 6, DIG exhibited a downward trend throughout the research period, increasingly contributing to the improvement of DEI. In the 11th FYP, DIG had a value of 0.70, reflecting a 27.3% decrease compared to the 10th FYP. This downward trend continued in the 12th FYP, with a decrease of 43.6%. DIG demonstrated a smoother and sharper decline compared to DEI, which exhibited a more moderate downward trend during the 11th and 12th FYPs.

As shown in Figure 7, PI initially had a positive effect on DIG. However, starting in the 11th FYP, its effect turned negative, with a value of 0.08, and it remained at 0.04 in the 13th FYP. In contrast, EI initially hindered DIG but began to improve decoupling in the 11th FYP, achieving a value of −0.30. By the 13th FYP, this value declined further to − 0.55, indicating a larger positive effect on DIG. Meanwhile, the ES index remained stable with a steady negative effect, averaging approximately 0.9.

The impacts of EI and ES on DIG differed significantly from their effects on DEI. Although the impact of EI on both DEI and DIG remained consistent, their specific effect values had notable differences. In the case of ES, its effect value on DEI exhibited a fluctuating downward trend, while it remained steady at approximately 0.9 for DIG. This indicates the necessity of separating the decoupling and decomposition processes into two distinct stages for more accurate results and recommendations.

4.2.2. Provincial-level generation decoupling and decomposition analysis

When analyzed from a two-stage perspective, the DIG of the WD

Table 5
Provincial driving factors of DEI in the WD group between 2000 and 2020

| Provinces	2000–2005			2006–2010			2011–2015			2016–2020		
	SEI	EI	ES	SEI	EI	ES	SEI	EI	ES	SEI	EI	ES
Tianjin	−0.28	−0.25	0.83	−0.58	−0.15	0.64	−0.62	−0.37	0.62	−3.69	−0.43	0.30
Hebei	−1.04	0.48	0.86	−0.79	−0.17	0.66	−0.66	−0.41	0.74	−2.69	−0.15	0.38
Shanghai	−0.32	−0.08	0.88	−0.42	−0.40	0.75	−0.74	−0.45	0.73	−3.07	−0.06	0.38
Jiangsu	−0.10	−0.36	0.88	−0.92	−0.28	0.59	−1.25	−0.55	0.59	−2.77	−0.54	0.28
Zhejiang	−0.94	0.41	0.84	−0.70	−0.20	0.63	−0.79	−0.27	0.70	−2.44	−0.35	0.37
Hubei	−0.41	0.21	0.94	−0.64	−0.30	0.66	−0.69	−0.46	0.73	−2.65	−0.09	0.33
Hunan	−0.63	0.11	0.84	−0.60	−0.27	0.65	−0.56	−0.39	0.74	−2.77	−0.14	0.36
Guangdong	−0.29	−0.05	0.93	−0.62	−0.21	0.65	−0.19	−0.68	0.73	−2.92	−0.57	0.36
Guangxi	−0.94	0.60	0.92	−0.56	−0.29	0.65	−0.19	−0.79	0.70	−2.14	−0.38	0.35
Chongqing	−0.47	0.10	0.89	−0.72	−0.21	0.65	−0.51	−0.83	0.66	−2.81	−0.06	0.39
Sichuan	−0.08	−0.02	0.98	−0.71	−0.10	0.66	−1.10	−0.32	0.54	−2.63	−0.06	0.44
Anhui	−0.11	−0.40	0.88	−0.72	−0.08	0.64	−0.40	−0.54	0.63	−2.06	−0.41	0.34
Hainan	−0.50	0.01	0.88	−0.90	0.04	0.65	−0.75	−0.39	0.63	−1.83	−0.57	0.42
Guizhou	0.46	−0.52	0.99	−0.45	−0.31	0.70	−0.59	−0.33	0.71	−1.98	−0.24	0.45
Shaanxi	−1.61	1.03	0.87	−0.25	−0.24	0.82	−0.55	−0.06	0.84	−2.53	−0.33	0.42
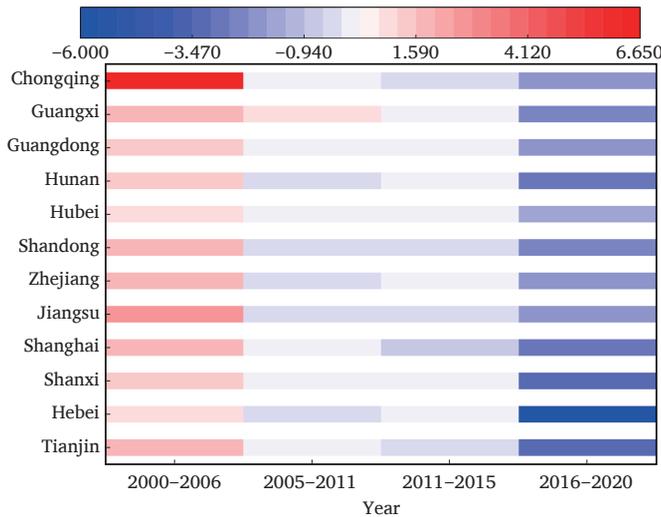
Figure 5. Provincial DEI values in the END group between 2000 and 2020

group evolved from "13WD + 4END" to "8SD + 9WD", further enhancing the DEI state (Table 7). Specifically, the DIG in Zhejiang, Hunan, and Anhui transitioned from being in the END state during the 10th FYP to the WD state in the 12th FYP, with Zhejiang achieving an SD state. This improvement in DIG also contributed to DEI reaching an SD state later on. From the perspective of driving factors, EI was the primary promoter of DIG. As shown in Figure 7, the elasticity values of EI were below zero in only seven provinces during the 10th FYP, where it exerted an impeding effect on DIG, resulting in an average value of 0.086.

As shown in Figure 8, by the 12th FYP, the elasticity values of EI for all provinces fell below zero, indicating a shift to a positive effect, with an average value of −0.55. The most significant changes occurred in Hunan and Guangdong, where EI values decreased from 0.91 to −0.88 in Hunan and from 0.12 to −1.07 in Guangdong. Additionally, PI fluctuated during the 11th FYP, with the average elasticity value rising from −0.24 to 0.31. For instance, the PI values in Shanxi, Jiangsu, Shandong, Guangzhou, Hainan, and Shaanxi varied from zero to below zero. However, during the 12th FYP, the average elasticity value dropped to 0.01, with significant reductions observed in Zhejiang and Chongqing, thus decreasing its impeding influence on DIG. Consequently, the improvement in EI significantly countered the negative effects of ES, allowing DIG to move steadily toward the SD state.

The DIG of the END group evolved from "8END + 4WD" to "2END + 10WD", further enhancing the DEI state (Table 8). Specifically, DIG in Heilongjiang, Fujian, Henan, Yunnan, Ningxia, and Qinghai transitioned from the END state in the 10th FYP to the WD state in the 12th FYP. From the perspective of driving factors, EI was the primary promoter of DIG. As shown in Figure. 8, the elasticity values of EI were below zero in only three provinces during the 10th FYP, indicating an impeding effect on DIG, with an average value of 0.41.

As shown in Figure 8, by the 12th FYP, the elasticity values of EI for the eight provinces were below zero, indicating a shift to a positive effect with an average value of −0.23. Jilin and Qinghai exhibited the most notable changes, with EI values dropping from 0.06 to −0.88 in Jilin and from 0.53 to −0.59 in Qinghai. Additionally, PI experienced a subtle change during the 11th FYP, with the average elasticity value decreasing from −0.54 to −0.47. However, in the 12th FYP, the average elasticity value sharply fell to −2.92, particularly in Inner Mongolia and Liaoning, which saw significant reductions. This decrease diminished the negative influence on DIG. Consequently, the improvement in EI effectively countered the adverse effects of ES, guiding DIG in the END group steadily toward a better WD state.

4.3. Treatment-stage decoupling and decomposition

4.3.1. National-level treatment decoupling and decomposition analysis

According to Equation (3), the decoupling states are calculated during the treatment stage. Figure. 9 shows that DIT during the research period followed a trend of first increasing and then decreasing, exerting a fluctuating negative effect on DEI. In the 11th FYP, the DIT value was 3.46, representing a 114.2% increase compared to the 10th FYP. However, by the 13th FYP this value decreased to 1.97, marking a reduction of 43.0%. The decline of DIT in the 11th FYP directly impacted DEI, which remained stagnant despite improvements in DIG. However, progress in the 12th FYP, combined with the advantages of DIG, advanced DEI into a more favorable SD state.

As shown in Figure 10, both TE and TI exhibited an inverted triangular trend with a positive effect on DIT. The key difference is that TE increased more sharply than TI. Its value dropped from −0.70 in the 10th FYP to −2.83 in the 11th FYP, a decrease of nearly three times. However, by the 13th FYP, TE rebounded to −1.02, nearly matching TI's value during this period. In contrast, TI's trend is milder, showing both upward and downward movements with a change rate of less than 30%, yet it consistently supported DIT. Regarding PS, it initially rose in the 11th FYP, increasing three-

Table 6
Provincial driving factors of DEI in the END group between 2000 and 2020

Provinces	2000–2005			2006–2010			2011–2015			2016–2020		
	SEI	EI	ES	SEI	EI	ES	SEI	EI	ES	SEI	EI	ES
Inner Mongolia	0.48	0.02	1.18	−0.49	−0.20	0.63	−0.72	−0.19	0.74	−4.32	0.54	0.46
Liaoning	0.18	−0.14	1.01	−0.64	−0.15	0.67	−0.12	−0.68	0.83	−6.45	0.04	0.43
Jilin	0.09	0.06	1.03	−0.40	−0.31	0.68	0.01	−0.80	0.79	−2.97	−0.88	0.42
Heilongjiang	1.47	−0.73	1.15	−0.31	−0.47	0.73	−0.73	−0.60	0.67	−2.82	−0.50	0.53
Fujian	0.21	1.07	1.27	−0.60	−0.19	0.67	−0.61	−0.37	0.69	−2.07	−0.30	0.41
Jiangxi	0.71	0.04	1.18	−0.76	−0.09	0.67	−0.53	−0.14	0.81	−1.93	−0.32	0.39
Henan	0.01	0.50	1.12	−0.74	−0.16	0.65	−0.32	−0.75	0.70	−2.49	−0.41	0.29
Yunnan	−0.97	1.00	1.01	−0.46	−0.26	0.75	0.10	−0.66	0.83	−1.94	−0.10	0.47
Gansu	−0.06	0.25	1.04	−0.63	−0.26	0.71	−0.28	−0.45	0.78	−2.83	−0.34	0.38
Ningxia	1.43	−1.04	1.09	−0.65	−0.14	0.71	−0.64	−0.04	0.82	−2.56	0.08	0.44
Xinjiang	−2.75	3.36	1.12	0.00	−0.19	0.95	−0.91	0.37	0.84	−2.71	0.00	0.43
Qinghai	4.18	0.53	1.92	−0.77	0.17	0.79	−0.83	−0.07	0.72	−1.90	−0.59	0.52

fold, aligning with the trend of DIT (which declined in the 11th FYP). Subsequently, PS fell in the 13th FYP, resulting in a less negative impact on DIT.
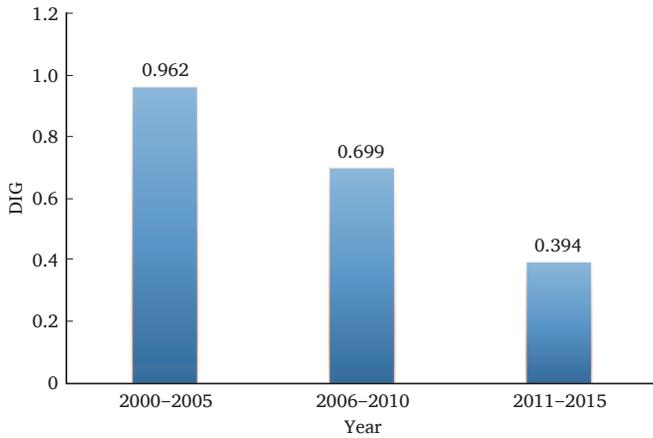

Figure 6. Status of DIG at the national level from 2000 to 2015
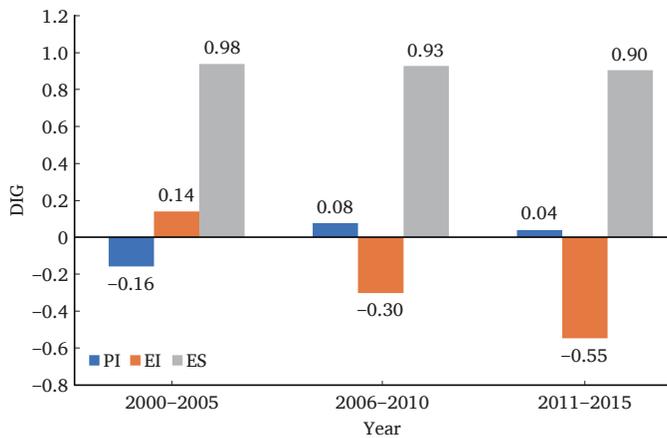

Figure 7. Driving factors of DIG at the national level from 2000 to 2015
Notes: PI = pollution intensity; EI = energy intensity; ES = economic scale.

4.3.2. Provincial-level treatment decoupling and decomposition

Regarding DIT, the WD group displays a trend of first improving and then decreasing. In the 10th FYP, as shown in Table 9, the DIT status was unsatisfactory (16ED + 1WND). This was primarily due to China's focus on increasing infrastructure construction to mitigate the adverse effects of the Asian financial crisis in 1997, which limited treatment input and further restricted the development of treatment capacity. During the 11th FYP, seventeen provinces were in a WD state concerning DIT. Despite DIG remaining unchanged, improvements in DEI (16SD + 1WD) during this period were driven by the enhancement of DIT. By the 12th FYP, the overall DIT declined, with 11 provinces experiencing negative decoupling (ND) states. For instance, in Hebei, the implementation of the "Coordinated Development Strategy of Beijing-Tianjin-Hebei Urban Agglomeration" in 2014 led to the transfer of more than 300 energy-intensive and high-pollution enterprises from Beijing to Hebei, significantly increasing the treatment load (Wu and Zeng, 2013).

Considering the driving factors, the primary driver of improved DIT during the 11th FYP was the increased TE, which saw its average elasticity value decrease from −0.47 to −3.61 (Figure 11). Specifically, the TE indicators for Sichuan and Shaanxi dropped from −0.21 to −10.79 and from −0.12 to −10.79, respectively. This aligns with findings from He (2010) and Zhang (2013), who indicated that the

Table 7
DIG in the WD group from 2000 to 2015

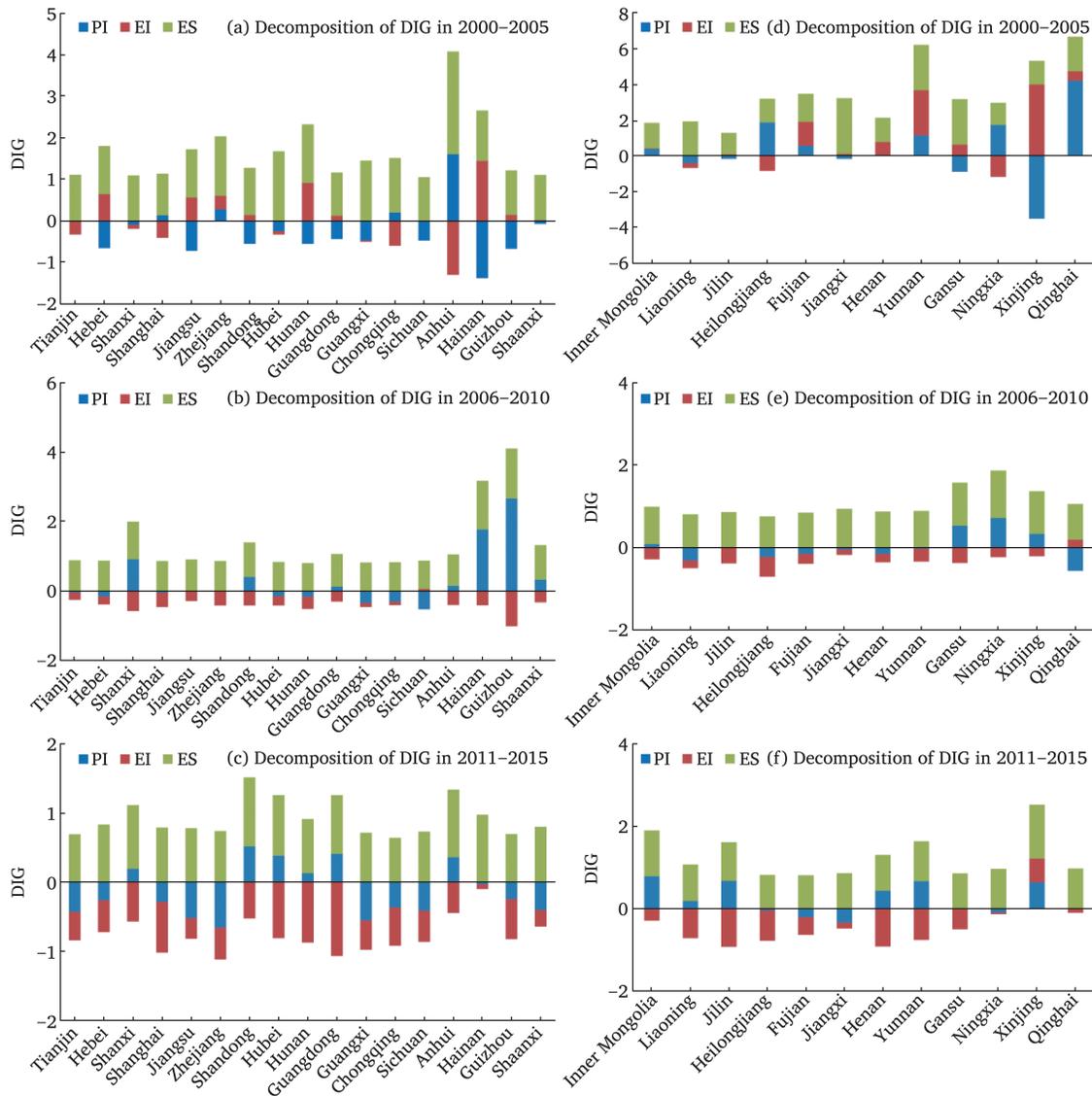| Provinces	2000–2005		2006–2010		2011–2015	
	DIG		DIG		DIG	
	Value	Status	Value	Status	Value	Status
Tianjin	0.66	WD	0.63	WD	−0.15	SD
Hebei	0.99	WD	0.49	WD	0.11	WD
Shanxi	0.78	WD	1.42	END	0.54	WD
Shanghai	0.68	WD	0.40	WD	−0.23	SD
Jiangsu	0.83	WD	0.62	WD	−0.04	SD
Zhejiang	1.60	END	0.44	WD	−0.38	SD
Shandong	0.58	WD	0.98	WD	0.99	WD
Hubei	0.77	WD	0.41	WD	0.45	WD
Hunan	1.32	END	0.28	WD	0.04	WD
Guangdong	0.64	WD	0.76	WD	0.19	WD
Guangxi	0.60	WD	0.35	WD	−0.27	SD
Chongqing	0.65	WD	0.42	WD	−0.28	SD
Sichuan	0.50	WD	0.35	WD	−0.13	SD
Anhui	1.16	END	0.65	WD	0.89	WD
Hainan	1.06	END	2.76	END	0.87	WD
Guizhou	0.46	WD	3.09	END	−0.13	SD
Shaanxi	0.94	WD	0.99	WD	0.16	WD

Notes: WD = weak decoupling status; SD = strong decoupling status; END = expansive negative decoupling status.

TE for SO$_2$ ranked highest in the western region, followed by the eastern and central areas. Additionally, the average elasticity value of PS decreased from −0.49 to −1.63, which enhanced its stimulatory effect on DIT. In the 12th FYP, however, the average elasticity value of TE increased from −3.61 to −1.50, reducing its positive impact on DIT. Notably, the TE for Shanghai rose from −0.24 to 16.26, while Guangxi's TE increased from 0.22 to 0.64, as shown in Figure 11. Consequently, DIT in these two provinces shifted from WD to SND. Similar findings were reported by Hang et al. (2019), who noted that while many provinces made stronger treatment inputs in the 12th FYP, they achieved lower TE. Overall, the conclusion is that DIT generally decreased during this period due to the slow growth in TE.

As shown in Table 10, DIT in the END group first improved and then decreased. In the 11th FYP, all provinces in the END group experienced WD, except for Qinghai, which had a decoupling indicator of zero due to a lack of treatment data. Correspondingly, DEI during this period reached SD in most provinces, with the exceptions of Yunnan, Xinjiang, and Qinghai. This outcome is closely linked to the improved DIT states. However, in the 12th FYP, DIT decreased again, as Fujian, Jiangxi, Gansu, Xinjiang, and Qinghai entered the RND state, which impeded DEI correspondingly. As shown in Figure 11, the TE effect improved, with the average elasticity value decreasing from −0.60 to −3.60, enhancing its stimulatory effect on DIT. Thus, although the PS effect remained unchanged and the TI effect decreased, the significant improvement in TE mitigated these negative impacts and promoted DIT to its best state across the three study periods. By the 12th FYP, however, the elasticity value of TE doubled, reducing its positive effect on DIT. Consequently, DIT decreased, despite the diminishing impeding effect of TI.

5. Conclusion

As a pioneering developing country, China's DEI states are crucial for achieving sustainable development. To evaluate low-SO$_2$ pathways, this study constructed a two-stage decoupling measurement

Figure 8. Driving factors of DIG from 2000 to 2015

Notes: PI = pollution intensity; EI = energy intensity; ES = economic scale; DIG = decoupling status of economic growth and industrial SO$_2$ generation.

Table 8
DIG in the END group from 2000 to 2015

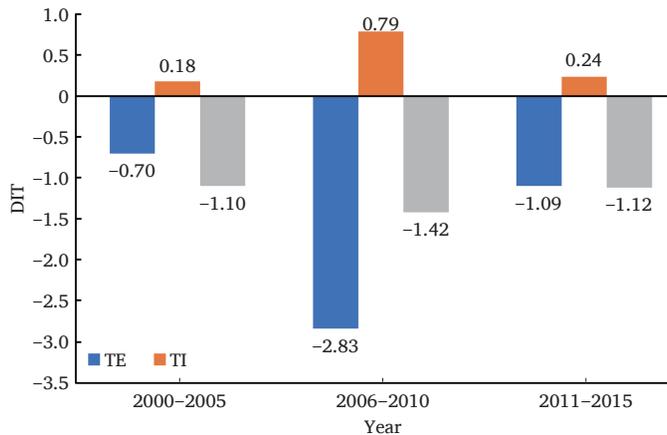| Provinces	2000–2005		2006–2010		2011–2015	
	DIG		DIG		DIG	
	Value	Status	Value	Status	Value	Status
Inner Mongolia	1.446	END	0.705	WD	1.608	END
Liaoning	0.589	WD	0.308	WD	0.346	WD
Jilin	0.896	WD	0.477	WD	0.673	WD
Heilongjiang	2.095	END	0.052	WD	0.034	WD
Fujian	2.920	END	0.454	WD	0.170	WD
Jiangxi	0.969	WD	0.760	WD	0.372	WD
Henan	1.798	END	0.514	WD	0.374	WD
Yunnan	3.272	END	0.551	WD	0.867	WD
Gansu	0.869	WD	1.199	END	0.350	WD
Ningxia	1.586	END	1.639	END	0.830	WD
Xinjiang	1.451	END	1.158	END	2.525	END
Qinghai	6.641	END	0.496	WD	0.863	WD
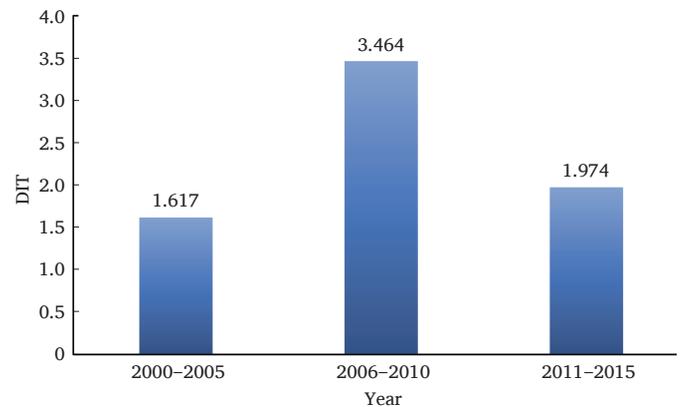
Figure 9. Status of DIT at the national level from 2000 to 2015

Notes: DIT = decoupling status of industrial SO$_2$ generation and industrial SO$_2$ treatment.

model and a decoupling decomposition model, examining the decoupling states of SO$_2$ emissions in China at the provincial level from

2000 to 2020. The major findings and policy recommendations are as follows.

Figure 10. Driving factors of DIT at the national level from 2000 to 2015
Notes: TE = treatment efficiency, TI = treatment intensity, PS = pollution generation scale.

Table 9
DIT in the WD group from 2000 to 2015

| Provinces | 2000–2005 | | 2006–2010 | | 2011–2015 | |
| | DIT | | DIT | | DIT | |
	Value	Status	Value	Status	Value	Status
Tianjin	3.82	ED	3.54	WD	0.14	WD
Hebei	5.33	ED	3.95	WD	3.34	RND
Shanxi	3.53	ED	4.21	WD	2.09	RND
Shanghai	6.26	ED	13.64	WD	−1.69	SND
Jiangsu	4.01	ED	3.57	WD	−2.81	SND
Zhejiang	2.94	ED	3.15	WD	0.95	WND
Shandong	2.73	ED	3.80	WD	1.53	ED
Hubei	1.31	ED	2.70	WD	1.61	ED
Hunan	2.66	ED	3.31	WD	6.29	RND
Guangdong	2.27	ED	7.87	WD	4.16	RND
Guangxi	0.23	WND	4.35	WD	−1.01	SND
Chongqing	2.04	ED	3.36	WD	0.94	WD
Sichuan	2.48	ED	8.31	WD	−2.06	SND
Anhui	1.14	ED	1.69	WD	1.37	ED
Hainan	4.52	ED	2.49	WD	1.23	ED
Guizhou	2.66	ED	4.75	WD	1.12	RND
Shaanxi	2.26	ED	8.49	WD	2.59	RND

Notes: WD = weak decoupling, ED = extensive decoupling, WND = weak negative decoupling, RND = regressive negative decoupling, and SND = strong negative decoupling.

DEI consistently improved between 2000 and 2020. During the research period, DIG exhibited a downward trend, while DIT followed a pattern of first increasing and then decreasing. Regarding the generation stage's drivers, the negative effect of ES was challenging to alter, while EI continued to enhance DIG. However, PI became a barrier to decoupling in the 10th FYP. Therefore, traditional fossil energy should be utilized more cleanly; for instance, manufacturing processes can be finely controlled, and SO_2 emissions can be better managed in advance. Additionally, the government should

Table 10
DIT in the END group from 2000 to 2015

| Provinces | 2000–2005 | | 2006–2010 | | 2011–2015 | |
| | DIT | | DIT | | DIT | |
	Value	Status	Value	Status	Value	Status
Inner Mongolia	0.377	WND	8.073	WD	1.828	ED
Liaoning	0.289	WND	2.834	WD	1.613	ED
Jilin	−0.475	SND	10.777	WD	2.469	ED
Heilongjiang	1.869	ED	11.341	WD	79.568	ED
Fujian	1.694	ED	5.476	WD	3.586	RND
Jiangxi	0.539	WND	1.947	WD	1.175	RND
Henan	1.529	ED	7.328	WD	2.604	ED
Yunnan	1.765	ED	1.434	WD	1.203	ED
Gansu	0.735	WND	1.885	WD	1.223	RND
Ningxia	1.539	ED	7.925	WD	1.438	ED
Xinjiang	0.170	WND	3.511	WD	3.555	RND
Qinghai	——	——	——	——	6.779	RND

promote the exploration and use of clean energy, along with modifications to the energy structure, to establish a safe and effective low-carbon energy system. Furthermore, transforming and upgrading the industrial structure to advance green and low-carbon initiatives should be a priority.

In the treatment stage, TE emerged as the primary promoter, followed by TI. To enhance TI, the government can strengthen environmental regulations by integrating administrative directives with market-based approaches. For instance, the government should include energy conservation and environmental protection as part of the performance evaluations for local government leaders. Additionally, the implementation of various special governance measures and emissions permit trading should be intensified, establishing stricter control indicators to compel enterprises to enhance their environmental protection practices and efficiencies. To improve TE, the government should invest more in environmental protection to develop green technologies, such as carbon energy storage and carbon capture technologies. Furthermore, carbon sinks should be widely utilized for SO_2 emission treatment, and environmental treatment facilities should be upgraded with more financial support policies and tax incentives.

Like all research, this study has limitations that present opportunities for future investigation. First, the research period for the two-stage decoupling and decomposition analysis was limited to 2000 to 2015 due to data constraints; future studies could benefit from a broader statistical scope. Second, further analysis could examine the coordination relationships and scenario simulations from both the generation and treatment stages. Despite these limitations, this study contributes to the field by exploring targeted mitigation approaches through the analysis of decoupling indicators and driving factors related to SO_2 generation and treatment stages.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author Contribution

All authors contributed to the conception and design of this study. Material preparation and methodology were performed by Yu-anna Tian. Data curation and investigations were conducted by Yi-zhong Wang. Conceptualization and visualization were handled by Ye
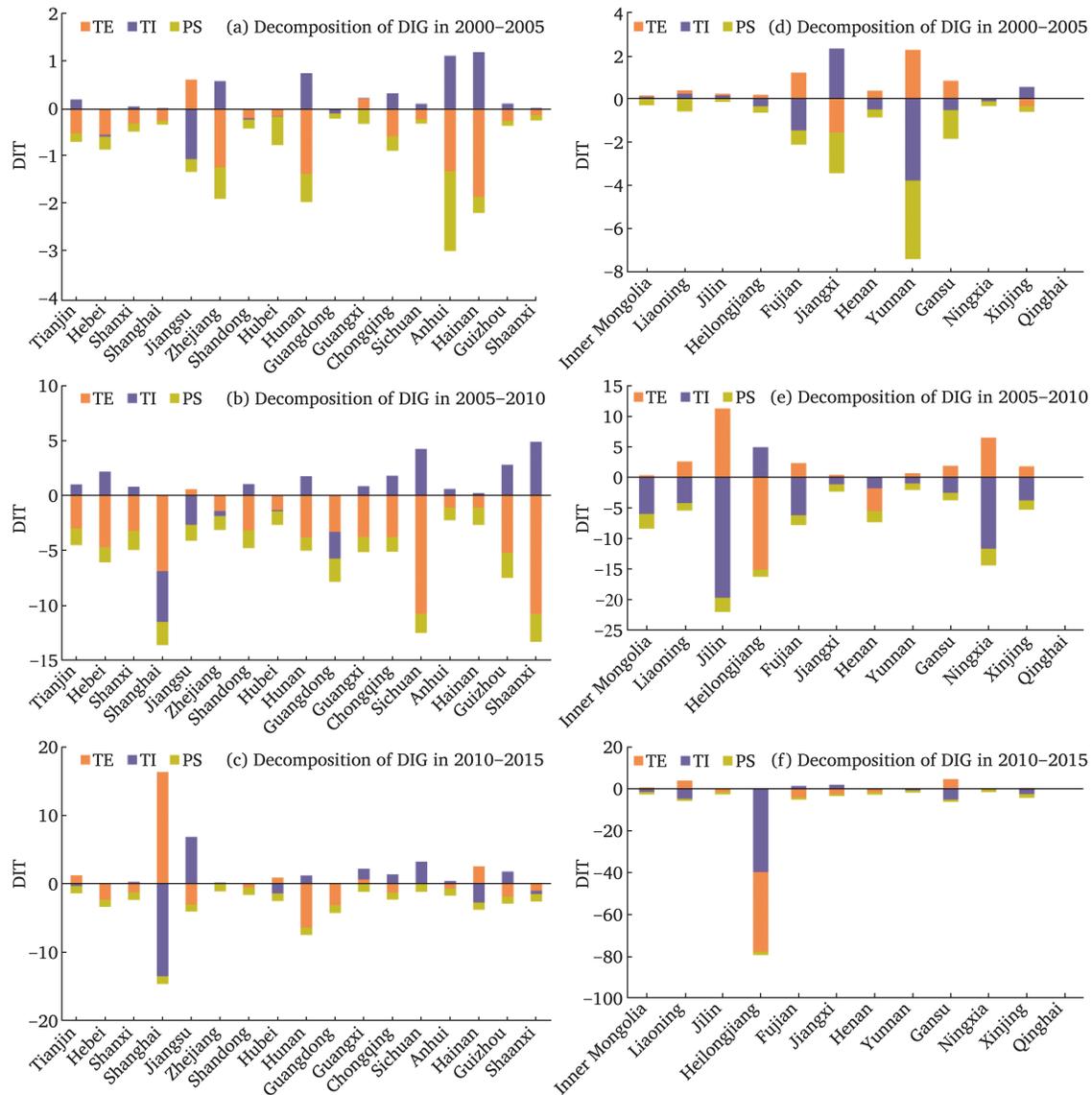
Figure 11. Driving factors of DIT from 2000 to 2015
Notes: TE = treatment efficiency; TI = treatment intensity; PS = pollution generation scale; END group = the provinces with an expansive negative decoupling status in DEI during 2000–2005.

Hang, Dequn Zhou, Xiurong Hu, and Qunwei Wang. The first draft of the manuscript was written by Yuanna Tian, with all authors providing feedback on earlier versions. All authors have read and approved the final version of the manuscript.

References

Cai, Y. Y., Hu, Z. Q., 2022. Industrial agglomeration and industrial SO$_2$ emissions in China's 285 cities: evidence from multiple agglomeration types. Journal of Cleaner Production 353, 131675.

Cao, X., Zhang, H.R., Wang, Y.H., 2021. Energy conservation and CO$_2$ emission reduction roadmap in China's energy-intensive industries based on a bottom-up approach. Sustainable Production and Consumption 27, 1424–1436.

Chang, M., Zheng, J., Inoue, Y., Tian, X., Chen, Q., Gan, T.T., 2018. Comparative analysis on the socioeconomic drivers of industrial air-pollutant emissions between Japan and China: insights for the further-abatement period based on the LMDI method. Journal of Cleaner Production 189, 240–250.

Diakoulaki, D., Mandaraka, M., 2007. Decomposition analysis for assessing the progress in decoupling industrial growth from CO$_2$ emissions in the EU manufacturing sector. Energy Economics 29, 636–664.

Dong, F., Li, J.Y., Li, K., Sun, Z.Y., Yu, B.L., Wang, Y., Zhang, S.N., 2020. Causal chain of haze decoupling efforts and its action mechanism: evidence from 30 provinces in China. Journal of Cleaner Production 245, 118889.

Dong, F., Li, J.Y., Zhang, X.Y., Zhu, J., 2021. Decoupling relationship between haze pollution and economic growth: a new decoupling index. Ecological Indicators 129, 107859.

Du, Y.W., Liu, Y.X., Hossain, M.A., Chen, S.S., 2022. The decoupling relationship between China's economic growth and carbon emissions from the perspective of industrial structure. Chinese Journal of Population, Resources and Environment 20, 49–58.

Fang, D.B., Yu, B.L., 2021. Driving mechanism and decoupling effect of PM$_{2.5}$ emissions: empirical evidence from China's industrial sector. Energy Policy 149, 112017.

Gao, C.C., Ge, H.Q., Lu, Y.Y., Wang, W.J., Zhang, Y.J., 2021. Decoupling of provincial energy-related CO$_2$ emissions from economic growth in China and its convergence from 1995 to 2017. Journal of Cleaner Production 297, 126627.

Hang, Y., Wang, F., Su, B., Wang, Y.Z., Zhang, W., Wang, Q.W., 2021. Multi-region multi-sector contributions to drivers of air pollution in China. Earth's Future 9, e2021EF002012.

Hang, Y., Wang, Q.W., Wang, Y.Z., Su, B., Zhou, D.Q., 2019. Industrial SO$_2$ emissions treatment in China: a temporal-spatial whole process decomposition analysis. Journal of Environmental Management 243, 419–434.

He, J., 2010. What is the role of openness for China's aggregate industrial SO$_2$ emis-

sion? a structural analysis based on the divisia decomposition method. Ecological Economics 69, 868–886.

Jia, J.S., Gong, Z.H., Gu, Z.Y., Chen, C.D., Xie, D.M., 2018. Multi-perspective comparisons and mitigation implications of SO_2 and NO_x discharges from the industrial sector of China: a decomposition analysis. Environmental Science and Pollution Research International 25, 9600–9614.

Kong, Y., He, W.J., Yuan, L., Zhang, Z.F., Gao, X., Zhao, Y.E., Mulugeta Degefu, D., 2021. Decoupling economic growth from water consumption in the Yangtze River Economic Belt, China. Ecological Indicators 123, 107344.

Liu, H.M., Cui, W.J., Zhang, M., 2022. Exploring the causal relationship between urbanization and air pollution: evidence from China. Sustainable Cities and Society 80, 103783.

Liu, Q.L., Wang, Q., 2013. Pathways to SO_2 emissions reduction in China for 1995–2010: based on decomposition analysis. Environmental Science & Policy 33, 405–415.

Liu, Q.L., Wang, Q., 2017. How China achieved its 11th Five-Year Plan emissions reduction target: a structural decomposition analysis of industrial SO_2 and chemical oxygen demand. Science of the Total Environment 574, 1104–1116.

Liu, S.T., Jia, J.S., Huang, H.Z., Chen, D.L., Zhong, Y.X., Zhou, Y.M., 2023. China's CO_2 emissions: a thorough analysis of spatiotemporal characteristics and sustainable policy from the agricultural land-use perspective during 1995–2020. Land 12, 1220.

Liu, Y., Wang, S.J., Qiao, Z.X., Wang, Y.H., Ding, Y.Y., Miao, C.H., 2019. Estimating the dynamic effects of socioeconomic development on industrial SO_2 emissions in Chinese cities using a DPSIR causal framework. Resources, Conservation and Recycling 150, 104450.

Lundquist, S., 2021. Explaining events of strong decoupling from CO_2 and NO_x emissions in the OECD 1994–2016. Science of the Total Environment 793, 148390.

Miao, Z., Liu, S.C., Chen, X.D., 2020. Driving factors and spatio-temporal features underlying industrial SO_2 emissions in "2 + 26" in North China and extended cities. Chinese Journal of Population, Resources and Environment 18, 296–318.

Ministry of Ecological Environment of the People's Republic of China (MEE), 2013. Notice on Printing and Distributing the Statistical and Monitoring Measures for Total Emission Reduction of Major Pollutants during the 12th Five Year Plan (in Chinese). http://www.mee.gov.cn/gkml/hbb/bwj/201302/t2 0130204_245884.htm.

Ministry of Ecological Environment of the People's Republic of China (MEE), 2019. China Bulletin of Ecological Environment 2019. China Environmental Science Press, Beijing. http://www. mee. gov. cn/hjzl/sthjzk/zghjzkgb/202006/ P020200602509464172096.pdf.

Organization for Economic Co-operation and Development (OECD), 2002. OECD environmental strategy for the first decade of the 21st century. Sustainable Production and Consumption 27, 1010-1020.

Peng, X., Tao, X.M., Zhang, H., Chen, J.D., Feng, K.S., 2021. CO_2 emissions from the electricity sector during China's economic transition: from the production to the consumption perspective. Sustainable Production and Consumption 27, 1010–1020.

Qian, Y., Cao, H., Huang, S.M., 2020. Decoupling and decomposition analysis of industrial sulfur dioxide emissions from the industrial economy in 30 Chinese provinces. Journal of Environmental Management 260, 110142.

Shan, Y.L., Fang, S., Cai, B.F., Zhou, Y., Li, D., Feng, K.S., Hubacek, K., 2021. Chinese cities exhibit varying degrees of decoupling of economic growth and CO_2 emissions between 2005 and 2015. One Earth 4, 124–134.

Shao, S., Yang, L.L., Gan, C.H., Cao, J.H., Geng, Y., Guan, D.B., 2016. Using an extended LMDI model to explore techno-economic drivers of energy-related industrial CO_2 emission changes: a case study for Shanghai (China). Renewable and Sustainable Energy Reviews 55, 516–536.

Song, X., Jia, J.S., Hu, W.H., Ju, M., 2021. Provincial contributions analysis of the slowdown in the growth of China's industrial CO_2 emissions in the "new normal". Polish Journal of Environmental Studies 30, 2737–2753.

Song, Y., Sun, J.J., Zhang, M., Su, B., 2020. Using the Tapio-Z decoupling model to evaluate the decoupling status of China's CO_2 emissions at provincial level and its dynamic trend. Structural Change and Economic Dynamics 52, 120–129.

Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transport Policy 12, 137–151.

Tian, Y.N., Wang, Y.Z., Hang, Y., Wang, Q.W., 2022. The two-stage factors driving changes in China's industrial SO_2 emission intensity: a production-theoretical decomposition analysis. Science of the Total Environment 814, 152426.

Wang, Q., Jiang, R., Zhan, L.N., 2019a. Is decoupling economic growth from fuel consumption possible in developing countries? A comparison of China and India. Journal of Cleaner Production 229, 806–817.

Wang, C.M., Chu, J.Y., Wang, C.H., Zhang, Y.Q., 2019b. Decoupling scenario of economic growth and ecological environment pressure and influence factors of carbon emissions in Shandong Province. Chinese Journal of Population Resources and Environment 17, 303–309.

Wang, Y.Z., Hang, Y., Wang, Q.W., Zhou, D.Q., Su, B., 2021a. Cleaner production vs end-of-pipe treatment: evidence from industrial SO_2 emissions abatement in China. Journal of Environmental Management 277, 111429.

Wang, Y.Z., Wang, Q.W., Hang, Y., Zhou, D.Q., 2021b. Decomposition of industrial pollution intensity change and reduction potential: a two-stage meta-frontier PDA method. Sustainable Production and Consumption 28, 472–483.

Wang, Z.L., Qiu, S.L., 2021. Can "energy saving and emission reduction" demonstration city selection actually contribute to pollution abatement in China? Sustainable

Production and Consumption 27, 1882–1902.

Wei, J.C., Guo, X.M., Marinova, D., Fan, J., 2014. Industrial SO_2 pollution and agricultural losses in China: evidence from heavy air polluters. Journal of Cleaner Production 64, 404–413.

Wu, L.Y., Zeng, W.H., 2013. Research on the contribution of structure adjustment on SO_2 emissions reduction: -case study Shijingshan district, Beijing. Procedia Environmental Sciences 18, 849–855.

Xu, Y., Zhang, W.S., Wang, J.H., Ji, S.P., Wang, C., Streets, D.G., 2021. Investigating the spatially heterogeneous impacts of urbanization on city-level industrial SO_2 emissions: evidence from night-time light data in China. Ecological Indicators 133, 108430.

Yang, X., Wang, S.J., Zhang, W.Z., Li, J.M., Zou, Y.F., 2016. Impacts of energy consumption, energy structure, and treatment technology on SO_2 emissions: a multi-scale LMDI decomposition analysis in China. Applied Energy 184, 714–726.

Yang, Y., Jia, J. S., Chen, C. D., 2020. Residential energy-related CO_2 emissions in China's less developed regions: a case study of Jiangxi. Sustainability 12, 2000.

Yu, B. L., Fang, D. B., 2021. Decoupling economic growth from energy-related $PM_{2.5}$ emissions in China: a GDIM-based indicator decomposition. Ecological Indicators 127, 107795.

Zhang, L.H., Ma, X., Wang, Y.X., Song, R., Li, J.J., Yuan, W.C., Zhang, S.S., 2020a. The increasing district heating energy consumption of the building sector in China: decomposition and decoupling analysis. Journal of Cleaner Production 271, 122696.

Zhang, P.D., 2013. End-of-pipe or process-integrated: evidence from LMDI decomposition of China's SO_2 emission density reduction. Frontiers of Environmental Science & Engineering 7, 867–874.

Zhang, X., Geng, Y., Shao, S., Song, X.Q., Fan, M.T., Yang, L.L., Song, J.K., 2020b. Decoupling $PM_{2.5}$ emissions and economic growth in China over 1998–2016: a regional investment perspective. Science of the Total Environment 714, 136841.

Zhang, Y., Liu, W., Cai, Y., Khan, S., Zhao, M., 2021a. Decoupling analysis of water use and economic development in arid region of China-Based on quantity and quality of water use. Science of the Total Environment 761, 143275.

Zhang, Y.Y., Sun, M.Y., Yang, R.J., Li, X.H., Zhang, L., Li, M.Y., 2021b. Decoupling water environment pressures from economic growth in the Yangtze River Economic Belt, China. Ecological Indicators 122, 107314.

Appendix

Table A1
List of abbreviations

Abbreviation	Full term
SO_2	Sulfur dioxide
DEI	Decoupling state of so_2 emissions from economic growth
DIG	Decoupling state of so_2 generation from economic growth
DIT	Decoupling state of so_2 removal and so_2 generation
GDP	Gross domestic product
OECD	Organization for economic cooperation and development
LMDI	Logarithmic mean divisia index
PDA	Production-theoretical decomposition analysis
PI	Pollution intensity
EI	Energy intensity
ES	Economic scale
TE	Treatment efficiency
TI	Treatment intensity
PS	Pollution generation scale
SD	Strong decoupling
WD	Weak decoupling
RD	Recessive decoupling
ED	Expansive decoupling
ND	Negative decoupling
SND	Strong negative decoupling
WND	Weak negative decoupling
END	Expansive negative decoupling
RND	Recessive negative decoupling
FYP	Five-Year Plan