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Keywords: thermal power units; CO₂; NO_x; synergistic drivers



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Article

Analysis of Synergistic Drivers of CO₂ and NO_x Emissions from Thermal Power Generating Units in Beijing-Tianjin-Hebei, 2010-2020

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Abstract: Synergistic control of emissions of air pollutants and CO₂ is critical to the dual challenges of air quality improvement and climate change in China. Based on the emission inventories of thermal power units in Beijing, Tianjin, and Hebei, this study analyzes the CO₂ and NO_x emission characteristics of these units, identifies and quantifies the synergistic drivers affecting these emission trends. Inventory data show that between 2010 and 2020, NO_x emissions were reduced by 86.1%, while CO₂ emissions were reduced by only 29.8%. Although significant progress has been made in reducing NO_x emissions through measures such as end-of-pipe treatment, controlling CO₂ emissions remains a difficult task. The index decomposition analysis reveals that economic growth is the main driver of CO₂ and NO_x emission growth, energy intensity reduction is the main driver of CO₂ emission reduction, and end-of-pipe treatment is the main driver of NO_x emission reduction. Currently, coal occupies about 87% of the energy consumption of thermal power units in the Beijing-Tianjin-Hebei, and remains the main type of energy for synergistic emissions, and the potential for emission reduction in the energy structure remains huge. For NO_x emissions, it is expected that 90% of the reduction potential can be achieved through energy restructuring and end-of-pipe treatment. In conclusion, the high-precision unit-by-unit emission study confirms the effectiveness of the control policy for thermal power units in the region and provides some scientific reference for future policy formulation.

Keywords: thermal power units, CO₂, NO_x, synergistic drivers

1. Introduction

China faces the dual challenges of improving air quality and addressing climate change [1–3]. The thermal power sector is an important emitter of CO₂ and air pollutants in China [4,5]. Due to the application of large-scale desulphurization and dust removal facilities, SO₂ and particulate matter in the thermal power generation industry have been significantly controlled [6–8], but CO₂ and NO_x emissions are still high [9]. Among them, NO_x emission load is huge, active and characterized by cross-regional transmission of environmental impacts [10], and is also a key precursor leading to PM_{2.5} and O₃ pollution [11,12], which is a serious threat to human health [13]. According to data from the National Pollution Source Census, coal-fired power plants, as China's largest energy-consuming sector [14], accounted for about 47% of the country's total NO_x emissions in 2010, and about 42.5% of the country's total CO₂ emissions in 2020. Therefore, it is important to carry out long time series NO_x and CO₂ emission characterization and driver analysis in the power sector to synergistically address climate change and air quality improvement. The Beijing-Tianjin-Hebei, with its high energy consumption, high population density, and long heating season, is the most polluted region in China,

and is also the key urban agglomeration area for air pollution prevention and control in China. The pollutant emission intensity per unit area in the Beijing-Tianjin-Hebei is close to four times the national average[15]. Therefore, identifying and quantifying the synergistic drivers of historical CO₂ and NO_x emission reductions from thermal power generation in the Beijing-Tianjin-Hebei will not only be valuable for the subsequent in-depth treatment and reduction of pollutants and CO₂ emissions from China's power plants, but will also provide a reference for the region to sustainably improve its air quality and to contribute to the realization of the goals of a "Beautiful China" and a "Dual-Carbon" approach.

Highly precise emission inventories of coal-fired power plants are the basis for assessing the effectiveness of pollution reduction and carbon control. There are few studies of CO₂ and NO_x emissions based on unit-level long time series. Mostly single pollutants are studied on a national or regional scale using provincial macro-measurements of energy consumption [16]. By assessing facility-level synergies at specific source locations in China, Wang Pu et al. [17] found significant spatial differences in the synergies of emission reductions in China's coal and power sectors, and suggested that emission reduction measures should be tailored to local conditions and precise policies should be formulated in relation to carbon pricing. By combining information on China's power plants from 2010-2015, Tong dan et al. [18] found that NO_x emissions decreased by 45% while CO₂ emissions increased by 15%, and explored various emission reduction pathways for power plants from a macro perspective. Zhang Hongyu et al. [19] used Kaya equation and LMDI decomposition to analyze the evolution of Beijing's electricity carbon emissions and the factors affecting them, and found that Beijing's thermal power carbon emissions showed an overall decreasing trend and the source of emissions shifted from raw coal to natural gas. Although the above studies provide information and direction for the development of carbon emission reduction programs for the electric power industry at the macro level, the summarized results do not quantify the contribution of synergistic emission reduction drivers in specific regions, and there is a lack of synergistic emission analyses for a specific type of air pollutant and CO₂, which makes it difficult to be translated into specific implementable policies. Although population growth and economic growth are widely regarded as key factors contributing to CO₂ emissions, the uneven development across different regions in China results in varying impacts on carbon emissions. In addition, there are even fewer studies on the estimation of bottom-up synergistic emissions of CO₂ and NO_x and the quantification of the contribution of the synergistic emission factors of the two on the basis of thermal power generating units. To address this gap, we developed an interdisciplinary approach to assess the synergistic benefits of site-specific unit-level emissions.

Structural Decomposition Analysis (SDA) [20,21] and Exponential Decomposition Analysis (IDA) [22] are commonly used to study the drivers of CO₂ emissions. SDA is generally supported by input-output table data, which has a large time horizon and is not conducive to in-depth research. IDA is based on aggregated data from various industries and is more suitable for time series analysis [23]. Currently, the Log Mean Divisia Index (LMDI) has become the most popular method in IDA because it has no unexplained residuals, the mathematical feature that ensures the independence of the decomposition results, avoids potential problems such as multiple covariance and endogeneity issues, and can deal with zero and negative values [24]. Therefore, the LMDI method has been widely used in the decomposition analysis for changes in CO₂ emissions. To address the issue of synergistic emission of CO₂ and NO_x from thermal power units, we collected data on the basic information, activity level, and control technology of each thermal power unit in Beijing-Tianjin-Hebei thermal power plants from 2010 to 2020, based on which we established a methodology for calculating the emission of CO₂ and NO_x from coal-fired power plants and compiled an emission inventory of CO₂ and NO_x. Finally, the Log Mean Divisia Index (LMDI) was applied to decompose the CO₂ emission and NO_x emission of the power plant, and the emission contribution rate of each influencing factor was calculated, evaluating the effect of the CO₂ and NO_x of thermal power units influenced by five factors, namely, emission coefficients (end-of-pipe treatment), energy structure, energy intensity, per capita GDP and population. It also identifies the synergistic drivers of emissions by studying the drivers in different years and between different fuel types, with a view to better providing certain

references for the policy-making authorities and effective information for the formulation of the next policy measures for emission reduction in China's power sector.

2. Materials and Methods

2.1. Methodology for Calculation of Emission Inventories

Based on the basic information, process type, activity level, emission factors, end-of-pipe treatment and other data of each thermal power unit in the Beijing-Tianjin-Hebei region from 2010 to 2020, an emission database covering all coal-fired units in the region (including stand-alone thermal power plant units, purely condensing coal-fired power generating units in captive power plants, and combined heat and power generating units) has been set up by adopting a bottom-up approach. Detailed NO_x and CO₂ emission inventories were prepared by measuring CO₂ and NO_x emissions on a unit-by-unit basis (472 coal-fired units in service in 2010 and 328 coal-fired units in service in 2020). To ensure a comprehensive understanding of CO₂ and NO_x emission trends, different fuel types were analyzed. Thermal power unit CO₂ and NO_x emissions were measured mainly based on coal consumption, emission coefficients and end-of-pipe treatment.

2.1.1. Calculation of CO₂ Emissions

Due to the lack of official data on CO₂ emissions, We account for CO₂ emissions from thermal power generating units in the Beijing-Tianjin-Hebei through unit energy consumption data combined with the "Technical Guidelines for Converged Emission Inventories of Air Pollutants and Greenhouse Gases" (2024) [25]. The formula is shown below:

$$C = \sum_i FC_i \times EF_i$$

where *i* is the type of energy; FC (expressed in terms of standard coal consumption) is the energy consumption in 10⁴ t; EF is the CO₂ emission coefficients in 10⁴ t of CO₂/10⁴ t of energy, i.e., the amount of CO₂ produced by combustion of a unit of energy. The energy consumption of thermal power units in the Beijing-Tianjin-Hebei is mainly based on coal and natural gas, supplemented by oil. In order to facilitate the calculation, and taking into account the limited availability of energy, the energy is divided into 17 categories. As shown in Table 1.

Since EF is usually expressed in terms of carbon content per unit of calorific value, it is necessary to convert different types of energy consumption into calorific units, taking into account the carbon content and carbon oxidation rate, and subsequently determining the EF by the following equation:

$$EF_i = NCV_i \times CC_i \times OF_i \times \frac{44}{12}$$

NCV denotes the average low-level heating value of fossil fuels (PJ/10⁴ t, PJ/10⁸ m³); CC denotes the carbon content per unit calorific value of fossil fuels (t C/TJ); OF denotes the carbon oxidation rate of fossil fuels (%) (The percentage of carbon in the fuel that is completely oxidized during combustion. Since different types of fuels are burned in different ways, research data are preferred, and where research data are difficult to obtain, the values recommended in this guide are used.); and 44/12 denotes the ratio of the molecular mass of carbon in CO₂.

Table 1. Energy emission coefficients.

Type of energy	Average low level heat generation	Carbon emission factors	Carbon content per unit calorific value	Carbon oxidation rate
	GJ/t (GJ/m ³)	t C/GJ	t C/GJ	
raw coal	20.934	0.091	0.026	0.94
Other coal washing waste rock (in coal mining)	8.363	0.084	0.025	0.9
	8.374	0.096	0.027	0.98

Other coking products	37.634	0.101	0.030	0.93
petroleum coke	35.530	0.099	0.028	0.98
crude oil	41.816	0.072	0.020	0.98
diesel fuel	42.705	0.073	0.020	0.98
fuel oil	41.868	0.076	0.021	0.98
gasoline	43.070	0.070	0.020	0.98
diesel	43.070	0.068	0.019	0.98
Other petroleum products	41.031	0.072	0.020	0.98
petroleum	0.036	0.056	0.015	0.99
coke oven gas	0.017	0.044	0.012	0.99
blast furnace gas	0.003	0.257	0.071	0.99
converter gas	0.008	0.180	0.050	0.99
refinery dry gas	0.004	0.065	0.018	0.98
Other gas	0.005	0.044	0.012	0.99

2.1.2. Calculation of NO_x Emissions

Measured according to energy consumption, NO_x removal rate, denitrification efficiency, and in conjunction with the Technical Guidelines for Convergence of Air Pollutant and Greenhouse Gas Emission Inventories (2024). The formula for measuring NO_x emissions from coal-fired units is.

$$E_i = M_i \times pf_i \times (1 - \xi_i) \times (1 - \eta_i) \times 10$$

where *i* denotes the *i*th unit; *M* denotes the coal consumption of the unit during the accounting period (10⁴ t); *pf* denotes the unit's pollution production intensity kg/t; ξ denotes the NO_x removal efficiency improved after the low-NO_x combustion retrofit relative to the pre-low-NO_x combustion; and η is determined by the following equation:

$$\xi_i = \frac{C_{\text{pre-remodeling}} - C_{\text{after remodeling}}}{C_{\text{pre-remodeling}}}$$

In the formula: $C_{\text{pre-remodeling}}$ Indicates the average NO_x concentration before the unit undergoes low-NO_x combustion technology retrofit, mg/Nm³; $C_{\text{after remodeling}}$ denotes the average concentration of NO_x after the unit undergoes low-NO_x combustion technological transformation. η denotes the comprehensive denitrification efficiency of the unit after the denitrification facilities have been stably operated during the accounting period.

2.2. Driver Decomposition Methods

Considering the possible correlations among the driving factors, we used the Log Mean Divisia Index (LMDI) to decompose the effects of each factor on the emission trends of CO₂ and NO_x in the Beijing-Tianjin-Hebei.

Due to many factors such as the level of economic development, energy consumption, end-of-pipe treatment, etc. will have a large impact on CO₂ and NO_x emissions from power plants. Therefore, in order to better understand the variables of CO₂ and NO_x emissions, we take 2010 as the base period, and based on the energy consumption of thermal power generating units in the Beijing-Tianjin-Hebei from 2010 to 2020, we decompose the CO₂ and NO_x emissions into five factors, namely, emission coefficients, energy structures, energy intensity, per capita GDP and population [26], and analyze the impacts of carbon emissions as well as NO_x emissions on thermal power generating units in the Beijing-Tianjin-Hebei region in terms of these five dimensions, based on the Log Mean Divisia Index(LMDI). aspects to analyze the impact of carbon emission as well as NO_x emission from thermal power generating units. The decomposition formula for total emissions is as follows:

$$C_i^t = \sum_i \left(\frac{C_i^t}{E_i^t} \times \frac{E_i^t}{E^t} \times \frac{E^t}{G^t} \times \frac{G^t}{P^t} \times P^t \right) = \sum_i EF_i^t \times ES_i^t \times EI^t \times A^t \times P^t$$

where *i* denotes the type of energy; *t* denotes the year; *C* denotes the total carbon emissions or total NO_x emissions (unit: 10⁴ t); *E* is the energy consumption; E_i^t and E^t are the consumption of the *i*th

type of energy and the total energy consumption (unit: 10^4 t); G is the gross domestic product (unit: 10^4 yuan); P represents the total population (unit: 10^4 people). EF represents the emission coefficients (end-of-pipe treatment); $ES = E_i/E$ is the energy structure influence factor; $EI = E/G$ is the energy intensity influence factor; A is the per capita GDP influence factor; P is the population influence factor. Since the EF for CO₂ is relatively consistent between two neighboring years, its effect is negligible. However, for NO_x emissions, the EF responds to the impact of end-of-pipe treatment. In order to calculate the difference between carbon emissions as well as NO_x emissions in two consecutive years, the decomposition and summation equations are obtained as follows:

$$\Delta C^{t,t-1} = C^t - C^{t-1} = \Delta C_{EF} + \Delta C_{ES} + \Delta C_{EI} + \Delta C_A + \Delta C_P$$

where, ΔC_{EF} represents CO₂ emission efficiency or the NO_x end-of-pipe treatment; ΔC_{ES} represents the change in CO₂ and NO_x emissions due to energy structure; ΔC_{EI} represents the change in CO₂ and NO_x emissions due to energy intensity; ΔC_A Represents changes in CO₂ and NO_x emissions due to per capita GDP; ΔC_p Represents changes in CO₂ and NO_x emissions due to population. Based on the LMDI summation equation, the cumulative emission reduction effect of each factor on CO₂ and NO_x was calculated as follows:

$$\Delta C_X = \sum_i \left(\frac{C_i^t - C_i^{t-1}}{\ln C_i^t - \ln C_i^{t-1}} \times \ln \frac{X_i^t}{X_i^{t-1}} \right)$$

where X represents the individual influencing factors.

2.3. Data Acquisition

Based on the basic information of each unit in the 2010-2020 total emission reduction data of the Beijing-Tianjin-Hebei, and combining with the on-site research in previous years, this database is established, as shown in Tables 2 and 3. GDP and population data are obtained from the "Statistical Yearbook"[27]. In addition, energy consumption data were converted to coal equivalent to facilitate comparison between different energy.

Table 2. Number of power plants, 2010-2020.

Year	Beijing	Tianjin	Hebei
2010	7	21	182
2011	18	19	165
2012	11	20	197
2013	10	20	197
2014	10	24	194
2015	13	25	195
2016	14	24	169
2017	15	25	153
2018	17	20	147
2019	15	26	105
2020	15	26	86

Table 3. Number of units, 2010-2020.

Year	Beijing	Tianjin	Hebei
2010	22	65	385
2011	51	64	403
2012	31	66	448
2013	31	66	449
2014	37	63	441
2015	48	66	452
2016	54	61	395
2017	58	62	308
2018	78	51	321

2019	87	70	215
2020	87	71	170

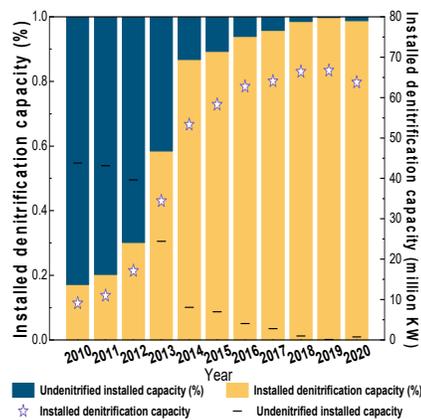
3. Results

3.1. Trends in CO₂ and NO_x Emissions

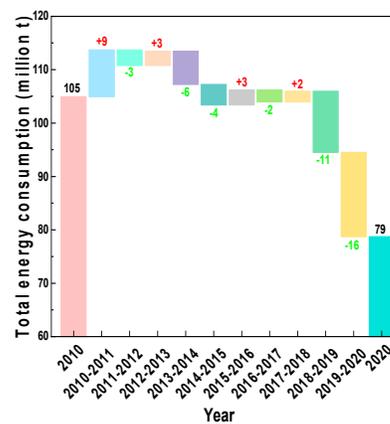
In this study, a comprehensive emission database of all coal-fired units in the Beijing-Tianjin-Hebei region was established, and long time-series CO₂ and NO_x emission inventories were compiled for about 200 power plants and nearly 500 units in the region for the period 2010-2020. Figure 1 summarizes the annual installed capacity of thermal power units in the Beijing-Tianjin-Hebei region, the capacity of denitrification units, energy use, power generation, and emissions from 2010 to 2020.

As shown in Figures 1a and 1e, there were 472 thermal power units in the Beijing-Tianjin-Hebei region in 2010, with a total installed capacity of $5,289.8 \times 10^4$ KW and a total generating capacity of 2764.9 hundred million kwh. With the increasing demand for power generation, the installed capacity of thermal power units is growing at an average rate of 2.2% per year, while the installed capacity of denitrification is also increasing continuously. By 2020, there will be 328 thermal power units in the Beijing-Tianjin-Hebei, with a total installed capacity of $6,454.7 \times 10^4$ KW and a generating capacity of 2580.3 hundred million kwh. This changing trend is mainly due to the fact that the Beijing-Tianjin-Hebei is one of the largest and most dynamic economic regions in northern China, with rapid economic development and increasing population concentration, leading to a huge demand for energy consumption. But coal consumption decreased from 105 million t in 2010 to 79 million t in 2020, a 25% reduction (as shown in Figures 1b) This trend is mainly due to the implementation of a series of clean energy transformation policies in the Beijing-Tianjin-Hebei region around 2010, such as the “coal-to-gas-to-electricity” policy, as well as the development of hydropower and solar power. The implementation of these policies has not only reduced coal consumption, but has also led to a reduction in standard coal consumption for thermal power generation. The amount of standard coal consumed by thermal power units in the Beijing-Tianjin-Hebei for power generation has decreased from 376.5g/kwh in 2010 to 295.7g/kwh in 2020, which is still 3.3% lower than the amount of standard coal consumed by thermal power plants of 6,000kw and above nationwide for power generation in 2020. As shown in Figures 1b, the amount of standard coal consumed for power generation in Beijing-Tianjin-Hebei has been reduced by 21.5% over the past 10 years. However, it increased by 9 million t, 3 million t, 3 million t and 2 million t in 2011, 2013, 2016 and 2018 respectively. It is worth mentioning that Beijing, as the capital of China, enforces more stringent environmental requirements and standards [28]. According to “Beijing Electricity Development Plan for the Eleventh Five-Year Plan Period” [29], between 2010 and 2020, Beijing’s energy structure of power generation has undergone significant restructuring. “By the end of the 11th Five-Year Plan period, compared with the end of 2005, the proportion of installed power generation from coal-fired power plants had decreased to 41.68%, the proportion of installed power generation from new and renewable energy power plants had increased by 6.25%, the proportion of natural gas had increased from zero in 2005 to 28.22%, and the scale of green power transferred from outside had increased from 45 hundred million kwh in 2015 to 145.6 hundred million kwh in 2020. This indicates that Beijing is actively expanding its sources of renewable energy and reducing its dependence on fossil fuels [30]. As a result, Beijing’s standard coal consumption for power generation in 2020 will only be 289.6g/kwh. CO₂ emissions from thermal power units in the Beijing-Tianjin-Hebei did not change much, with an overall decreasing trend from 0.432 billion t in 2010 to 0.303 billion t in 2020, a decrease of 29.8%, reaching a peak of 0.469 billion t in 2011. In the time series, CO₂ emission trends are similar to energy consumption trends. However, per capita GDP has been increasing year by year over the past 10 years, from 41,900 yuan in 2010 to 78,300 yuan, with an average annual growth rate of 6.55%. In contrast to CO₂ emissions, NO_x emissions are significantly lower. As shown in Figure 1d, total NO_x emissions peaked in 2011 and then declined every year. From 2010 to 2020, NO_x emissions were reduced by 80.2×10^4 t, a reduction of 86.1%. The maximum annual reduction of 23.5×10^4 t was reached during 2013-2014. This is due to the fact that less action was taken on NO_x emissions before 2010, and

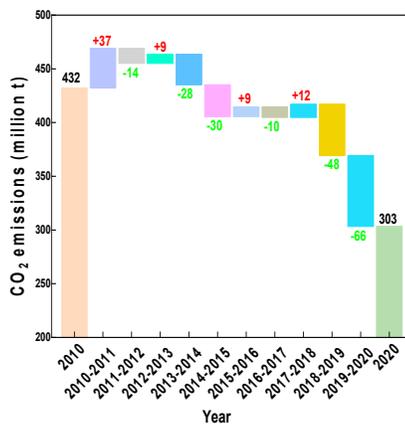
that a 10% reduction in NO_x emissions was set for the first time during the 12th Five-Year Plan [31]. Moreover, the implementation of “Ten Articles of the Atmosphere”, “Three-Year Action Plan for Winning the Battle for the Blue Sky” and related supporting measures has led to significant NO_x emission reduction in the Beijing-Tianjin-Hebei, with ultra-low emission retrofit contributing to 40% of the NO_x emission reduction. “Upgrading and Action Plan for Energy Saving and Emission Reduction of Coal Power (2014-2020)”[32] even limits NO_x emission concentration to 50 mg/m³. The proportion of installed denitrification capacity has increased from 17.2% to 99.8% in this decade, which is also an important reason for the reduction of NO_x emissions in the 12th Five-Year Plan. Despite a 6.7% reduction in power generation, coal consumption was reduced by 33% as older units were phased out and new units were built. This shows that the new units have higher combustion technology and proves the necessity and science of retiring old units to build new ones [33]. During the period 2010-2020, the economy of Beijing-Tianjin-Hebei have been developed, but the emission of CO₂ and NO_x from thermal power units have been effectively controlled. Thanks to the 12th Five-Year Plan and 13th Five-Year Plan, Beijing-Tianjin-Hebei has changed its development model and implemented measures for economic restructuring and energy restructuring [34].



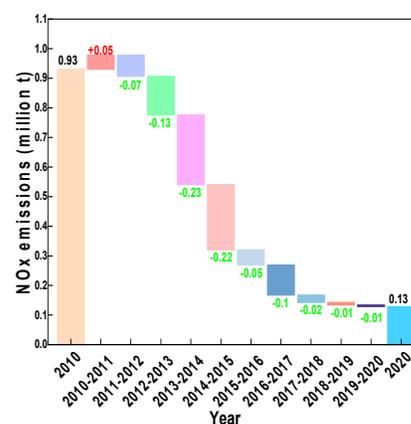
a Installed capacity of thermal power units, installed capacity of denitrification



b coal equivalent



c CO₂ emissions



d NO_x emissions

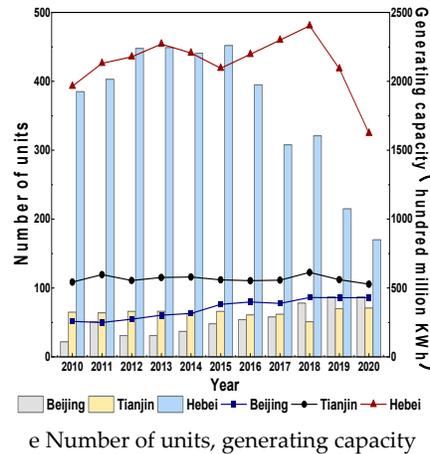


Figure 1. Installed capacity of thermal power units, installed capacity of denitrification, coal equivalent, power generation, CO₂ and NO_x emissions in Beijing-Tianjin-Hebei.

3.2. Analysis of CO₂ and NO_x Emission Drivers

We assessed the impact of emission coefficients (end-of-pipe treatment), energy structure, energy intensity, per capita GDP and population on CO₂ and NO_x emissions associated with energy consumption of thermal power units from 2010 to 2020 by means of LMDI decomposition analysis. From the decomposition results, a positive number indicates that the factor contributes to CO₂ and NO_x emissions, and a negative number indicates that the factor favors the reduction of CO₂ and NO_x emissions. During the 10-year period, the cumulative CO₂ emissions in the Beijing-Tianjin-Hebei were reduced by $12,880.3 \times 10^4$ t and NO_x emissions by 80.2×10^4 t. The effect of the CO₂ emission coefficients is negligible due to its relative consistency between two adjacent years. per capita GDP and population are positively correlated with CO₂ emissions, while energy structure and energy intensity have a negative impact on CO₂ emissions. The order of magnitude of the contribution of each factor to CO₂ emissions is per capita GDP, energy intensity, population and energy structure. per capita GDP, an important indicator of economic growth, is the main driver of the increase in CO₂ emissions from thermal power units in Beijing-Tianjin-Hebei, which reached $23,070 \times 10^4$ t. At the same time energy intensity is the main reason for the decrease in CO₂, with a reduction of $36,689 \times 10^4$ t.

Among the factors affecting NO_x emissions, per capita GDP and population were positively correlated, while emission coefficients, energy structure and energy intensity were negatively correlated on NO_x emissions. The order of magnitude of the contribution of each factor to NO_x emissions is per capita GDP, emission coefficients (end-of-pipe treatment), energy intensity, population, and energy structure. Unlike CO₂ emissions the emission coefficients of NO_x are important indicators of end-of-pipe treatment. per capita GDP was the main driver of the increase in NO_x emissions from thermal power units in the Beijing-Tianjin-Hebei, which reached 36.7×10^4 t. Meanwhile, end-of-pipe management and energy intensity were the main drivers of the decrease in NO_x emissions, which decreased by 77.3×10^4 t and 43.3×10^4 t, respectively.

Thus, per capita GDP is the main synergistic driver leading to an increase in CO₂ and NO_x emissions from thermal power units in Beijing-Tianjin-Hebei, while energy intensity is the main synergistic driver leading to a decrease in emissions. To combat climate change and improve air quality, Beijing-Tianjin-Hebei has stepped up its efforts to save energy and reduce emissions. For example, it has implemented a comprehensive work program for energy conservation and emission reduction in the 13th Five-Year Plan, and has promoted the improvement of energy efficiency in key industries and the control of total coal consumption [35]. These initiatives all contribute to reducing energy consumption and pollutant emissions, thereby reducing energy intensity. Among them, technological progress is a key factor in reducing energy intensity. During this period, Beijing-Tianjin-Hebei enterprises adopted more advanced production processes and equipment, the industrial structure was continuously optimized and upgraded, high-energy-consuming enterprises

were eliminated or reformed, and the proportion of new industries and service industries increased [36]. At the same time, with the government proposing energy restructuring policies such as “coal to gas”, Beijing-Tianjin-Hebei is making great efforts to develop clean energy technologies and reduce the proportion of traditional energy sources. The development of smart grids has also improved the efficiency of energy transmission and distribution in the power system. In addition, China has been conducting carbon emissions trading pilot projects in seven provinces and cities, including Beijing, since 2013, with the aim of utilizing market mechanisms to prompt enterprises to reduce greenhouse gas emissions. Carbon emissions trading policy is an important means of promoting emission reduction through market mechanisms, and such a policy may have an impact on energy intensity reduction in the Beijing-Tianjin-Hebei.

To further understand the influence and change process of these five factors on CO₂ and NO_x emissions from thermal power units, Figures 2 and 3 show the contribution of several decomposition factors to CO₂ and NO_x emissions. On this basis, the effects of each factor on CO₂ and NO_x emissions from thermal power units in Beijing-Tianjin-Hebei are discussed in detail.

Table 4. Decomposition results of CO₂ emission influencing factors of thermal power units in Beijing-Tianjin-Hebei, 2010-2020.

Year($t_i - t_{i+1}$)	ΔC	ΔC_{EF}	ΔC_{ES}	ΔC_{EI}	ΔC_A	ΔC_P
2010-2011	3696.27	0.00	-14.22	-4615.76	7563.11	763.14
2011-2012	-1387.15	0.00	-114.20	-5517.02	3558.49	685.58
2012-2013	855.60	0.00	-165.06	-2360.83	3328.94	52.55
2013-2014	-2901.10	0.00	-366.00	-4889.64	2024.38	330.16
2014-2015	-2964.48	0.00	-1188.03	-2788.70	839.09	173.15
2015-2016	900.45	0.00	-191.60	-2034.23	2976.80	149.47
2016-2017	-983.70	0.00	-95.75	-3198.49	2345.53	-34.99
2017-2018	1234.25	0.00	599.97	-1441.71	2164.51	-88.53
2018-2019	-4772.41	0.00	-4.18	-2435.86	-2426.42	94.04
2019-2020	-6600.54	0.00	3.26	-7406.31	695.39	107.12
Total	-12922.82	0.00	-1535.80	-36688.55	23069.83	2231.70

Table 5. Decomposition results of NO_x emission influencing factors of thermal power units in Beijing-Tianjin-Hebei, 2010-2020.

Year ($t_i - t_{i+1}$)	ΔC	ΔC_{EF}	ΔC_{ES}	ΔC_{EI}	ΔC_A	ΔC_P
2010-2011	4.757	-3.356	-0.000	-9.647	16.113	1.647
2011-2012	-7.152	-4.408	0.029	-11.448	7.275	1.400
2012-2013	-13.086	-14.768	-0.002	-4.472	6.106	0.051
2013-2014	-23.672	-19.793	-0.219	-7.039	2.910	0.469
2014-2015	-21.999	-19.899	-0.162	-2.847	0.747	0.163
2015-2016	-5.197	-6.056	0.002	-1.337	2.081	0.112
2016-2017	-10.148	-9.651	-0.003	-1.692	1.193	0.005
2017-2018	-2.481	-2.782	-0.003	-0.486	0.805	-0.015
2018-2019	-0.842	0.944	-0.003	-0.997	-0.820	0.035
2019-2020	-0.508	2.432	0.003	-3.295	0.318	0.033
Total	-80.328	-77.337	-0.359	-43.261	36.729	3.900

In Tables 4 and 5: ΔC represents the sum of the driving factors; ΔC_{EF} represents CO₂ emission efficiency or the NO_x end-of-pipe treatment; ΔC_{ES} represents the change in CO₂ and NO_x emissions due to energy structure; ΔC_{EI} represents the change in CO₂ and NO_x emissions due to energy intensity; ΔC_A Represents changes in CO₂ and NO_x emissions due to per capita GDP; ΔC_P Represents changes in CO₂ and NO_x emissions due to population.

The overall efficiency of energy consumption and economic development is usually measured by the indicator of energy intensity, which is the amount of energy consumed to generate a unit of GDP. As shown by the contribution of the decomposition factors (Figure 2), the contribution of energy intensity to CO₂ emissions is the most significant in the period 2010-2020, reaching an average of 52.1% per year, and even 90.2% in 2019-2020. This point suggests that energy intensity is the dominant factor in reducing CO₂ emissions for thermal power units in Beijing-Tianjin-Hebei. Energy intensity is also the second largest contributor to NO_x emission reductions, averaging 26% per year. This result is mainly attributed to the success of the Beijing-Tianjin-Hebei in reducing energy intensity and reducing emissions by improving energy efficiency and promoting the optimization of the energy structure during the period 2010-2020. In this process, the government's green development policies, industrial restructuring, environmental protection regulations and synergistic energy development planning play an important role. As shown in Figure 4, the energy intensity of the Beijing-Tianjin-Hebei shows a continuous downward trend during the period of 2010-2020, with a cumulative reduction of 37.9% and 38.9% during the 12th and 13th Five-Year Plan periods, respectively. According to the "12th Five-Year Plan" energy-saving targets announced by the Development and Reform Commission, Beijing and Hebei have been assessed as having exceeded their targets. During the "13th Five-Year Plan" period, the target of eliminating outdated production capacity was completed three years ahead of schedule, and the installed capacity structure was further optimized. These measures have had a positive impact on reducing CO₂ emissions. These energy-saving policies not only meet the need to reduce carbon emissions, but also drive down the energy intensity of thermal power units in the Beijing-Tianjin-Hebei, laying a solid foundation for a greener and more sustainable future. Although both the 12th Five-Year Plan and the 13th Five-Year Plan address the reduction of energy intensity of thermal power units, the 13th Five-Year Plan emphasizes more environmental protection and energy efficiency initiatives, and further strengthens the restructuring of the thermal power industry, such as optimizing the structure of thermal power units and increasing the proportion of cogeneration units. At the same time, the 13th Five-Year Plan also eliminated a number of backward production capacity and encouraged the development of more efficient supercritical and ultra-supercritical generating units. These measures not only reduce energy intensity, but also promote environmental protection and sustainable development.

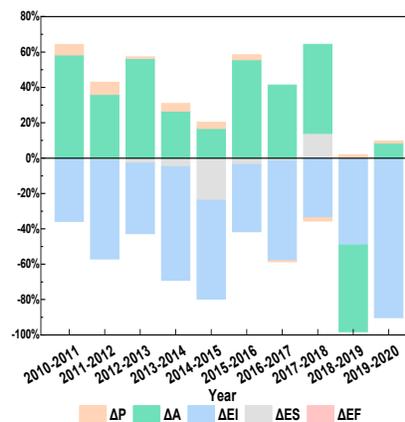


Figure 2. Contribution rate of each influencing factor of CO₂ emission from thermal power units in Beijing-Tianjin-Hebei, 2010-2020.

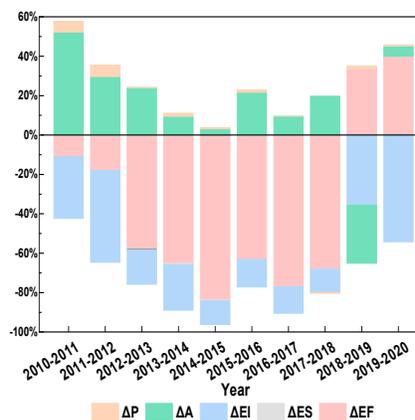


Figure 3. Contribution rate of each influencing factor of NO_x emission from thermal power units in Beijing-Tianjin-Hebei, 2010-2020.

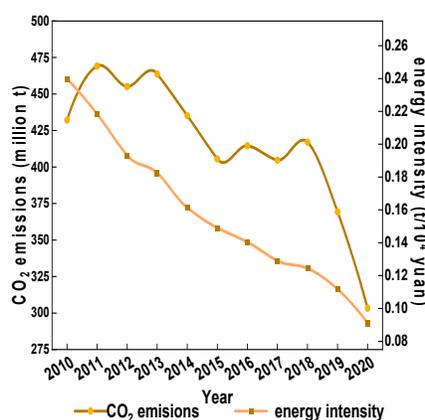


Figure 4. Energy intensity and CO₂ emissions of thermal power units in Beijing-Tianjin-Hebei region, 2010-2020.

Between 2010 and 2020, the Beijing-Tianjin-Hebei thermal power units reduced CO₂ emissions by $1,535.8 \times 10^4$ t and NO_x by 0.36×10^4 t due to the energy structure adjustment. It was found that energy restructuring did not make a significant contribution to CO₂ and NO_x reduction. While Beijing's coal use for thermal power units has dropped from 72% to 18%, Tianjin and Hebei's use of coal in 2020 will be 99.7% and 99.9%, respectively. As a result, the share of coal use in the Beijing-Tianjin-Hebei, although on a downward trend over the 10-year period, remains high, accounting for 87% in 2020. As shown in Figure 5, Beijing's share of coal shows a downward trend year by year, from 685.78×10^4 tons in 2010 to 227.79×10^4 tons in 2020, a reduction of 66.8%. Between 2013-2017, Beijing's four major coal-fired power plants have completed their conversion to natural gas, a move that has significantly reduced CO₂ emissions. Natural gas supply is also ensured through price subsidies and the construction of natural gas pipelines. Tianjin's share of coal declined by 13% from 2013 to 2017. This is because Tianjin's energy structure changed between 2014 and 2017, with coal consumption growing at a slower rate than other energy types and natural gas consumption expanding sharply. Changes in the energy structure may be the result of policy guidance and industrial restructuring aimed at reducing coal consumption and increasing the proportion of clean energy, but then rose to 99.7% in 2018 and remained stable. Coal prices are likely to decline after 2018, making thermal power generation less costly and thus improving its competitiveness. At the same time, considering the security and stability of energy supply, the policy allows or encourages a moderate increase in coal consumption, so Tianjin needs to maintain a certain amount of coal

production capacity and inventory. And Hebei's share of coal has always been higher, all around 99%. Therefore, adjusting the energy structure has a huge potential for CO₂ and NO_x emission reduction, especially in Tianjin and Hebei, and it is more important to promote energy structure adjustment to reduce CO₂ and NO_x emissions, and to actively develop clean energy while ensuring energy security and economic development.

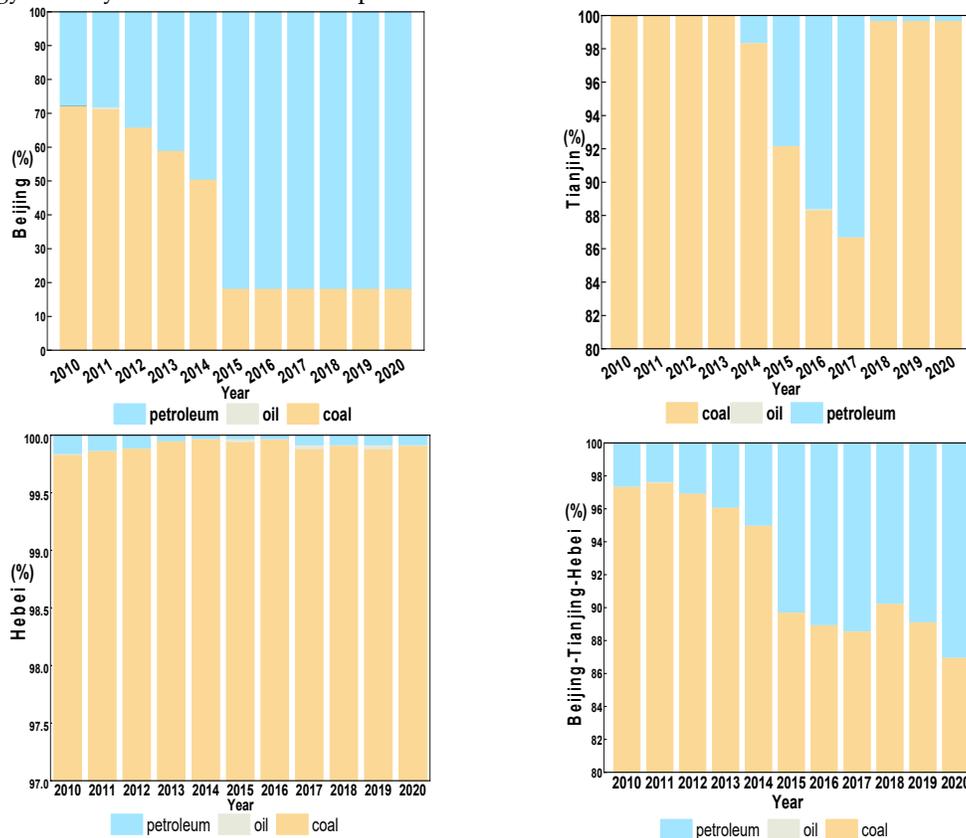


Figure 5. Analysis of the energy structure of thermal units in the Beijing-Tianjin-Hebei, 2010-2020.

3.3. Analysis of Synergistic Drivers of CO₂ and NO_x Emissions

As shown in Figure 6a and 9, from 2010 to 2020, the low-carbon policy reduces CO₂ emissions from thermal power units in the Beijing-Tianjin-Hebei. Despite a 22% increase in installed capacity, the associated CO₂ emissions decreased by 30%, from 0.432 billion t in 2010 to 0.303 billion t. The most effective measure to reduce CO₂ emissions is the reduction of energy intensity, which has led to an 84.8% reduction in CO₂ emissions without the influence of other factors. For the energy mix, CO₂ emissions are reduced by about $1,842 \times 10^4$ t in the period 2010-2015, but increased by 312×10^4 t in 2015-2020. This phenomenon is mainly due to the fact that coal consumption by thermal power units in Tianjin accounted for 99.7% of total energy consumption during 2017-2018, contributing 99.2% of CO₂ emissions due to the region's energy structure in the year. This is closely related to Tianjin's high-carbon energy structure as the most prominent industrial base in northern China. It also reflects the potential of energy restructuring for future emission reductions. As shown in Figures 6b and 9, end-of-pipe treatment plays a crucial role in NO_x reduction. The two most effective factors for reducing NO_x emissions are end-of-pipe treatment and energy intensity reduction. Without the influence of other factors, end-of-pipe treatment and energy intensity reduction reduce NO_x emissions by 82.9% and 46.4%, respectively, 38.4% smaller than CO₂-related energy intensity reduction ratio. Although energy restructuring has a smaller impact on NO_x emissions than other factors, it synergistically reduces CO₂ emissions, reinforcing the advantages of restructuring the energy structure. Together, Figures 6a,b and 8 show the synergistic effect of each factor on CO₂ and NO_x emissions from thermal

power units in Beijing-Tianjin-Hebei. Economic growth drives increased synergistic trends in CO₂ and NO_x, and the most effective synergistic mitigation measure is energy intensity reduction.

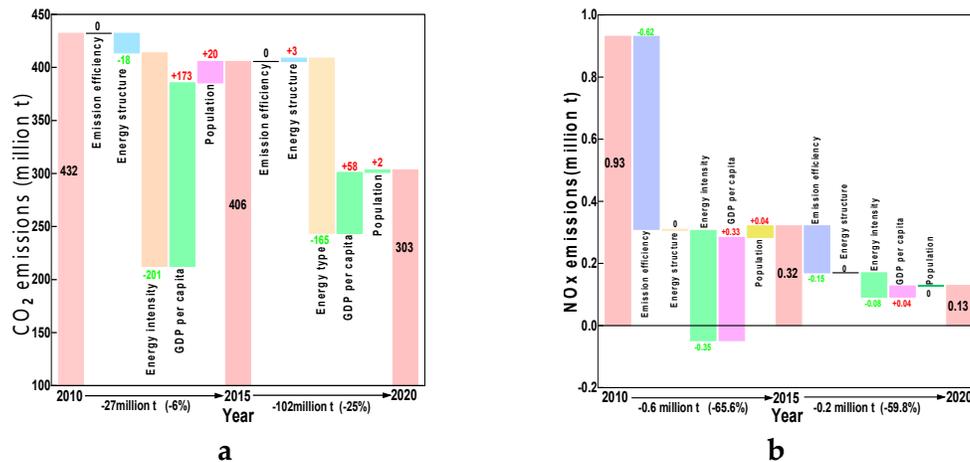


Figure 6. Different drivers of CO₂ and NO_x emissions from thermal power units in Beijing-Tianjin-Hebei, 2010-2020.

The trend in emissions due to coal consumption by thermal power units in Beijing-Tianjin-Hebei is generally consistent with the trend in overall energy emissions from power plants. NO_x emissions decreased by 86% and CO₂ emissions decreased by 33%. Figures 7a and b show the synergistic effects of CO₂ and NO_x emission factors due to coal consumption of thermal power units in the Beijing-Tianjin-Hebei from 2010 to 2020. Per capita GDP (economic growth) and population are the main drivers of increased emissions. Without the influence of other factors, an increase in per capita GDP (economic growth) and population would result in a 52% and 39% increase in CO₂ and NO_x emissions. Conversely, reducing energy intensity leads to a downward trend in CO₂ and NO_x emissions. The end-of-pipe treatment led to a significant reduction in NO_x emissions. Unaffected by other factors, the reduction in energy intensity led to an 84% decrease in CO₂ emissions, while end-of-pipe treatment led to an 81% decrease in NO_x emissions. The share of coal in the total energy for power generation in Beijing-Tianjin-Hebei declined from 97% in 2010 to 87% in 2020. It shows that China's energy structure is moving in the direction of cleaner and more diversified, with the proportion of non-fossil energy sources increasing year by year. Although the decline in the share of coal reflects China's progress in energy restructuring, 87% is still high. Consideration could be given to strengthening the development of clean energy to further promote the optimization of the energy structure and reduce reliance on coal, while continuing to vigorously develop clean energy sources such as wind power, solar power and hydropower. Reduce overall energy consumption by improving energy consumption and energy efficiency measures. For the use of coal, priority should be given to the adoption of clean and efficient utilization technologies, such as supercritical power generation technology. As shown in Figure 8, there is a general positive correlation between CO₂ emissions and NO_x emissions resulting from coal usage. However, in Figure 8a, the CO₂ and NO_x emissions associated with petroleum in Beijing exhibit a certain negative correlation. As CO₂ emissions increase, NO_x emissions show a decreasing trend. This indicates that end-of-pipe treatment plays a crucial role in NO_x reduction during the adjustment of the energy structure.

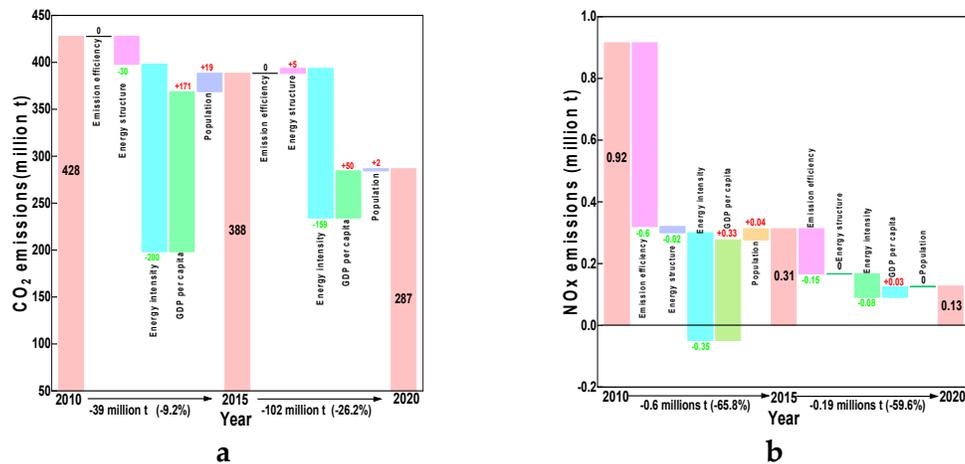


Figure 7. Different drivers of coal combustion emissions from thermal power units in Beijing-Tianjin-Hebei, 2010-2020.

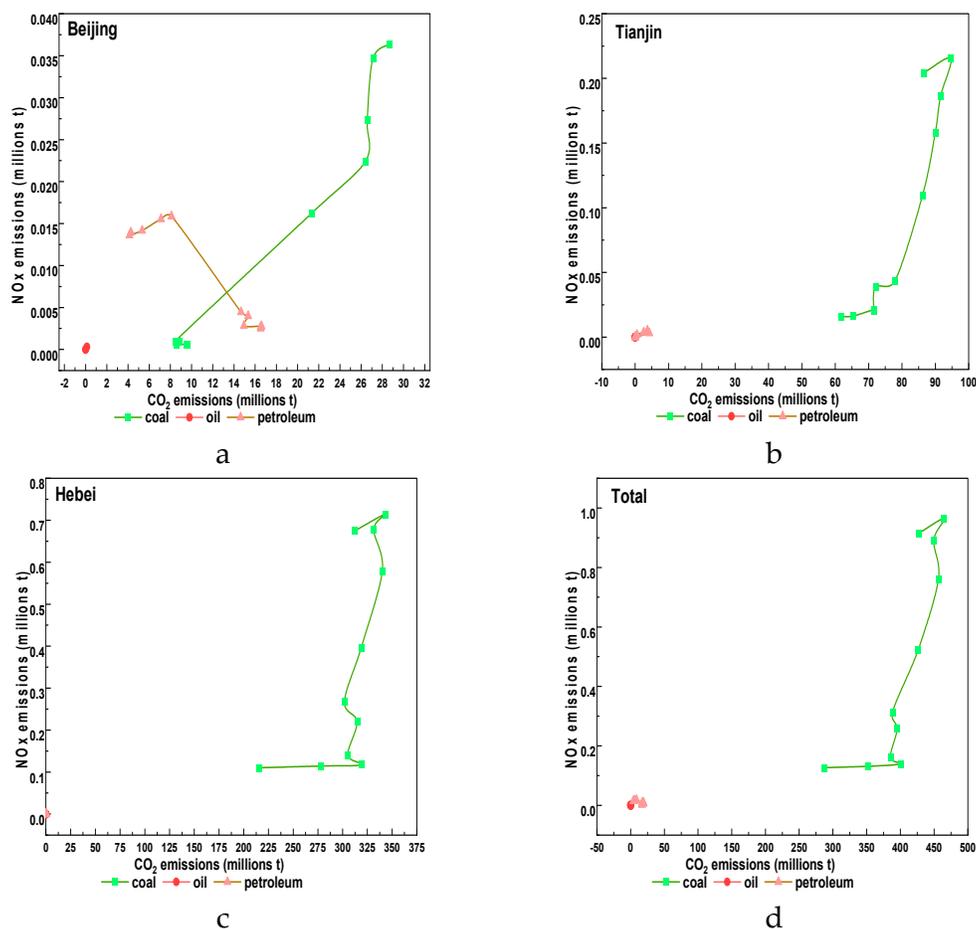


Figure 8. Synergistic trend of fuel types for CO₂ and NO_x emissions from thermal power units in Beijing-Tianjin-Hebei, 2010-2020.

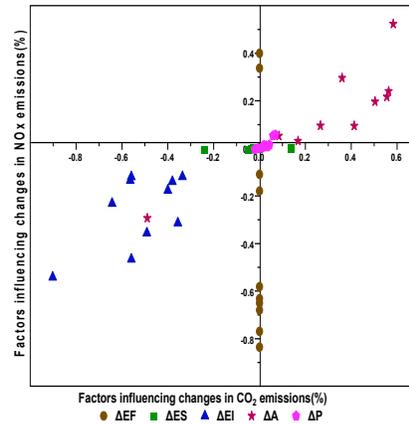


Figure 9. Synergistic effects of different factors on CO₂ and NO_x emissions from thermal power units in Beijing-Tianjin-Hebei (symbols located in the first and third quadrants indicate synergistic growth and synergistic reduction of NO_x and CO₂ emissions).

4. Conclusions

An in-depth understanding of the synergistic drivers of NO_x and CO₂ emissions from thermal power plants is of great significance to the realization of the vision of “Beautiful China” and the strategic goal of “Carbon Peak and Carbon Neutrality”. The detailed NO_x and CO₂ emission inventories of Beijing-Tianjin-Hebei were compiled and analyzed in depth by using the Log Mean Divisia Index (LMDI). Synergistic trends between emission changes are revealed and key synergistic factors influencing these trends are identified.

The analysis results show that the implementation of the policy effectively reduces NO_x emissions, but the effect on CO₂ reduction is not obvious. Economic growth is a key driver of increased emissions, while reductions in energy intensity are a key synergistic mitigating factor. However, reductions in energy intensity have a more significant effect on reducing CO₂ emissions, because reductions in energy consumption directly reduce CO₂ production. For NO_x emissions, although reductions in energy intensity also contribute to emission reductions, their effect is 38.4% smaller than the reduction in CO₂ because NO_x emissions are mainly influenced by other factors (e.g., combustion technology and control measures). Beijing-Tianjin-Hebei is located in China’s “Capital Economic Circle”, which is an important engine for economic development in the northern region, and therefore may hinder emissions reduction in the future economic growth process. However, we find that the potential to reduce emissions from the energy structure is still huge. Therefore, the pressure to reduce emissions brought about by the process of economic growth can be offset by implementing more effective and sustained synergistic emission reduction measures through energy restructuring. The economy, as an important development goal, should be shifted towards sustainable development while maintaining reasonable economic growth and reducing CO₂ emissions and pollutant emissions resulting from economic development.

Future synergistic emission reduction efforts can learn from the experience of past policy implementation in order to optimize and avoid past shortcomings. An in-depth analysis of different energy types and their emission reduction control measures can provide guidance for future policy formulation. The study analysis shows that reducing energy intensity plays a significant role in controlling the growth of NO_x and CO₂ emissions. This finding implies that emission reduction measures that have been proven to be effective, such as the implementation of more stringent emission standards and lower standard coal consumption requirements, should be consistently applied to both coal and gas-fired.

In addition, the analysis for coal-fired emissions reveals that the energy structure of thermal power units in Beijing-Tianjin-Hebei is still coal-biased, especially in Hebei and Tianjin. Although the share of coal in total energy for power generation has declined by 10 percent, the potential for energy

restructuring remains huge. Therefore, in order to achieve strong control of emissions, multifaceted policies need to be designed that go beyond traditional means of control. For example, studies have shown that the use of natural gas as a substitute for coal is an effective synergistic control strategy. Beijing has achieved significant results in reducing NO_x and CO₂ emissions through this pathway. At the same time, several studies have assessed the potential benefits of reducing emissions from coal-fired power generation in China and have confirmed that reducing the demand for coal-fired power can radically reduce CO₂ and NO_x emissions. In addition, the structural optimization of gensets can improve energy efficiency and significantly reduce CO₂ and NO_x emissions, which can simultaneously improve air quality and climate benefits. And end-of-pipe treatment will continue to reduce NO_x emission levels. Widespread adoption of more advanced control measures can reduce CO₂ and NO_x emissions from thermal power units, but cannot completely eliminate emissions. It also demonstrates the future competitiveness of clean energy and the necessity to work towards replacing coal-fired power generation with clean and renewable energy.

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