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Study on Synergistic Emission Reduction in Greenhouse Gases and Air Pollutants in Hebei Province

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Abstract: Addressing climate change and improving air quality are prominent tasks facing China's ecological environment. The synergistic emission reduction in greenhouse gases (GHGs) and air pollutants has become an important task of environmental governance in different provinces. In this study, Hebei Province was taken as the research object. Firstly, the emission factors of GHGs (CO_2, CH_4, and NO_2) and air pollutants (SO_2, NO_X, and smoke & dust) in Hebei Province from 2011 to 2020 were calculated and analyzed. Seven socio-economic indicators were selected to analyze the trend during the study period. The Spearman rank correlation coefficient method was used to analyze the correlation between GHG and air pollutant emissions. Finally, the synergistic control effect coordinate system and the cross-elasticity coefficient of emission reduction were used to study the synergistic emission reduction effect of GHGs and air pollutants. The results showed that the total amount of GHG emissions fluctuated slightly from 2011 to 2020, and energy activities were the main source of total GHG emissions. The total emissions of air pollutants decreased year by year, and decreased by 71.13% in 2020 compared with 2011. During the study period, the emission synergy between smoke & dust and GHG was better than that between SO_2, NO_X, and GHG. GHG and SO_2, NO_X, and smoke & dust achieved synergistic emission reduction in most years, but the overall emission reduction synergy was poor.

Keywords: synergistic emission reduction; socio-economic indicators; rank correlation coefficient; greenhouse gases; air pollutants

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1. Introduction

In 2006, China became one of the largest CO_2 emission countries in the world, contributing 14.3% of the sum of the world's CO_2 emission. In 2020, CO_2 emission reached 10.1×10^9 t [1], an increase of 382.63% compared with 1990, and accounted for about 29% of the total global CO_2 emission. In 2020, China proposed to increase the country's autonomous contribution, and strive for CO_2 emission to peak by 2030, and achieve carbon neutrality by 2060 [2]. The Air Pollution Prevention Action Plan ("Ten Air Regulations") in 2013 and the Three-Year Action Plan for Winning the Battle of Defending the Blue Sky ("Blue Sky Defense War") in 2018 were released and implemented, and China's air quality has been significantly improved. In order to realize synergies between energy saving, carbon reduction, and pollution reduction, and sustained improvement in ecological and environmental quality, and to ensure the completion of the energy saving and emission reduction targets of the 14th Five-Year Plan, the State Council issued the "Comprehensive Work Program for Energy Saving and Emission Reduction of the 14th Five-Year Plan" and the "New Pollutant Management Action Program" in 2022, but 37.2% of the 339 cities at the prefecture level or above still exceeded the ambient air quality standards (GB 3095-2012) in 2022. As the main sources of greenhouse gas (GHG) and air pollutants are fossil energy consumption, industrial production, and residential life, with the characteristics of "the same root, the same source, and the same process", which means that carbon reduction and pollution reduction have the same control targets and can be synergistically promoted [3–5].

Most foreign scholars use models to simulate the synergistic emission reduction in GHGs and air pollutants. The models used mainly include the Air Pollution Emission Experiments and Policy Analysis Model (APEEP), GHGs, Regulated Emissions, Energy Use in Transportation (GREET), and Computable General Equilibrium (CGE) [6]. Muller [7] used the APEEP and GREET model for simulation to monetize the consideration of damages caused by pollutants associated with CO_2, and the results show that different forms of energy in the electricity generating sector have different costs of environmental pollution. Schwanitz et al. [8] synthesized eleven equilibrium models and conducted a scenario analysis of low-carbon energy policies in the European region. The findings demonstrate that low-carbon policies can help decrease energy dependence, boost energy security, and encourage the development of renewable energy sources other than biomass.

Most of the existing studies in China have focused on the assessment of the synergistic effect of engineering and technological emission reduction measures in a city or an industry, and have focused on the synergistic effect brought about by pollution control policies [9]. By creating a synergistic emission reduction equivalence index, Liu et al. [10] assessed the comprehensive emission reduction effect of individual technical measures on the major air pollutants (CO_2, SO_2, and NO_x) and came to the conclusion that the NO_x emission reduction target in China's iron and steel industry can only be attained by front-end and process control measures, while CO_2 and SO_2 emission reduction may be realized by implementing end treatment measures with higher costs. Zhou et al. [11] used the energy–environment–economy input–output method to calculate China's energy–environmental complete consumption coefficient in 2007, based on which they analyzed the changes in emissions of CO_2, SO_2, and NO_x and the degree of synergistic emission reduction in the thermal power industry after adopting a variety of abatement measures, and the results showed that optimizing the energy structure and the coal-fired power generation structure are the fundamental measures to reduce air pollutants in the thermal power industry. To assess the synergistic control effect of technical emission reduction measures on CO_2, SO_2, and NO_x in the thermal power industry, Mao et al. [12] used the synergistic control effect coordinate system, cross elasticity analysis of pollutant emission reduction, and unit pollutant emission reduction cost. The results showed that the end-of-pipe control measures are not synergistic, while the front-end control measures and the process control measures have a better synergistic effect. In addition, the priority of end-of-pipe control measures is ranked later. The results show that the end-of-pipe measures are not synergistic, while the front-end control measures and process control measures have better synergistic effects.

Socio-economic indicators are closely related to GHG and air pollutant emission, with factors like population growth and economic development influencing emission levels, while emission reduction measures and sustainable development policies help to protect the environment while enhancing economic efficiency. Common socio-economic indicators include the gross domestic product (GDP), GDP per capita, per capita income, population size, population growth rate, carbon emission, pollutant emission, and natural resource consumption. Zhang et al. [13] analyzed the relationship between air quality and per capita GDP over 13 years by taking 64 cities under key environmental protection in China as samples, and the study showed that the economic development of these cities is based on environmental pollution, and found that PM_{10} is the main pollutant affecting urban air quality from it. Li et al. [14] explored the GHG emissions from urban domestic waste treatment and disposal in China and its socio-economic factors by constructing the STIRPAT model, and the study showed that the urban population and the per capita GDP had a positive impact on the GHG emissions from urban domestic waste. Li et al. [15] explored the factors affecting Beijing's air quality by constructing a multivariate nonlinear econometric model and adopting a principal component analysis and found that the relationship between GDP per capita and air quality indicators is an inverted "N" curve, i.e., when the relationship is in the downward part of the inverted "N" curve, air quality decreases with the growth of GDP per capita, and on the contrary, when the relationship is in the upward part of the inverted "N" curve, air quality increases with the growth of GDP per capita. Wu et al. [16] explored the relationship between economic growth and air pollution using the Spatial Durbin Lag Model and a Semiparametric Spatial Lag Model, and their findings demonstrated a nonlinear association resembling an oscillatory curve, suggesting that economic growth impacts air quality to some extent. Wang et al. [17] analyzed panel data covering all Chinese provinces from 2000 to 2016, and they employed both a Dynamic Panel Data Model and a Panel Threshold Model to examine the influence of energy consumption structure and other factors on air pollution, and the results indicated that energy consumption structure contributes to air pollution in China's eastern, central, and western regions. Firtescu et al. [18] empirically assessed, from 1995 to 2019, 28 countries in Europe and their effect of environmental tax levels on GHG emissions, and the results showed that in most countries, the increase in environmental taxes leads to a decrease in GHG emissions.

Along with aims relating to the reduction in pollutant emission, China includes targets related to the drop in carbon emission per unit of GDP (carbon intensity) during the 12th Five-Year Plan period in the binding targets of the 5-year plan outline. The People's Republic of China planned to "implement synergistic control of GHG and air pollution, such as particulate matter, SO_2, NO_X, volatile organic compounds, ammonia and other air pollutants and GHGs" in its Law on the Prevention and Control of Air Pollution in 2015. In 2016, it was suggested to "strengthen the synergistic control of carbon emission and air pollutant emission" in the "13th Five-Year Plan" for the control of GHG emissions. In 2021, the "Guiding Opinions on Coordinating and Strengthening the Work Related to Climate Change and Ecological Environment Protection" emphasized the coordinated control of GHG and pollutant emissions as the key work, and clarified the tasks from five major areas, marking the stage of carbon reduction and pollution reduction from "weak correlation" to "strong combination". Hebei Province ranks among China's provinces with the highest energy consumption intensity and the most severe air pollution. The carbon emission of Hebei Province in 2019 totaled 914×10^6 t, roughly accounting for 8.02% of the nation's overall carbon emission [19,20]. Among the bottom 10 cities in the air quality ranking of 168 key cities in China in 2022, there were 4 cities belonging to Hebei Province (Baoding, Handan, Shijiazhuang, and Xingtai). The number of mildly polluted or worse days in Hebei province in 2022 with ambient air quality that was remained 95, making up 26.02% of the total number of days in the year. Therefore, research on the synergistic emission reduction effect of GHGs and air pollutants in Hebei Province is of great scientific significance and practical value, which is also one of the effective ways to cope with climate change [21].

In this study, the emission factor method was used to calculate and analyze the emissions of GHGs and air pollutants in Hebei Province from 2011 to 2020. Seven socio-economic indicators of Hebei Province directly related to GHGs and air pollutant emissions were selected to analyze the trend during the study period. The Tapio decoupling model was used to study the relationship between economic growth and GHG emissions. The Spearman rank correlation coefficient method was applied to analyze the correlation between GHG and air pollutant emission. Finally, the synergistic control effect coordinate system and the cross-elasticity coefficient of emission reduction were used to quantitatively measure and compare the synergistic emission reduction effect of GHGs and air pollutants.

2. Methods and Data Sources

2.1. GHG Emission Measurement Methods and Data Sources

According to the "Provincial GHG Inventories Guidelines" (referred to as "Provincial Guidelines") [22], the "2006 IPCC Guidelines for National GHG Inventories" (referred to as "IPCC Guidelines") [23] was used to calculate the GHG emissions in Hebei Province, including energy activities, industrial production processes, agriculture, land use change and forestry, and waste disposal. In this study, the types of GHGs included CO_2, CH_4, and N_2O.

2.1.1. Energy Activities

The GHG emissions generated by energy activities are mainly the calculation of CO_2 produced by fossil fuel combustion. This study selects three types of energy sources: coal, oil, and natural gas. The formula is as follows:

$$E_e = \sum_i \left(C_i \times NCV_i \times CEC_i \times COF_i \times 44/12 \times 10^{-3}\right) \quad (1)$$

where E_e is the GHG emissions from energy activities (10^4 t); C_i is the consumption of fuel i (10^4 t or 10^8 m^3); NCV_i is the average low calorific value of fuel i (TJ/Gg or TJ/10^8 m^3); CEC_i is the carbon content per unit calorific value of fuel i (tC/TJ); COF_i is the CO_2 factor of fuel i; 44/12 is the molecular weight ratio of CO_2 to C; 10^{-3} is the unit conversion coefficient.

2.1.2. Industrial Production Process

The GHGs produced in the industrial production process are used to calculate the CO_2 released during the cement production process and the steel production process.

(1) The calculation formula of CO_2 emission in the cement production process is as follows:

$$E_i = AD \times EF \times C_{cl} \quad (2)$$

where E_i is the CO_2 emission from the cement production process (10^4 t); AD is cement production (10^4 t); EF is the emission factor of a cement clinker; C_{cl} is the proportion of the cement clinker (%), using 75% [24].

(2) The calculation formula of CO_2 emission in the iron and steel production process is as follows:

$$E_j = AD_l \times EF_l + AD_d \times EF_d + (AD_r \times F_r - AD_s \times F_s) \quad (3)$$

where E_j is the CO_2 emission (10^4 t) from the steel production process; AD_l is the amount of limestone consumed by iron and steel enterprises (10^4 t); EF_l is the emission factor of limestone consumption; AD_d is the amount of dolomite consumed by iron and steel enterprises (10^4 t); EF_d is the emission factor consumed by dolomite; AD_r is the amount of pig iron consumed in steelmaking (10^4 t); F_r is the average carbon content of pig iron for steelmaking; AD_s is the steel output of steelmaking (10^4 t); F_s is the average carbon content of steel production.

2.1.3. Agriculture

Agricultural GHG emissions mainly include CH_4 emission from paddy fields, N_2O emission from agricultural land, CH_4 emission from animal intestinal fermentation, and CH_4 and N_2O emissions from animal manure management.

(1) The calculation formula of CH_4 emission from paddy field is as follows:

$$E_r = AD \times EF \times 10^{-3} \quad (4)$$

where E_r is CH_4 emission from the paddy field (10^4 t); AD is rice planting area (10^4 hm^2); EF is the CH_4 emission factor (kg/hm^2).

(2) N_2O emission from agricultural land

The calculation of N_2O emission from agricultural land includes two parts: direct emission and indirect emission. Direct emission refers to the emission caused by nitrogen input such as nitrogen fertilizer, manure, and straw returning. The calculation formula is

$$E_{f1} = (N_c + N_s) \times EF \quad (5)$$

where E_{f1} is the direct emission of N_2O from agricultural land (calculated as N_2O); N_c is fertilizer nitrogen input (10^4 t); N_s is the nitrogen input of straw returning (10^4 t); EF is the corresponding emission factor of N_2O (kgN_2O-N/kgN). The main crops involved in the calculation of the straw returning amount are wheat, corn, cotton, soybean, tobacco, peanut, hemp, sugar beet, potato, and vegetables.

Indirect emission refer to emission caused by atmospheric nitrogen deposition and nitrogen leaching runoff. The calculation formula is

$$E_{f2} = (N_{in} \times 20\% + N_{in} \times 10\%) \times EF_i \quad (6)$$

where E_{f2} is the indirect emission of N_2O from agricultural land (calculated as N_2O); N_{in} is the nitrogen input of agricultural land (10^4 t); EF_i is the emission factor (kgN_2O-N/kgN); i is the emission caused by atmospheric nitrogen deposition and leaching, and runoff loss.

(3) Regarding animal intestinal fermentation and manure management (CH_4), the manure management N_2O emission calculation formula is

$$E_n = \sum\left(AP_j \times EF_{nj} \times 10^{-3}\right) \quad (7)$$

where E_n is the GHG emissions from intestinal fermentation or manure management (10^4t/year); AP_j is the year-end inventory of class j animals (10^4 heads); EF_{nj} is the emission factor (kg/head/year) of class j animals, including cattle, horses, donkeys, mules, pigs, goats, and sheep.

2.1.4. Land Use Change and Forestry

Land use change and forestry mainly consider the change in forest land area and the change in the carbon pool caused by the growth of various tree species. The calculation formula is

$$C = V \times \overline{SVD} \times \overline{BEF} \times (CR - GR) \times 0.5 \times 44/12 \quad (8)$$

where C is the carbon sequestration of forest land ($10^4 CO_2$); V is the total volume of standing trees (10^4 m^3); $\overline{SVD}$ is the weighted mean of wood density (t/m^3); $\overline{BEF}$ is the weighted mean of the biomass conversion coefficient; GR and CR are the growth rate (%) and consumption rate (%) of the annual volume of standing trees, respectively. 0.5 is the biomass carbon content.

2.1.5. Waste Disposal

(1) The calculation formula of CH_4 emission from municipal solid waste landfill is

$$E_l = (MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12 - R) \times (1 - OX) \quad (9)$$

where E_l is the CH_4 emission (10^4 t) produced by landfill treatment; MSW_T is the total amount of solid waste generated (10^4 t); MSW_F is the landfill disposal rate of solid waste; MCF is the CH_4 correction factor of landfill; DOC is degradable organic carbon (kg/kg waste); DOC_F is the proportion of decomposable DOC; F is the CH_4 ratio of landfill gas; R is the amount of methane recovery (10^4 t); 16/12 is the molecular weight ratio of CH_4/C; OX is an oxidation factor.

(2) The calculation formula of CO_2 emission from municipal solid waste incineration is

$$E_m = \sum_i (IW_i \times CCW_i \times FCF_i \times EF_i \times 44/12) \quad (10)$$

where E_m is the CO_2 emission from waste incineration (10^4 t/a); i represents urban solid waste; IW_i is the amount of waste incineration (10^4 t/a); CCW_i is the proportion of carbon content in waste; FCF_i is the proportion of mineral carbon in the total carbon in the waste; EF_i is the combustion efficiency of the waste incinerator; 44/12 is the molecular weight ratio of CO_2 to C.

(3) The calculation formula of CH_4 emission from domestic sewage treatment is

$$E_{wt} = TOW \times B_0 \times MCF_{wt} - R_{wt} \tag{11}$$

where E_{wt} is the CH_4 emission from domestic sewage treatment (10^4 t); TOW is the total amount of organic matter in domestic sewage (kg BOD/year); B_0 is the maximum production capacity of CH_4 (kg CH_4/kg BOD); MCF_{wt} fouling is a CH_4 correction factor; R_{wt} is CH_4 recovery (10^4 t).

The main activity level data of methane emission from domestic sewage treatment are *TOW*, with biochemical oxygen demand (BOD) as an important indicator. In Hebei Province, there is only statistical data of chemical oxygen demand (COD). In this study, the correlation between BOD and COD recommended by Provincial Guidelines was used for conversion.

(4) The calculation formula of N_2O emission from wastewater treatment is

$$E_t = ((P \times P_r \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_S) \times EF_E \times 44/28 \times 10^{-3} \tag{12}$$

where E_t is the N_2O emission from wastewater treatment (10^4 t); P is the number of the population (10^4); P_r is the annual per capita protein consumption (kg/person/year); F_{NPR} is the nitrogen content in protein (kg N/kg protein); $F_{NON\text{-}CON}$ is a non-consumptive protein factor in wastewater; $F_{IND\text{-}COM}$ is an industrial and commercial protein emission factor; EF_E is the N_2O emission factor (kg N_2O/kg N), and 44/28 is the conversion coefficient of N_2 and N_2O.

In this study, the data of coal, oil, natural gas, cement, steel, limestone, dolomite, rice planting area, crop yield, livestock number, COD, and population were derived from "Hebei Statistical Yearbook" [25], and the data of solid waste and part of the total volume of standing trees were derived from "China Statistical Yearbook" [26] and "China Forestry and Grassland Statistical Yearbook" [27]. It should be noted that the total volume of standing trees only counted the data of 2009, 2013, and 2018, and the data of other years were obtained by interpolation and extrapolation recommended by the Provincial Guide. The emission factors recommended by the Provincial Guidelines are used in the calculation, and the missing part adopts the default value. The total amount of GHG emissions is calculated with the CO_2 equivalent (CO_2e), and the contribution of different types of GHGs to the greenhouse effect is multiplied by the corresponding GHG global warming potential (GWP). The GWPs of CH_4 and N_2O are 25 and 298 [23].

2.2. Air Pollutant Emission Measurement Methods and Data Sources

The emission data of air pollutants (SO_2, NOx, and smoke & dust) from 2011 to 2020 were derived from the "China Statistical Yearbook". Firstly, the conversion coefficients of three kinds of air pollutants were calculated based on the pollution equivalent value of air pollutants stipulated in the Environmental Protection Tax Law of the People's Republic of China (2018) (Table 1). The comprehensive emissions of air pollutants were calculated [28] by the formula as follows:

$$Q_{AP} = \sum_{i=1}^{j} Q_j \times \alpha_j \tag{13}$$

where Q_{AP} is the total amount of air pollutant emissions (10^4 t); Q_j is the emission of the jth air pollutant (10^4 t); α_j is the conversion coefficient of air pollutants. Because the data on smoke & dust in the yearbook were not counted separately, the conversion coefficient of smoke & dust in this study was the average value of general dust and smoke [29].

Table 1. SO_2, NO_X, smoke & dust air pollutant equivalent values.

Pollutants	Equivalent Pollution Value	Conversion Coefficient Value
SO_2	0.95	1/0.95
NO_X	0.95	1/0.95
General dust	4	1/4
Smoke	2.18	1/2.18
Smoke & dust	/	0.35

2.3. Analysis of Socio-Economic Indicators

In this study, seven socio-economic indicators of Hebei Province, which were directly related to GHG and air pollutant emissions, were analyzed from 2011 to 2020, including gross domestic product (GDP), energy consumption, power generation, steel production, cement production, car ownership, and food production. The data were from the "Hebei Statistical Yearbook".

2.4. Tapio Decoupling Model

In order to further explore the mechanism behind the socio-economic indicators and GHG emissions in Hebei Province, a decoupling model was used to study the relationship between economic growth and GHG emission. It is generally believed that there is a decoupling relationship between economic growth and GHG emissions when a region brings the same or faster economic growth with lower resource consumption and environmental pressure over a certain period [30]. The most widely applied model in a decoupling analysis is the Tapio model proposed by Tapio in 1970. This model uses the concept of "elasticity" to dynamically reflect the relationship between economy and carbon emission [31]. The Tapio decoupling model divides the decoupling state into three categories and eight subcategories according to the decoupling index T, as shown in Table 2. Strong decoupling is the most ideal state, representing that the economy is growing, but carbon emission is declining. Strong negative decoupling is the worst state, representing that the economy is declining, and carbon emission are increasing. Each decoupling state represents different meanings.

Table 2. Decoupling index and its corresponding state.

Type	Decoupling State	ΔCO_2	ΔGDP	T
Decoupling	Strong decoupling	<0	>0	T < 0
	Weak decoupling	>0	>0	0 < T < 0.8
	Recession decoupling	<0	<0	T > 1.2
Negative decoupling	Expansion negative decoupling	>0	>0	T > 1.2
	Strong negative decoupling	>0	<0	T < 0
	Weak negative decoupling	<0	<0	0 < T < 0.8
Connection	Expansion connection	>0	>0	0.8 < T < 1.2
	Fading connection	<0	<0	0.8 < T < 1.2

This study selects the Tapio model to explore the relationship between GHG emissions and economic growth in Hebei Province. GHG emissions and GDP growth were selected to establish a decoupling model [32]. The calculation formula is

$$T = \frac{\Delta C / C_n}{\Delta GDP / GDP_n} \tag{14}$$

where T is the decoupling elastic coefficient; ΔC is the difference in GHG emissions between the nth year and the $n-1$th year (10^4 t); Cn is the GHG emissions in the nth year (10^4 t); ΔGDP is the difference between the GDP of the nth year and the GDP of the $n-1$th year (CNY billion); GDP_n is the gross regional product (CNY billion) of the nth year.

2.5. Rank Correlation Coefficient Method

The link between GHGs (CO_2, CH_4, and NO_2) and air pollutants (SO_2, NO_X, smoke & dust) was assessed using Spearman rank correlation coefficient [33]. The calculation formula is as follows:

$$r_s = 1 - \frac{6\sum_{i=1}^{N} d_i^2}{N(N^2 - 1)} \tag{15}$$

$$d_i = X_i - Y_i \tag{16}$$

where r_s is Spearman rank correlation coefficient, X_i and Y_i are the serial numbers of GHGs and air pollutants arranged from small to large, d_i is the difference between X_i and Y_i, and N is the number of samples.

The r_s is in the range of -1 to 1. When $r_s > 0$, GHGs and air pollutants are positive, whereas $r_s < 0$, it suggests that they are negatively associated; when r_s is close to zero, it means that they are either little or no linear association. The Sig. (two-tailed significance) value is a statistical criterion used to determine whether the correlation coefficient is significant. It represents the probability value of the correlation coefficient observed in the hypothesis test, which is used to determine whether the correlation coefficient really exists in the population or is only due to random sampling errors. In general, the significance level is usually used to determine the critical point of the Sig. value. Common significance levels included 0.05 (5%) and 0.01 (1%). If the Sig. value is less than or equal to the significance level regarded as significant; if the Sig. value is greater than the significance level typically regarded as not significant.

2.6. Evaluation Method of Synergistic Control Effect

2.6.1. Coordinate System of Synergistic Control Effect

The coordinate system of the synergistic control effect refers to marking the emission changes in GHGs and air pollutants in the rectangular coordinate system [34]. When the coordinate value is positive, it represents an increase in emission, and vice versa represents a decrease in emission. Therefore, when the emission change coordinate point falls in the first quadrant, it represents that the GHGs and air pollutants increase at the same time. When it falls in the third quadrant, it represents that the GHGs and air pollutants have emission reduction synergy. When it falls in the second and fourth quadrants, it represents that GHGs and air pollutants emission increase and decrease, and there is no emission reduction synergy.

2.6.2. Collaborative Control of Cross-Elasticity

In order to further evaluate the degree of synergy between GHG emission reduction and emission reduction in air pollutants (SO_2, NO_X, and smoke & dust), the cross-elasticity coefficient of synergistic emission reduction is introduced [12]. The calculation formula is as follows:

$$Els_{CE\text{-}SE} = \frac{\Delta CE/CE}{\Delta SE/SE} \tag{17}$$

$$Els_{CE\text{-}NE} = \frac{\Delta CE/CE}{\Delta NE/NE} \tag{18}$$

$$Els_{CE\text{-}SDE} = \frac{\Delta CE/CE}{\Delta SDE/SDE} \tag{19}$$

In the formula, $Els_{CE\text{-}SE}$, $Els_{CE\text{-}NE}$, and $Els_{CE\text{-}SDE}$ are the cross-elasticity coefficients of synergistic emission reduction in GHG and SO_2, NO_X, and smoke & dust, respectively. ΔCE is the emission reduction in GHG (million tons). ΔSE, ΔNE, and ΔSDE are the emission reduction in SO_2, NO_X, and smoke & dust (million tons). $\Delta CE/CE$ is the emission reduction rate of GHG. $\Delta SE/SE$, $\Delta NE/NE$, and $\Delta SDE/SDE$ are the emission reduction rates of air pollutants.

3. Results and Analysis

3.1. Analysis of Changes in GHG Emissions

Figure 1 displays the overall amount of GHG emissions in Hebei Province from 2011 to 2020 as well as the emission of each component. Overall, the total amount of GHG emissions from 2011 to 2015 fluctuated slightly, reaching a peak of 526 × 10^6 t CO_2e in 2013. Since 2015, it has shown a slow downward trend and fell to 510 × 10^6 t CO_2e in 2020. This is mainly due to the "13th Five-Year Plan" period, Hebei Province has vigorously adjusted its industrial structure, optimized its energy structure, strengthened energy conservation and consumption reduction, and increased forestry carbon sinks to effectively control GHG emissions.

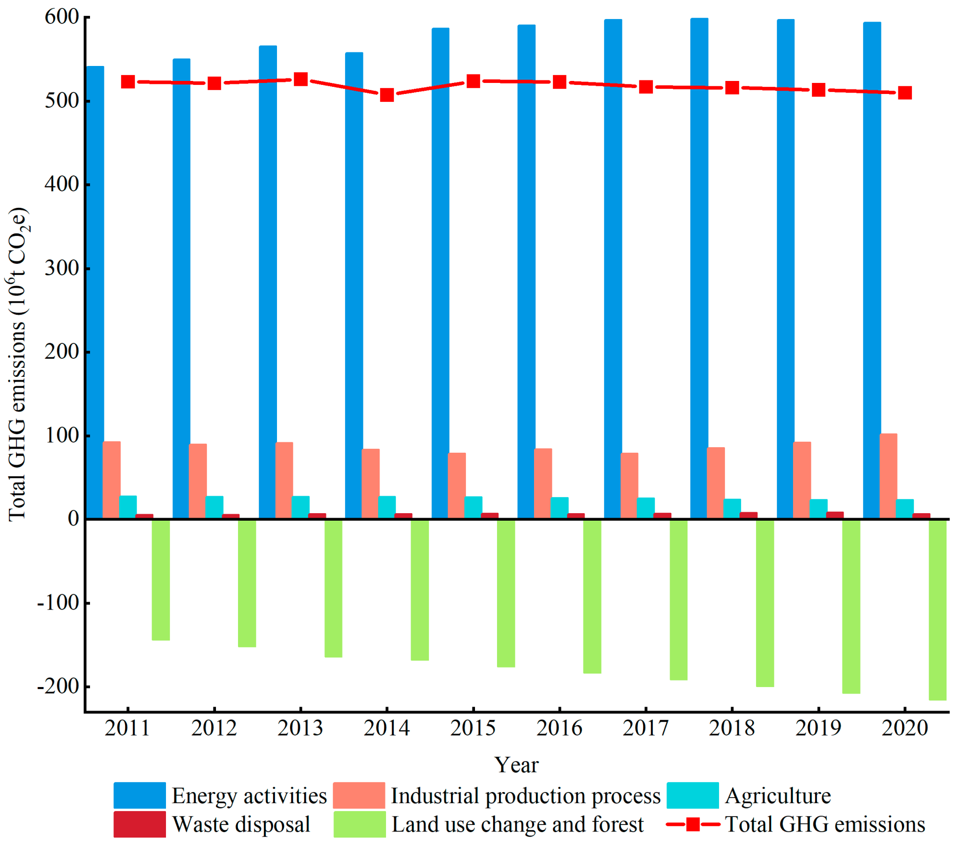

Figure 1. Change in total GHG emissions from 2011 to 2020.

From the perspective of emission sources, the GHG emissions from energy activities in Hebei Province from 2011 to 2020 are 541 × 10^6~598 × 10^6 t CO_2e, accounting for about 103.42~116.35% of the total GHG emissions, which is far more than other emission sources and is the primary source of emissions of GHGs. From 2011 to 2020, the GHG emissions from energy activities showed an overall upward trend. This is related to the rapid economic development and increasing energy consumption in Hebei Province since the 18th National Congress of the Communist Party of China. The total energy consumption of the whole society increased from 281 × 10^6 tce (ton of standard coal equivalent, referred to as tce) in 2011 to 328 × 10^6 tce in 2020, an increase of 16.77%, with 1.68% yearly growth on average. With the gradual implementation of policies such as air pollution control, removal of outdated production capabilities, and coal reduction and substitution in 2013, energy conservation and emission reduction have been further promoted, and energy consumption has continued to operate at a low level. In 2014, GHG emissions from energy activities decreased. From 2015 to 2020, its emissions increased but the growth rate was slow. This is because, since 2015, Hebei Province has combined energy conservation, coal cutting, and pollution reduction with structural adjustment, pollution control, and benefiting people's livelihood; vigorously promoted the thorough handling of air pollution; and implemented dual control of total energy consumption and intensity, and energy consumption has been effectively controlled.

After energy-related activities, the second biggest source of GHG emissions is industrial production process, which accounting for 15.09~19.98%. GHG emissions experienced fluctuations from 2011 to 2020, closely related to the production of industrial products, particularly steel and cement. Influenced by the global economic crisis in 2008, China initiated an investment of CNY 4 trillion in infrastructure development, which significantly accelerated the growth of the iron and steel sector in Hebei Province. By the end of 2012, the crude steel production in Hebei Province accounted for 25.18% of the total national output. Since 2013, the state has increased efforts to eliminate backward production capacity, which has contributed to the decline in steel production in Hebei Province to a certain extent. As of 2015, the proportion of crude steel production in Hebei Province has dropped to 23.42%. Hebei Province has accelerated the adjustment and optimization of the industrial structure and has continued to push the reduction in production capacity after the production of crude steel in the province removed a certain amount of production capacity. The ability to produce steel was decreased by 8.21×10^7 t during the "13th Five-Year Plan" period, and it fell down from a peak of 3.20×10^8 t to less than 2×10^8 t. Cement production is an industry with high emission and energy usage. Under the influence of environmental protection pressure and production restriction policy in Hebei Province, cement production decreased from a peak of 1.41×10^8 t in 2011 to 1.17×10^8 t in 2020, a decrease of 21.06%.

The GHG emissions from agriculture and waste treatment accounted for a relatively low proportion, representing 4.63~5.44% and 1.02~1.59% of the overall emissions of GHGs, respectively. The highest GHG emissions from agriculture in Hebei Province in 2011 were 2.77×10^7 t CO_2e, and the lowest in 2019 were 2.36×10^7 t CO_2e, showing a downward trend year by year. The GHG emissions from waste treatment increased from 5.33×10^6 t CO_2e in 2011 to 6.35×10^6 t CO_2e in 2020 due to the increase in population and consumption.

The amount of GHGs absorbed via land use change and forestry increased from 143×10^6 t CO_2e in 2011 to 215×10^6 t CO_2e in 2020, with a 5.01 percent yearly growth rate on average, which is closely related to the forestry development policy in Hebei Province. In 2011, Hebei Province issued the "12th Five-Year Plan for Forestry Development in Hebei Province" to strengthen forest scientific management, combine forestry construction with farmers' poverty alleviation and prosperity, and create a strong atmosphere for accelerating forestry development. At the same time, the implementation of key forestry ecological projects such as Taihang Mountain greening, Beijing-Tianjin-Hebei sandstorm source control, Three North Shelterbelt, Grain for Green, Coastal Shelterbelt, etc., has effectively alleviated the trend of ecological deterioration in some areas.

3.2. Analysis of Changes in Air Pollutant Emissions

The emissions of three types of air pollutants (SO_2, NO_X, and smoke & dust) in Hebei Province from 2011 to 2020 are shown in Figure 2. It is evident that Hebei Province's air pollution emissions from 2011 to 2020 typically followed a declining trend: SO_2 emission decreased year by year, from 1.48×10^6 t in 2011 to 0.17×10^6 t in 2020, with a decrease of 88.55%. NO_X decreased from 1.90×10^6 t in 2011 to 0.81×10^6 t in 2020, with a decrease of 57.27%. The amount of smoke & dust decreased from 0.47×10^6 t in 2011 to 0.13×10^6 t in 2020, a decrease of 71.97%. The results obtained are closely related to the air pollution control policy of Hebei Province. Beijing, Tianjin, and Hebei are three provinces and cities that are considered vital locations according to China's "Ten Air Regulations", which were published in 2013. The Beijing–Tianjin–Hebei region and the neighboring territories (referred to as "2 + 26" cities) were designated as critical locations in both the "2017 Air Pollution Prevention and Control Work Plan for Beijing-Tianjin-Hebei region and neighbouring territories" and the "Blue Sky Defense War". With the advancement of the process of air pollution control, the scope of key areas is constantly optimized and adjusted, reflecting the scientific and accurate improvement in air pollution control in China. In addition, Beijing–Tianjin–Hebei and the surrounding regions keep pushing for changes to the energy, transportation, and industrial structures in order to reduce air pollution emission; this is carried out in terms of governance measures. Along with reducing the negative effects of heavy pollution weather, it has also continued to carry out regional joint prevention and control, regularly organized air pollution tackling actions in the autumn and winter, and implemented special projects on the causes and treatment of heavy air pollution. These actions have provided strong scientific and technological support for accurate pollution control in the future.

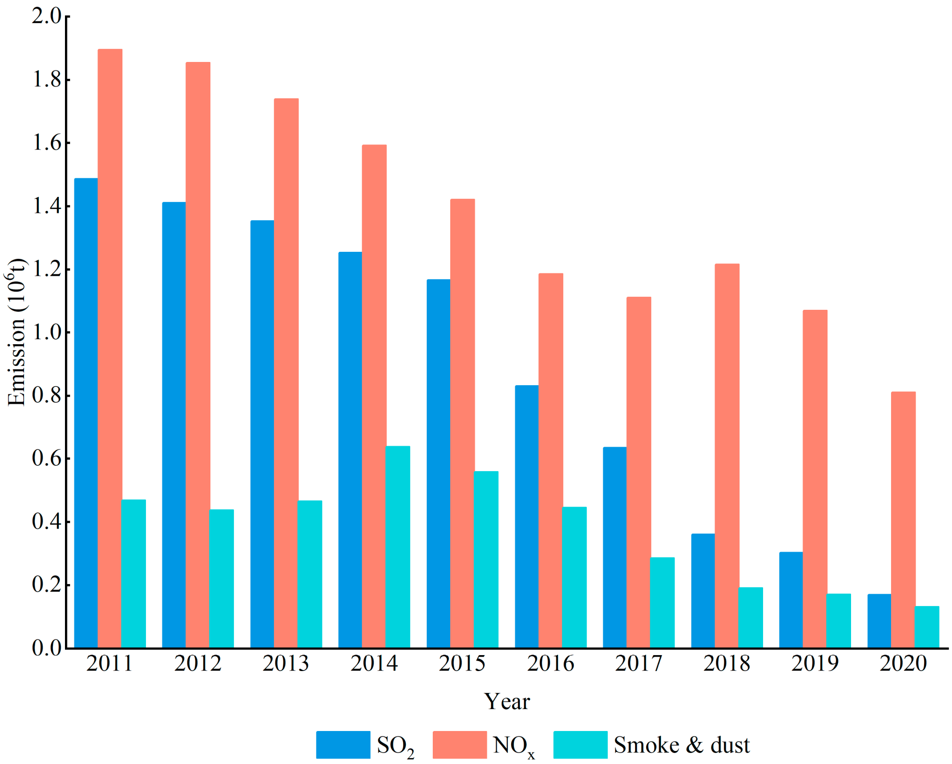

Figure 2. Air pollution emissions from 2011 to 2020.

3.3. Analysis of Socio-Economic Indicators

The trend of national economic and social development indicators in Hebei Province from 2011 to 2020 is shown in Figure 3. GDP and energy consumption affect almost all major GHG and air pollutant emissions [35]. Steel and cement are typical industrial products in Hebei Province. The output of steel and cement in 2021 ranks 1st and 11th in the country, respectively [26], which has a greater impact on GHG and air pollutant emissions [36–38]. There is a strong correlation between grain output and agricultural sources [39]. Power generation is closely related to power sources [40]. Compared with 2011, the GDP, energy consumption, steel production, cement production, car ownership, grain production, and power generation of Hebei Province in 2020 increased by 169.31%, 116.77%, 162.63%, 83.14%, 211.78%, 119.65%, and 149.04%, respectively.

Through the comparison of pollutant emissions and economic trends, it can be seen that Hebei Province has achieved effective reductions in major GHG and air pollutant emissions while maintaining stable and sustainable socio-economic development from 2011 to 2020. Although some measures are used to control emissions, such as banning the operation of “scattered” enterprises and eliminating old vehicles in advance, which may lead to certain economic losses and additional financial expenses, the former can promote the reform of high-energy-consuming and high-emission enterprises and promote the upgrading of traditional industries. The latter is expected to release the demand for new car sales and promote the growth of the automobile industry. Since the 18th National Congress of the Communist Party of China, China has eliminated more than 20 million yellow-labeled vehicles and old vehicles, which has promoted new vehicle sales to reach CNY 3.5 trillion. Air pollution control is organically combined with the optimization of industrial, energy, and transportation structures, which not only helps to continuously reduce GHG and air pollutant emissions, but also meets the needs of high-quality economic development [41].

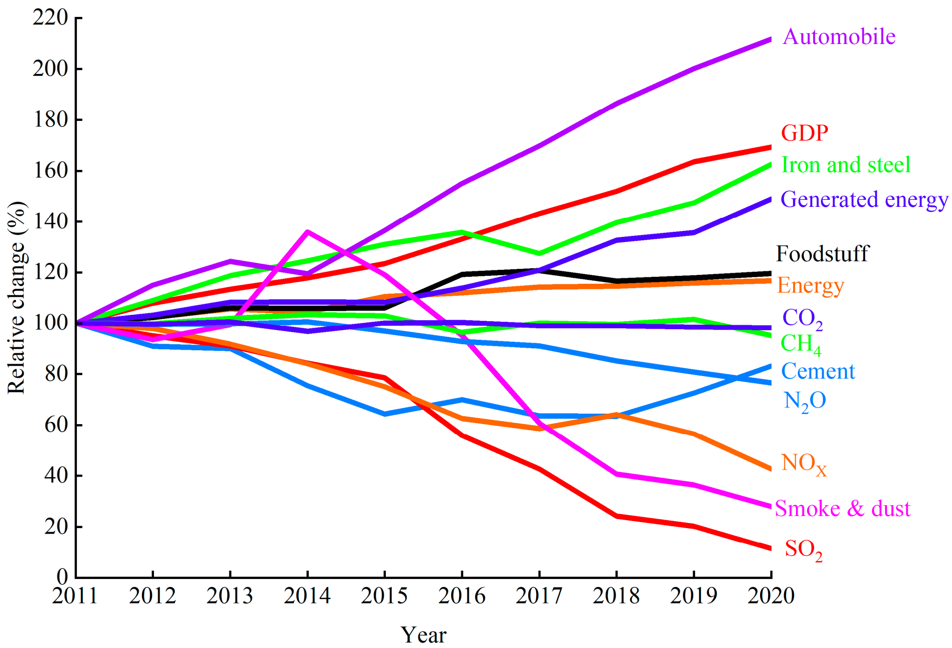

Figure 3. Development status of the main indicators of national economic and social development.

3.4. Decoupling Elasticity Analysis of GHG Emissions in Hebei Province

The results of the decoupling model between the change in GHG emissions and economic development in Hebei Province from 2012 to 2020 are shown in Table 3. It can be seen that from 2012 to 2020, the relationship between GHG emissions and economic growth in Hebei Province was in a weak decoupling state in 2013 and 2015, and the remaining years were in a strong decoupling state. It shows that the GHG emission rate of Hebei Province is negative, and the economic growth rate is positive. There is a negative correlation between GHG emissions and economic growth in Hebei Province. It is an ideal state that GHG emissions in Hebei Province are declining while economic growth is rising. This is related to the fact that Hebei Province has gradually attached importance to environmental protection and vigorously advocated for a low-carbon economy since 2011. For example, Hebei Province vigorously promotes industrial green upgrading, focusing on steel, petrochemical, chemical, and building material industries, and vigorously implements industrial energy-saving and low-carbon transformation, which not only improves energy efficiency but also reduces the waste of fossil fuels. In addition, there is the full implementation of cleaner production, accelerating the green development of agriculture and other ways to gradually achieve the development of low-carbon economy.

Table 3. Decoupling elasticity index and state of GHG emissions and economic growth in Hebei Province from 2012 to 2020.

Year	$\Delta C/C_n$	$\Delta GDP/GDP_n$	T	State
2012	−0.004	0.073	−0.050	Strong decoupling
2013	0.009	0.049	0.193	Weak decoupling
2014	−0.037	0.038	−0.978	Strong decoupling
2015	0.031	0.045	0.691	Weak decoupling
2016	−0.002	0.073	−0.022	Strong decoupling
2017	−0.011	0.071	−0.161	Strong decoupling
2018	−0.002	0.057	−0.029	Strong decoupling
2019	−0.005	0.071	−0.071	Strong decoupling
2020	−0.007	0.034	−0.208	Strong decoupling

3.5. Rank Correlation Analysis of GHGs and Air Pollutants

In order to understand the correlation between GHG and air pollutant emissions, the rank correlation analysis of GHGs (CO_2, CH_4, and NO_2) and air pollutant (SO_2, NO_X, and smoke & dust) emissions in Hebei Province from 2011 to 2020 was carried out. Table 3 presents the findings. As Table 4 illustrates, all Sig. (two-tailed) values are less than 0.05 at the significance level of 0.05, which suggests that these correlation coefficients are statistically significant. The Spearman rank correlation coefficients of SO_2 with NO_X and NO_2 were 1.000 and 0.915, respectively ($p < 0.01$), indicating that there was a high positive correlation between SO_2 and NO_X and NO_2. The Spearman rank correlation coefficient between NO_X and NO_2 was 0.915 ($p < 0.01$), indicating that there was a high positive correlation between NO_X and NO_2. In addition, the Spearman rank correlation coefficient between smoke & dust and NO_2 was 0.903 ($p < 0.01$), indicating that there was a high positive correlation between smoke & dust and NO_2, and the correlation between other variables was not significant. In general, these correlation coefficients indicate that there is a certain degree of correlation between different pollutant indicators.

Table 4. Rank correlation coefficient between GHGs and air pollutants.

			r_s					
			SO_2	**NO_X**	**Smoke & Dust**	**CH_4**	**NO_2**	**CO_2**
r_s	SO_2	Correlation coefficient	1.000	1.000 **	0.758 *	0.358	0.915 **	0.491
		Sig. (two-tailed)			0.011	0.310	0.000	0.150
	NO_X	Correlation coefficient	1.000 **	1.000	0.758 *	0.358	0.915 **	0.491
		Sig. (two-tailed)			0.011	0.310	0.000	0.150
	Smoke & dust	Correlation coefficient	0.758 *	0.758 *	1.000	0.661 *	0.903 **	0.345
		Sig. (two-tailed)	0.011	0.011		0.038	0.000	0.328
	CH_4	Correlation coefficient	0.358	0.358	0.661 *	1.000	0.564	−0.018
		Sig. (two-tailed)	0.310	0.310	0.038		0.090	0.960
	NO_2	Correlation coefficient	0.915 **	0.915 **	0.903 **	0.564	1.000	0.297
		Sig. (two-tailed)	0.000	0.000	0.000	0.090		0.405
	CO_2	Correlation coefficient	0.491	0.491	0.345	−0.018	0.297	1.000
		Sig. (two-tailed)	0.150	0.150	0.328	0.960	0.405	

"**" means at the 0.01 level (two-tailed), the correlation is significant; "*" indicates that at the 0.05 level (two-tailed), the correlation is significant.

3.6. Cross-Elasticity Analysis of Synergy Degree and Emission Reduction

3.6.1. Synergy Analysis

Because the emissions of GHG and air pollutant are positive, all the points fall in the first quadrant, so the first quadrant is selected as the research object. By observing the four-quadrant diagram of the total amount of GHG emissions in Hebei Province from 2011 to 2020 with the emissions of SO_2, NO_x, smoke & dust and the total amount of air pollutants (Figure 4a–d), we can intuitively see the emission synergy of their emissions in different years. In 2011~2012, 2013~2014, and 2015~2020, all the emissions of GHG, SO_2, NO_X, smoke & dust, and air pollutants decreased, with good emission synergy. In addition, the emissions of smoke & dust and GHG in 2012~2013 were rising, indicating that the synergistic effect of smoke & dust and GHG emissions is better than SO_2 and NO_x.

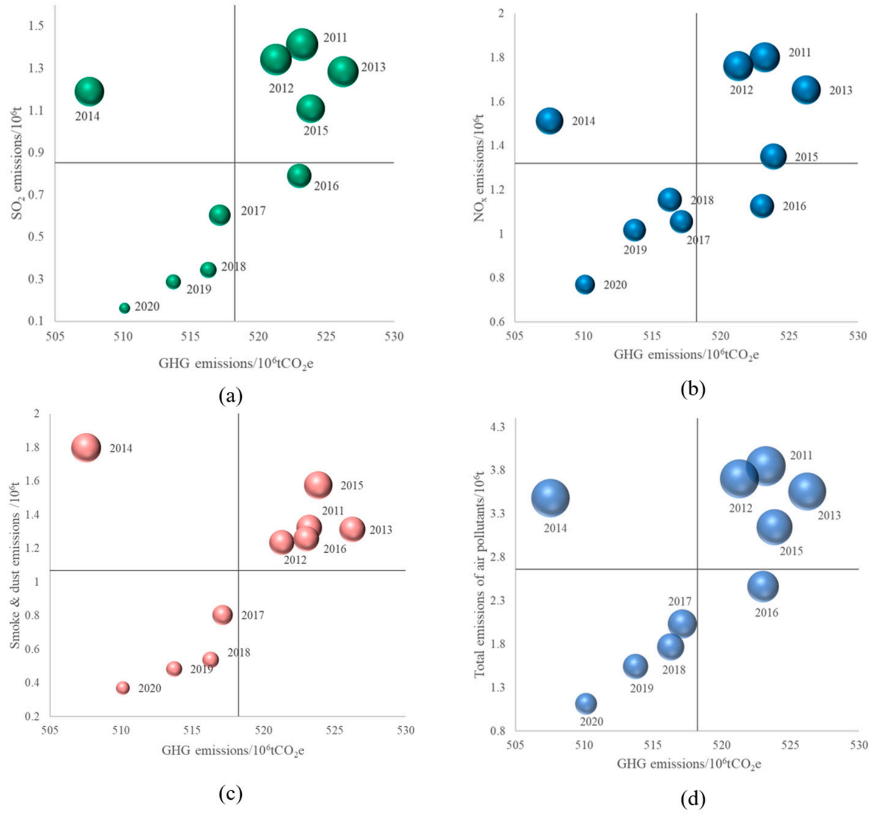

Figure 4. Four−quadrant diagram of total GHG emissions and air pollutants from 2011 to 2020. (**a**–**d**) represent the emissions of SO_2, NO_X, smoke & dust, and total air pollutants, respectively.

From Figure 5, it is evident that 7 years of GHG and air pollutants from 2011 to 2020 have achieved simultaneous emission reduction, and the emission reduction situation is relatively concentrated in the quadrant diagram except for 2014. The remaining 2 years only achieved air pollutant emission reduction, and the years of emission reduction were not continuous.

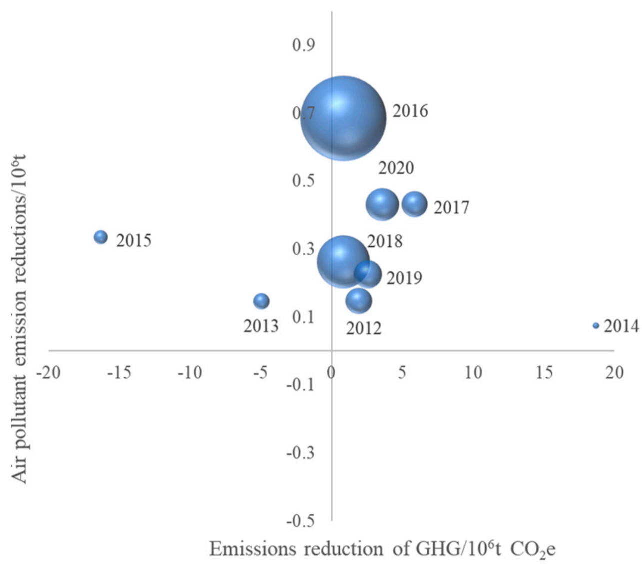

Figure 5. Four−quadrant diagram of GHG and air pollutant emission reduction from 2011 to 2020.

3.6.2. Cross-Elasticity Analysis of Emission Reductions

From Table 5, it is evident that $ELs_{CE\text{-}SE}$ was less than 0 in 2012~2013 and 2014~2015, indicating that only SO_2 achieved emission reduction in that year. In other years, $ELs_{CE\text{-}SE}$ is greater than 0, indicating that the GHG and air pollutants have achieved synergistic emission reduction, but in 2015~2016 and 2017~2018, $ELs_{CE\text{-}SE}$ is less than 1, and the decrease in SO_2 emissions is greater than the decrease in GHG emissions.

Table 5. Cross-elasticity coefficient of synergistic emission reduction in GHG and air pollutants from 2011 to 2020.

Year	ΔCE/CE (%)	ΔSE/SE (%)	ΔNE/NE (%)	ΔSDE/SDE (%)	$Els_{CE\text{-}SE}$	$Els_{CE\text{-}NE}$	$Els_{CE\text{-}SDE}$
2011~2012	0.37	5.02	2.22	6.55	7.32	16.55	5.61
2012~2013	−0.95	4.21	6.17	−6.26	−22.55	−15.40	* 15.17
2013~2014	3.55	7.38	8.47	−36.88	48.15	41.94	−9.63
2014~2015	−3.21	6.85	10.69	12.37	−46.89	−30.04	−25.97
2015~2016	0.16	28.78	16.60	20.22	0.55	0.95	0.78
2016~2017	1.12	23.69	6.27	36.05	4.75	17.94	3.12
2017~2018	0.16	43.03	−9.38	33.02	0.38	−1.73	0.49
2018~2019	0.50	16.40	11.99	10.42	3.04	4.16	4.78
2019~2020	0.70	43.64	24.28	23.11	1.61	2.89	3.03

"*" indicates that the molecules and denominators of $Els_{CE\text{-}APE}$ are negative.

4. Discussion

4.1. Uncertainty Analysis

In the process of calculating GHG emissions in Hebei Province, a large amount of data and emission factors need to be collected. Due to the statistical errors in the acquisition process of data and emission factors, the calculation results deviate from the actual situation. For example, in terms of energy activity emissions, the GHG emissions from coal, oil, and natural gas consumption are mainly considered, and the power transfer in and out is not included in the calculation; in the industrial production process, only the GHG emissions in the production of cement and steel are calculated, while other industries such as lime and adipic acid are not included; in the process of agricultural production, the calculation of N_2O produced by manure nitrogen application is lacking, and the classification of animals in intestinal fermentation is not refined into scale feeding, farmer feeding, and grazing feeding; land use change and forestry only considered the change in biomass carbon storage of forest and other woody biomass, while the carbon emission of forest conversion was not calculated. In terms of waste emissions, there is no BOD-related measured data in the methane emission of domestic sewage treatment, which is obtained by the conversion of the correlation between BOD and COD recommended by the Provincial Guidelines. In addition, the assumption that all the waste is domestic waste in the incineration of solid waste will lead to a deviation between the calculation results and the actual total GHG.

In the process of calculating the emission of air pollutants in Hebei Province, only the emissions of SO_2, NO_X, and smoke & dust are considered, while other air pollutants such as $PM_{2.5}$ and PM_{10} are not included, which will lead to the deviation between the calculation results and the actual total amount of air pollutants.

4.2. Analysis of Calculation Methods

In addition to the IPCC emission factor method, the production method and the input–output method are also used to calculate GHG emissions. The production method can be more intuitive and can be traced back to specific production activities, which helps to formulate industrial and regional emission reduction strategies. However, it does not consider indirect emissions caused by consumption, which may lead to emission reduction in production areas and an actual increase in emissions in consumption areas. The input–output method considers the emissions of different links in the entire industrial chain, which helps to reveal the key points in the supply chain. However, it has high computational complexity and requires a large amount of data, which makes it easy to introduce uncertainty. Compared with the two methods, the emission factor method is based on the average emission factor of each economic activity, which simplifies the calculation process but may ignore the differences in actual production, resulting in inaccurate results. In general, different accounting methods apply to different purposes and backgrounds. The comprehensive application can better understand the situation of GHG emissions, weigh the advantages and disadvantages of each method, and better guide emission reduction policies and actions.

4.3. Limitation

This study demonstrates the phenomenon of synergistic emission reduction in different pollutants but does not further explore the reasons behind it and propose corresponding emission reduction measures. Therefore, future work will conduct in-depth research on this part, which is of great significance for formulating comprehensive emission reduction strategies and controlling air pollution.

5. Conclusions

With the continuous improvement in the urbanization level in Hebei Province, the annual emissions of GHGs and air pollutants are still at a high emission level. Since the sources of GHGs and air pollutants are the same, their emission reduction measures have a synergistic effect. Hebei Province is one of the provinces with the largest energy consumption intensity and the most serious air pollution in China. Therefore, quantifying the emissions of GHGs and air pollutants in Hebei Province and the synergistic emission reduction effect between them will help to jointly control the emissions of GHGs and air pollutants.

The results show that from 2011 to 2020, the GHG emissions in Hebei Province generally showed a trend of increasing first and then decreasing, reaching a maximum of 5.26×10^8 t CO_2e in 2013. From the perspective of emission sources, the GHG emissions generated by energy activities are the main source of total GHG emissions in Hebei Province, followed by the GHG emissions generated by industrial production processes. The GHG emissions generated by waste treatment accounted for the lowest proportion, while the land use change and forestry part showed the absorption of GHGs, effectively controlling the growth of total GHG emissions. From 2011 to 2020, the total amount of air pollutant emissions in Hebei Province decreased year by year, from 3.85×10^6 t in 2011 to 1.12×10^6 t in 2020, with a significant decrease. The total amount of air pollutant emissions in 2020 decreased by 71.13% compared with 2013.

The results show that among the seven socio-economic indicators, GDP and energy consumption have the greatest impact on GHG and air pollutant emissions. In 2020, compared with 2011, GDP and energy consumption in Hebei Province increased by 169.31% and 116.77%, respectively.

The decoupling model of GHG emissions and economic growth shows that there is a negative correlation between them. The GHG emissions in Hebei Province are declining while the economy is growing, reaching an ideal state.

The rank correlation analysis of GHG and air pollutant emissions shows that there is a strong correlation between SO_2, NO_x, smoke & dust emissions and NO_2 emissions. The correlation between other different pollutant indicators is not significant, but there is still a certain degree of correlation.

The results of the coordinate system of the synergistic control effect of GHG and air pollutant emissions show that the total amount of GHG emissions in Hebei Province from 2011 to 2020 is synergistic with the emissions of SO_2, NO_X, smoke & dust, and the total amount of air pollutant emissions, and the synergistic effect of smoke & dust and GHG emissions is better than that of SO_2, NO_x, and GHG emissions. During the study period, in addition to 2013 and 2015, the emissions of GHG and air pollutant in the remaining years have achieved simultaneous emission reductions, with emission reduction synergies.

Considering the calculation results of the cross-elasticity coefficient of GHG–air-pollutant synergistic emission reduction, the overall emission reduction synergy between GHG emission reduction and three types of air pollutants in Hebei Province from 2011 to 2020 is poor, usually in the state of "only air pollutant emission reduction" or "both synergistic emission reduction, but the reduction in GHG emissions is not as great as the reduction in emissions of air pollutants". It also reflects that compared with the change in emission reduction of three kinds of air pollutants, the change in GHG emission reduction is smaller. In general, the GHG emission reduction and air pollutant control in Hebei Province have shown a synergistic effect, but the degree of synergy is different due to the types of air pollutants.

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