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RESEARCH ARTICLE

Research on the relationship between China's greenhouse gas emissions and industrial structure and economic growth from the perspective of energy consumption

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Abstract

A comprehensive understanding of the relationships between greenhouse gas (GHG) emissions and industrial structure and economic growth holds great significance for China to realize the development of a green economy. This paper calculates GHG emissions based on China's energy consumption, divides the industrial structure in detail, and uses the extended Stochastic Impacts by Regression on Population, Affluence, and Technology model that is realized by PLS method and Tapio decoupling model to study the relationship of GHG emissions to industrial structure and economic growth. The results show that (1) China's total GHG emissions showed a year-on-year growth trend from 2000 to 2017. For CO_2, CH_4, and N_2O, only N_2O emission showed a significant downward trend, while CO_2 and CH_4 emissions showed a slow growth trend. (2) The proportions of added value of industry and construction are positively correlated with GHG emissions, while those of farming, forestry, animal husbandry, and fishery; wholesale and retail trade; transport; and accommodation and catering are negatively correlated with GHG emissions. (3) China's GHG emissions and overall economic growth are in a decoupling state, but in the energy field, N_2O emission reduction control has the best effect. Additionally, the overall economic growth of China's industrial sector and GHG emissions have experienced the process of decoupling-link-negative decoupling-link-decoupling.

Keywords Greenhouse gas emissions · Industrial structure · Economic growth · STIRPAT model · PLS method · Tapio decoupling model

Introduction

After the Industrial Revolution, while the productivity of countries around the world increased significantly, fossil energy such as coal and oil was unrestrictedly mined and used, a large number of forests were felled, and vehicles emitted a large amount of exhaust gas. These actions have led greenhouse gas (GHG) emissions to increase rapidly, and the result of the global warming caused by the greenhouse effect is now being experienced by humans. Global climate change is not only one of the largest and most profound challenges facing humankind but also one of the most important factors in social

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development affecting the development of the world economy; curbing climate warming by reducing GHG emissions has become a common goal of countries worldwide. GHGs mainly include CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3, SF_5CF_3, H_2O (gas), and O_3. Although HFCs, PFCs, SF_6, NF_3, and SF_5CF_3 have a greater impact on the greenhouse effect, they have a low concentration in the air and a smaller impact on global warming. Changes in H_2O and O_3 levels are not directly related to human actions, and so in general, these two gases are not considered for GHG emissions reduction. The radiation effects caused by CO_2, CH_4, and N_2O account for 80% of all GHG radiation effects, and the growth of these three greenhouse gases is the main driving factor for global warming. Therefore, CO_2, CH_4, and N_2O, which have a significant impact on global warming, are the main subjects of study in this paper.

According to the IPCC Fifth Assessment Report on Climate Change, air concentrations of CO_2, CH_4, and N_2O increased significantly after the Industrial Revolution (as shown in Fig. 1). Taking CO_2 as an example, in 1750, its air concentration was approximately 280 ppm, and by 2011, its air concentration was approximately 391 ppm (IPCC 2013). But before the Industrial Revolution, the air concentration of CO_2, CH_4, and N_2O remained relatively stable and did not fluctuate greatly, indicating that human activities have broken the boundaries of normal development in nature and are the major factor in global warming (Nordhaus 1977). The Industrial Revolution caused huge consumption of fossil energy such as coal and oil, and a large number of greenhouse gases were discharged, which made global warming increasingly serious. Based on the results of GHG emissions measured by various agencies, GHG produced by energy consumption is the main source of atmospheric GHG. Among the gases, CO_2 contributes the most to GHG emissions, at approximately 55%. Studies have shown that 75% of the total amount of CO_2 emitted by human activities worldwide comes from the burning of fossil fuels (Gao et al. 2001). In particular, China accounted for 25% of global energy consumption in 2009, contributing to 20% of global GHG emissions (Liu et al. 2012). According to the IEA survey, China surpassed

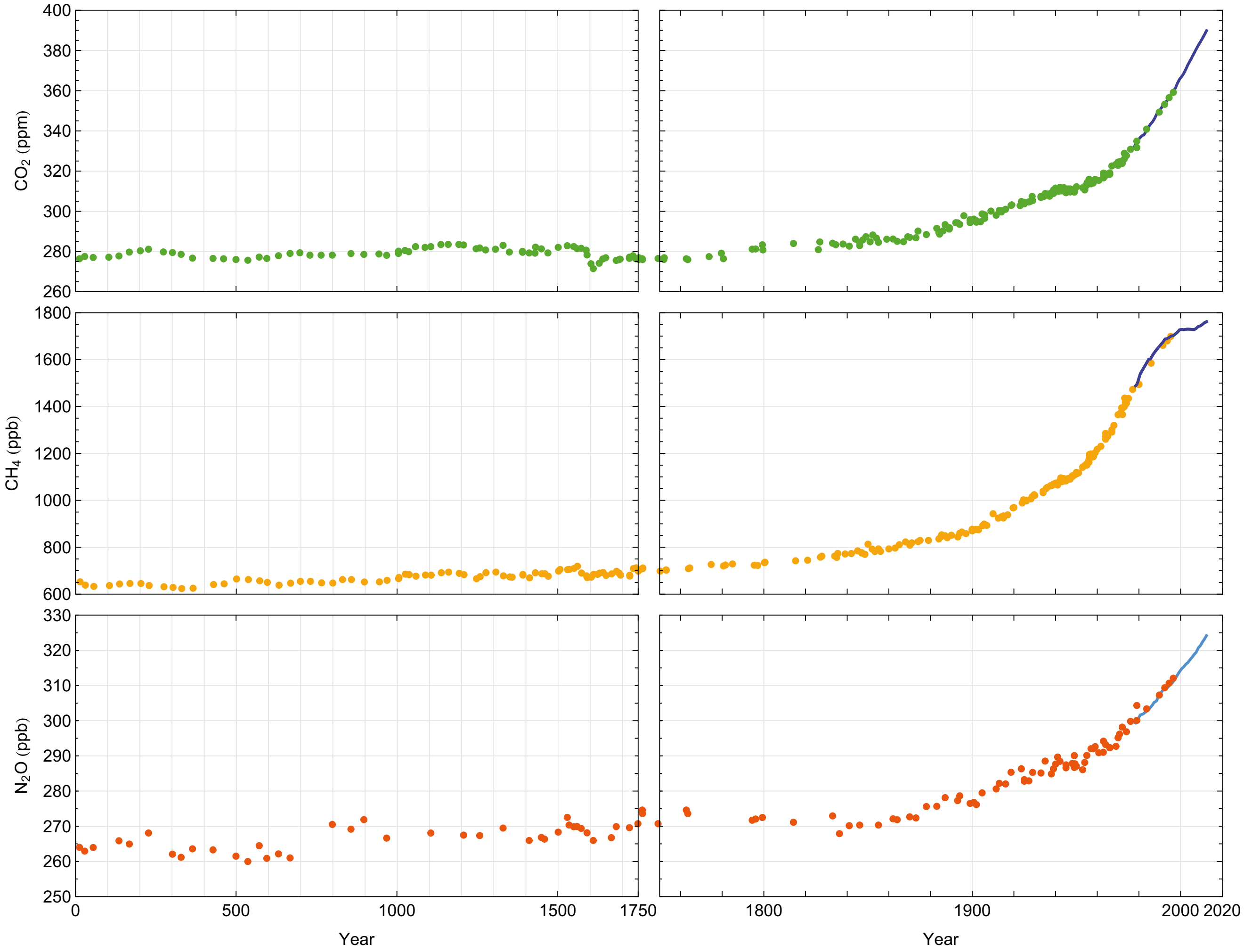


Fig. 1 Atmospheric CO_2, CH_4, and N_2O levels before and after the industrial revolution

the USA in CO_2 emissions after 2006, becoming the world's largest emitter of GHG. Therefore, China plays a pivotal role in global action to reduce emissions. The Chinese government has also formulated a series of emission reduction policies, actively changing the mode of economic growth and adjusting the industrial structure to reduce GHG emissions. However, the harmonious development of energy, economy, and environment is bound to experience a long process. Reducing GHG emissions, adjusting industrial structure, and maintaining stable economic growth are the realistic issues that China and the world are focusing on; many scholars have studied the relationship between them.

Grossman and Krueger (1991) studied the relationship between environment and economy for the first time; they found that the concentration of SO_2 and "smoke" increased with an increase in GDP when the national income level was low but decreased with growth in GDP when the income level was high. In other words, the relationship between the environmental pollution level and economic growth exhibits the inverted "U" curve: this is the famous Environmental Kuznets Curve (EKC). Since that pioneering work, many scholars have studied the relationship between the economy and the environment. Since the burning of fossil fuels is an important source of GHG such as CO_2, many scholars have conducted empirical studies on the relationship between economic growth and GHG from the perspective of energy consumption. Roberts and Grimes (1997) replace SO_2 in the EKC with CO_2, finding that GDP and CO_2 intensity also exhibit an inverted "U" curve relationship. With the development of economy, the trend of CO_2 emissions will show an obvious inflection point, that is, there is an inverted "U" relationship between economic growth and CO_2 emissions, which has also been proved by many scholars (Dinda 2005; Verbeke and Clercq 2006; Saboori et al. 2012; Wang et al. 2018). However, many scholars hold the opposite view: they have found that the relationship between economic growth and carbon emissions does not always exhibit an inverted "U" curve, and it can also exhibit linear, nonlinear, and "N" relationships (Uddin et al. 2016; Wang and Ye 2017; Wang and He 2019). This is mainly because the economic systems in different countries make their economic situations obviously different, and regional economic differences will exacerbate national energy intensity. At the same time, the spatial spillovers of carbon emissions are significantly heterogeneous in different regional contexts, which makes the uncertain relationship between economic growth and carbon emissions in different regions and different spaces (Li et al. 2014; Wang and Huang 2019). For example, Chen et al. (2010) studied the causal relationship between carbon emissions and economic growth at different development stages in six typical developed countries: the results show that the Granger causality between carbon emissions and economic growth is different in different countries at different stages of development. Even in the same development period, the Granger causality between carbon emissions and economic growth is different. Mamun et al. (2014) conducted a study on the relationship between global per capita CO_2 emissions and economic growth from 1980 to 2009: the results show that during the transition to a service economy, high-income countries generated more carbon emissions than low-income countries.

Studies on the relationship between GHG and industrial structure have found that the development of industry depends on energy consumption, which contributes to GHG emissions. The development of the primary industry has an important impact on the GHG cycle. Agriculture can not only promote GHG emissions through land use, but also reduce GHG emissions through reasonable land management. Land use change has become the second largest source of GHG emissions after fossil fuel combustion. The conversion of farmland to construction land, internal changes of land use in farmland, and internal changes of land use in construction land all have an impact on CO_2 emissions, contributing 24% to the greenhouse effect (Goldewijk and Ramankutty 2004; Qu et al. 2011). But at the same time, land use can absorb carbon emissions through cultivated land and forest land (Zhou et al. 2019). In addition, many scholars have studied the influencing factors of agricultural carbon emissions, and believe that economic growth, regional differences, industrial structure, average labor productivity, and the use of nitrogen all have an impact on carbon emissions, and economic growth is the most critical driving factor for agricultural carbon emissions (Li et al. 2011; Robaina-Alves and Moutinho 2014; Guo et al. 2018). The secondary industry is the main supporting industry of the national economy and the main industrial sector of energy consumption and GHG emissions. Industry, power industry, and construction are the major energy-consuming sectors, among which the amount of energy consumed of industry far exceeds that of other industrial sectors and becomes the focus of the secondary industry (Xu et al. 2014). For the research on the driving factors of industrial carbon emissions, it is generally believed that the industrial structure, industrial scale, technology input, and energy consumption scale are the main factors for the increase of industrial carbon emissions (Ma et al. 2017; Ma et al. 2019). Due to the uneven energy efficiency and emission level, increasing technology investment, upgrading internal industrial structure, and optimizing energy structure are the main strategies in the mid- to long-term low-carbon development of the secondary industry (Liu et al. 2019). With the increasingly obvious marginal diminishing effect of the emission reduction results of primary and secondary industries, the service industry is becoming a new field of energy conservation and emission reduction in various countries. At the macrolevel, the transition to a service economy can reduce the overall energy intensity, and if energy efficiency is improved, energy intensity reduction becomes more obvious. Therefore, increasing the proportion of tertiary industry in

GDP can significantly increase the carbon emission reduction potential (Mulder et al. 2014; Yu et al. 2015). At the microlevel, Hojjati and Wade (2012), Nie and Kemp (2014), and Nie et al. (2018) conducted research on residents' energy consumption. They found that household's electricity consumption, space heating, the use of natural gas, and the number of household appliances are the main contributors to household energy consumption. Studies by many scholars have shown that the primary, secondary, and tertiary industries will increase GHG emissions, the economic structure dominated by the secondary industry is the main reason for aggravating the greenhouse effect. In conclusion, structural changes in primary, secondary, and tertiary industries are highly correlated, and differences in the industrial structure of different regions severely affect GHG emissions. The changes in the three industrial structures, the internal structure of the three industries will cause carbon emission intensity to rise to varying degrees. Therefore, industrial structure is also a key factor affecting carbon emissions, and adjusting industrial structure will be an effective way to achieve low-carbon development (Zhang 2010; Wu et al. 2012; Tian et al. 2014; Chang 2015; Dong et al. 2020).

Domestic and foreign scholars have used various models and methods to analyze and predict the relationships between industrial structure, economic growth, and carbon emissions. For the decomposition research of GHG emissions, the decomposition of carbon emissions is the most common. Specific methods include factor decomposition method, structural decomposition method, Kaya identity, and input-output model, et al. Among them, factor decomposition methods include Logarithmic Mean Divisia Index (LMDI) method, Sample Average Division (SAD) method, and Adaptive Weighting Divisia (AWD) method, et al. (Ang 2004; Rhee and Chung 2006; Ang et al. 2009). For the research on the impact mechanism of carbon emissions and industrial structure, economic growth, mathematical methods, and socioeconomic methods are often used in combination, such as Granger causality test, Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) method, gray correlation analysis, BP neural network, and decoupling model, et al. In addition, LMDI method and input-output analysis method are also commonly used (Uddin et al. 2016; Zhang and Wang 2016; Long et al. 2018; Wang et al. 2019). The Granger causality test is more sensitive to time selection than other methods, which sometimes results in poor robustness in the research results. The input-output method is based on the input-output model and top-down accounting principles and is easily limited by the number of input-output tables. The LMDI decomposition method is not conducive to studying the impact of various industries on carbon emissions. However, the STIRPAT method discards the assumption of unit elasticity, is more stochastic, and allows for expansion, which is conducive to improving the explanatory ability of the model. The Tapio decoupling model is often used to study the relationship between economic growth and environmental pressure, and the size and symbol of the decoupling value can reflect the degree and direction of correlation in a certain period. Therefore, the STIRPAT model and the Tapio decoupling model are chosen to study the relationship between China's GHG emissions and industrial structure and economic growth.

Currently, countries around the world have deeply realized the negative effects of global warming on the environment and economy. Therefore, the development of green economy has undoubtedly become the new direction of economic development for all countries. As the second biggest economy in the world, China's GHG emissions reduction actions and achievements will play a vital role in global GHG emissions reduction. In summary, based on China's terminal energy consumption from 2000 to 2017, this paper analyzes the overall GHG emissions, and makes improvements in the following aspects. The research on China's GHG emissions mainly focuses on the analysis of the growth factors of CO_2 emissions, ignoring other GHG emissions, especially the impact of other GHG emissions which is greater in some industrial sectors. In this paper, CH_4 and N_2O are included in the accounting scope, with CO_2, CH_4, and N_2O being the main accounting objects to comprehensively understand China's GHG emissions. At present, China's economy is shifting from a high-speed growth stage to a high-quality development stage, and the changes in industrial structure are very obvious. Many scholars regard industry as the key research object of industrial structure and do not systematically analyze various industries of the national economy. The industrial structure is an important link between economic growth and GHG emissions; it is necessary to study the GHG emissions of China's major economic sectors. Therefore, this paper divides China's economic sector into seven industrial sectors in detail (farming, forestry, animal husbandry, and fishery; industry; construction; transport; wholesale and retail trade; accommodation and catering; and other industries). Taking these seven industries as research objects provides a supplement and reference for research on GHG emissions from all industries in China. In addition, this paper expands the STIRPAT model. To solve the potential problems of multicollinearity and heteroscedasticity in its variables, the Partial Least Squares (PLS) method is used to implement the extended STIRPAT model. Afterwards, the STIRPAT model and the Tapio decoupling model are applied to explore the relationship between China's GHG emissions and industrial structure and economic growth. This paper hopes to provide a theoretical basis for China's GHG emissions reduction, industrial structure optimization, and early realization of green economic development.

Data sources and theoretical models

Data sources

This article studies China's GHG emissions from the perspective of energy consumption from 2000 to 2017, where GDP and population (including urban and rural populations) are derived from the "China Statistical Yearbook." GDP and sectoral GDP are converted to constant 2000 prices.

In the process of accounting for GHG emissions, this paper divides industrial structure into seven industries based on "China Statistical Yearbook" and "Elementary Course of National Accounts" (Jiang et al. 2019), including farming, forestry, animal husbandry, and fishery; industry; construction; transport; wholesale and retail trade; accommodation and catering; and other industries. At the same time, this article divides the types of energy consumption, including 17 types of fossil energy, electricity, and heat, of which fossil energy includes raw coal, cleaned coal, washed coal, briquettes, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, other petroleum products, and natural gas. The specific energy consumption data comes from "China Energy Statistics Yearbook." The oxidation rate, net calorific value, and GHG emissions coefficient of 17 types of fossil fuels come from "Provincial Greenhouse Gas Inventory Guidelines" and "2006 IPCC Guidelines for National Greenhouse Gas Inventories." The GHG emissions coefficients of electricity and heat are calculated by the author according to relevant formulas, and the data comes from "China Electric Power Yearbook" and "China Energy Statistics Yearbook."

Theoretical model

The theoretical model used in this paper is divided into three main parts. The first part is an accounting of China's GHG emissions based on energy consumption. The second part expands the STIRPAT model, and the STIRPAT model is realized by PLS to study the relationship between GHG emissions and industrial structure. The third part uses the Tapio model to study the relationship between GHG emissions and economic growth.

Accounting for China's GHG emissions based on energy consumption

The GHGs studied in this paper include CO_2, CH_4, and N_2O, and emissions of CH_4 and N_2O are converted into CO_2 emissions based on their Global Warming Potential (GWP). The sum of the three types of emissions is the total GHG emissions from energy consumption. Among them, the corresponding GWPs of CO_2, CH_4, and N_2O are 1, 25, and 298, respectively. Based on the accounting methods provided in the guidelines of the United Nations Intergovernmental Panel on Climate Change (IPCC), we use total energy consumption, carbon emissions coefficients, and oxidation rates to calculate CO_2 emissions. The specific formula is as follows (1), and the emissions of CH_4 and N_2O are also calculated according to (1).

$$CO2_i^t = \sum_j CO2_{ij}^t = \sum_j E_{ij}^t \times EF_j \times O_j \tag{1}$$

Among them, $CO2_i^t$ represents the total CO_2 emissions generated by the energy consumption of industry i in year t, and the unit is Mt; $CO2_{ij}^t$ represents the amount of CO_2 emissions generated by fuel j consumed by industry i in year t, and the unit is Mt; E_{ij}^t represents the consumption of fuel j in industry i in year t, in units of TJ; EF_jrepresents the carbon emissions coefficients of fuel j in units of ton CO_2/TJ; O_j represents the corresponding oxidation rate during the combustion process of fuel j. The corresponding oxidation rates, net calorific values, and carbon emissions coefficients of the 17 fossil fuels studied in this paper are shown in Table 1.

The GHG emissions coefficients produced by electricity and heat in China change every year, and so the emission factors are not a fixed value. Therefore, the emission coefficients need to be calculated according to the consumption of electricity and heat produced each year. But the specific data of the heat is missing; this article adopts the recommended value of 0.11 t CO_2/GJ in 32151.12-2018 issued by the China Standardization Administration.

China's power production is dominated by thermal power generation, which is the main source of GHG produced by the electricity industry. At the same time, with the rapid development of national science and technology, cleaner power generation methods such as nuclear power, hydropower, and wind power are emerging annually, and so the GHG emissions generated by thermal power cannot fully represent the GHG emissions of the electricity industry. In this paper, nuclear power, hydropower, and wind power are included in the calculation. The carbon emissions factor of electricity is calculated as shown in Eq. (2).

$$EF_t = \frac{\sum CO2_t}{G_{fossil,t} + G_{wind,t} + G_{nuclear,t} + G_{hydro,t}} \tag{2}$$

Among them, EF_t represents the carbon emissions factor of electricity in year t, and the unit is ton CO_2e/kWh; $\sum CO2_t$ is the equivalent CO_2 emissions generated by the fuel consumed for power generation in year t, and the unit is ton; $G_{fossil,\ t}$ is the power generated by fossil fuel in year t, and the unit is kWh; $G_{wind,\ t}$ is the power generated by wind energy in year t, and the unit is kWh; $G_{nuclear,\ t}$ is the power generated by nuclear energy in year t, and the unit is kWh; $G_{hydro,\ t}$ is the power generated by water energy in year t, and the unit is kWh.

Table 1 GHG emission factors for different energy types

	Carbon oxidation rate	Net calorific value (TJ/10^{3}ton)	EF (CO$_2$) (tonCO$_2$/TJ)	EF (CH$_4$) (tonCH$_4$/TJ)	EF (N$_2$O) (tonN$_2$O/TJ)	EF (GHG) (tonCO$_2$e/TJ)
Raw coal	0.94	20.91	94.60	0.001	0.0015	1.87
Cleaned coal	0.90	26.34	98.30	0.001	0.0015	2.34
Washed coal	0.90	8.36	97.90	0.001	0.0015	0.74
Briquettes	0.90	26.34	97.90	0.001	0.0015	2.33
Coke	0.93	28.44	107.07	0.001	0.0015	2.84
Coke oven gas	0.99	17.35[a]	44.37	0.001	0.0001	7.63[b]
Other gas	0.99	17.35 [a]	44.37	0.001	0.0001	7.63 [b]
Other coking products	0.93	33.46	107.07	0.001	0.0015	3.35
Crude oil	0.98	41.82	73.33	0.003	0.0006	3.02
Gasoline	0.98	43.07	74.07	0.003	0.0006	3.14
Kerosene	0.98	43.07	71.87	0.003	0.0006	3.04
Diesel oil	0.98	42.65	74.07	0.003	0.0006	3.11
Fuel oil	0.98	41.82	77.73	0.003	0.0006	3.20
LPG	0.98	50.18	63.07	0.001	0.0001	3.10
Refinery gas	0.98	46.06	66.73	0.001	0.0001	3.01
Other petroleum products	0.98	41.87	73.30	0.003	0.0006	3.02
Natural gas	0.99	38.93 [a]	56.10	0.001	0.0001	21.64 [b]

[a] In MJ/m^3

[b] In ton CO$_2$e/10^4 m^3

The carbon emissions factor (kg/kWh) for China's electricity from 2000 to 2017 is shown in Fig. 2. China's electricity coefficient is decreasing year by year—from 0.94 kg/kWh in 2000 to 0.76 kg/kWh in 2017—indicating that the efficiency of fuel utilization in the power generation process is gradually improving.

STIRPAT model

Based on Dietz and Rosa (1994) viewpoint, any theory of environmental change should take population, affluence, and technology levels into account as the main drivers. He was the first to propose the STIRPAT model of environmental stress, as shown in Eq. (3).

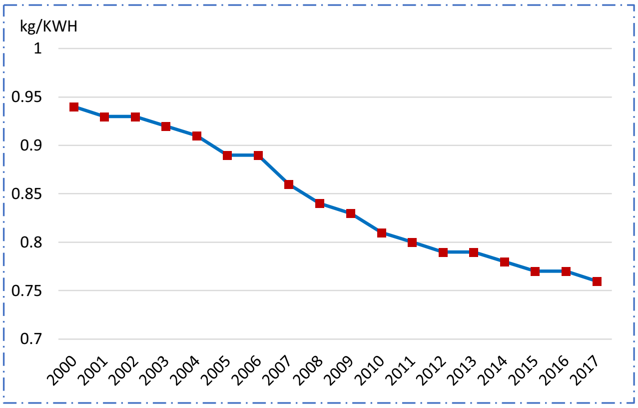


Fig. 2 China's carbon emission factors for electricity from 2000 to 2017

$$I = aP^bA^cT^{d_e} \tag{3}$$

Among them, I represents environmental pressure; P, A, and T represent population size, affluence, and technical factors, respectively. a is a constant term; b, c, and d represent the corresponding elasticity coefficients of P, A, and T, respectively; and e indicates the random error. The STIRPAT model is a nonlinear stochastic regression model. To reduce the heteroscedasticity that exists in the model data, the logarithms of both sides of the equation of the model are often taken at the same time. In addition, the model has relatively strong flexibility, so it can be widely used and expanded in academic research. Some scholars have extended it to study the drivers of carbon emissions, such as GDP, urbanization rate, population size, energy consumption structure, and industry structure (Chen et al. 2014; He and Yu 2018). Based on these works, this paper extends the STIRPAT model and divides the industrial structure in detail to study the impact of industrial structure on GHG emissions in China. The specific model is shown in Eq. (4).

$$E = aF^bI^cC^dW^eT^fH^gO^h\varepsilon \tag{4}$$

By taking the logarithm of both sides of Eq. (4), Eq. (5) is obtained:

$$\ln E = \ln a + b\ln F + c\ln I + d\ln C + e\ln W + f\ln T + g\ln H + h\ln O + \ln\varepsilon \tag{5}$$

E denotes the environmental impact, and in this paper, it represents the total GHG, CO_2, CH_4, and N_2O emissions produced by energy consumption. F, I, C, W, T, H, and O represent the proportion of added value of seven industries, respectively, farming, forestry, animal husbandry, and fishery; industry; construction; transport; wholesale and retail trade; accommodation and catering; and other industries. a is a constant term; b, c, d, e, f, g, and h represent the corresponding elasticity coefficients of F, I, C, W, T, H, and O, respectively, and ε indicates the random error.

The PLS method is used to implement the extended STIRPAT model in this paper. The PLS model realizes the combined application of various data analysis methods, and it focuses on the advantages of multiple linear regression, principal component analysis, and typical correlation analysis. It can effectively solve the problems of multiple covariance, low degrees of freedom, and the failure of ordinary time series methods due to the short time series of the autoinvariant, and the results are more accurate and reliable.

The main steps in the PLS model are as follows. (1) Standardize the dependent variable Y and the independent variable X to obtain the corresponding matrix. (2) Extract the first pair of component factors $t_1$and u_1 from the matrix of the dependent variable and independent variable, respectively. The extracted components can largely reflect the variation in the dependent variable and independent variable. Its principal components are independent of each other, the degree of correlation is the largest, and u_1 has a strong explanatory ability for t_1. (3) Establish regression equations of dependent variables Y to t_1 and independent variables X to u_1. If the regression equation results meet the statistical index, the algorithm terminates. If not, the second principal component extraction and regression analysis are carried out. (4) Repeat the above steps until an equation that meets the corresponding statistical index and accuracy is obtained.

Tapio decoupling model

The word decoupling comes from the field of physics and was applied by the OECD to agricultural policy research. Later, scholars extended it to the fields of resources, the environment, and the economy and analyzed the relationship between economic development, resource consumption, and environmental pressure (Yu et al., 2013; Che et al. 2015; Wang et al. 2019). Common decoupling analysis methods include the OECD decoupling model, the Tapio decoupling model, and the decoupling model based on the IPAT equation. This article mainly refers to the second Tapio decoupling model to analyze the relationship between China's GHG emissions and economic growth. The specific calculation method is as follows (6).

$$t = \frac{\%\triangle E_i/E_i}{\%\triangle GDP_i/GDP_i} \tag{6}$$

Among them, t represents the decoupling elasticity of environmental pressure brought by energy consumption and GDP. Environmental pressure includes the total GHG emissions generated by energy consumption and the emissions of CO_2, CH_4, and N_2O. $\% \triangle E_i/E_i$represents the change in the total GHG emissions of industry i from the base period to the end; $\% \triangle GDP_i/GDP_i$ represents the change in the total GDP of industry i from the base period to the end. There are eight situations for the degree of decoupling, as shown in Table 2.

Table 2 shows that in all decoupling states, the decoupling indicates a reduction in environmental pressure. Among them, the strong decoupling is the optimal state, where environmental pressure decreases and the economy grows, while the negative decoupling indicates a state where environmental pressure increases, implying increased GHG emissions. Strong negative decoupling is the worst state, where environmental pressure increases and the economy is in recession. The link state indicates that environmental pressure keeps the same trend as economic growth.

Empirical analysis

China's GHG emissions accounting based on energy consumption

Status of China's energy consumption

From the perspective of China's overall energy consumption (Fig. 3), in the 2000–2017 period, both total and per capita energy consumption showed an upward trend. The total energy consumption increased from 1061.73 Mtce in 2000 to 3270.78 Mtce in 2017, with an average annual growth rate of 6.84%. China's per capita energy consumption increased from 0.84 tce per person in 2000 to 2.35 tce per person in 2017, with an average annual growth rate of 6.24%. From 2000 to 2007, the total energy consumption kept a high growth rate, which was as high as 18.29% in 2004. Since 2004, the growth rate of total energy consumption began to decline in varying degrees. But the growth rate increased

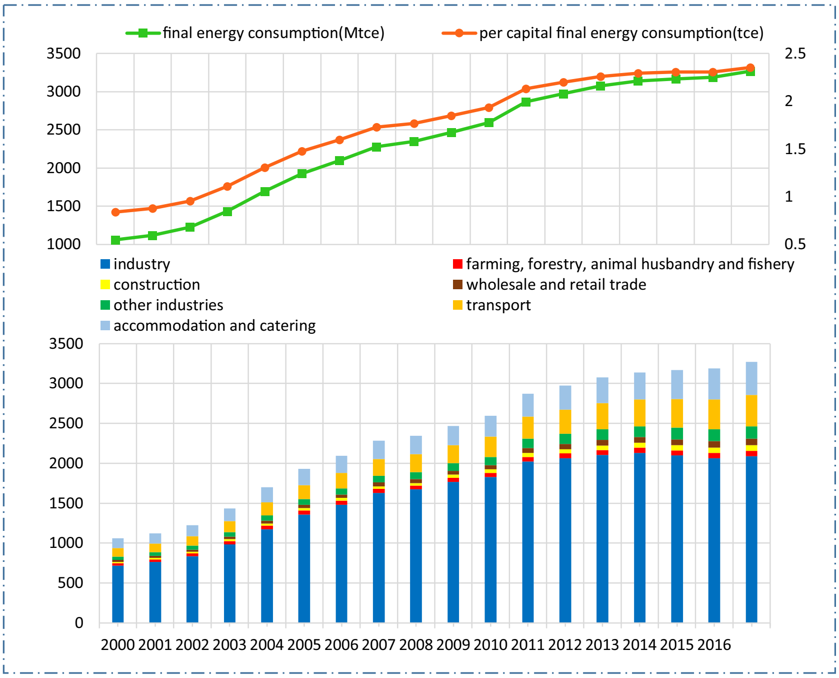
Table 2 Judgment criteria for Tapio decoupling degree

Degree of decoupling		ΔE (environmental pressure)	ΔGDP (economic growth)	t
Decoupling	Weak decoupling	> 0	> 0	$0 < t < 0.8$
	Strong decoupling	< 0	> 0	< 0
	Recessive decoupling	< 0	< 0	1.2<
Negative decoupling	Weak negative decoupling	< 0	< 0	$0 < t < 0.8$
	Strong negative decoupling	> 0	< 0	< 0
	Expansive negative decoupling	> 0	> 0	1.2<
Link	Expansive link	> 0	> 0	$0.8 < t < 1.2$
	Recessive link	< 0	< 0	$0.8 < t < 1.2$

significantly in 2011, which is related to China's "four trillion plan" to stimulate economic activity. At present, China has gradually transformed itself from adopting an industrial-led to an urban-led economic development approach, which has also led to a marked slowdown in the energy consumption growth trend.

From the perspective of energy consumption in various sectors, industry accounts for the largest share of total energy consumption among the seven sectors, but the total consumption of the industry has not always shown an increasing trend. In the period 2000–2017, using 2011 as the time point, the share of energy consumption by industry showed a trend of growth before declining, from 67.70% in 2000 to 70.52% in 2011 and then to 63.8% in 2017. This is mainly because after 2011, China advocated for the parallel economic development approach of urbanization and industrialization, and vigorously adjusted industrial structure. At the same time, with the development of science and technology, the production of products and consumption of raw materials did not increase in the same proportion, resulting in a slow growth trend in the proportion of energy consumed by industry. However, China's large share of heavy industry, the large number of labor-intensive industries, and huge consumption of basic raw materials make industrial energy consumption far exceed the sum of other industries. Industry's consumption in 2017 was 1.77 times higher than that of other industries combined, and its share basically remained at a high level of 63%, with industry being the main contributor to energy consumption in China. The second contributor is accommodation and catering, and the proportion of its energy consumption is approximately 10.85%, which is closely related to the population base of China. China's population is an important reason for the huge

Fig. 3 Status of overall energy consumption and energy consumption by sectors in China



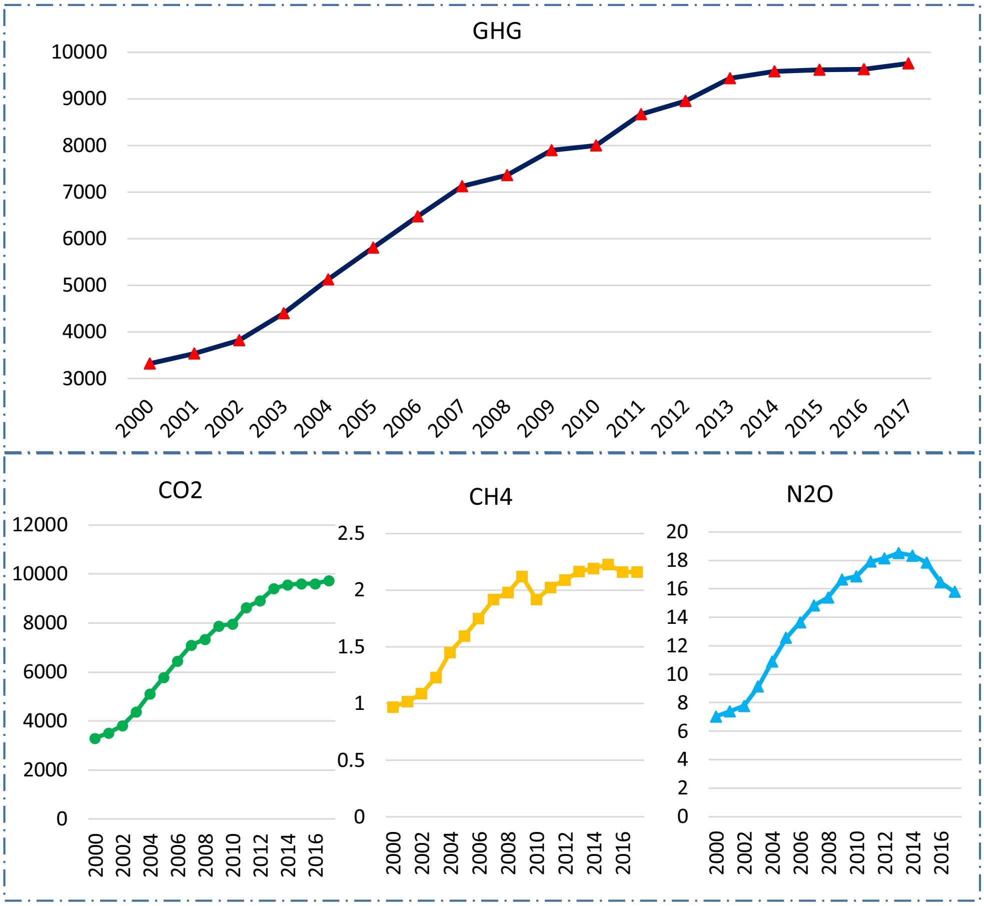
consumption of energy for residents' lives. The proportion consumed by transport is slightly lower than that of accommodation and catering, at 10.01%. The proportions of energy consumption in farming, forestry, animal husbandry, and fishery and in wholesale and retail trade are 2.30% and 2.18%, respectively. The proportion of energy consumption in construction is the smallest, accounting for 1.73%. On the whole, except for industry, the energy consumption of other sectors has increased annually, but their share of total energy consumption has basically remained at a stable level, with small fluctuations.

Status of China's GHG emissions

With China's rapid economic development and rising energy consumption, increasing amounts of GHG are being released into the atmosphere. In this paper, we estimate China's GHG emissions for the period 2000–2017 from the energy consumption terminal. The results are shown in Fig. 4, which are also consistent with the data published by the IEA. From 2000 to 2017, total GHG emissions increased from 3320.7 to 9759.7 Mt, with an average annual growth rate of 6.55%. But the growth rate in different periods showed obvious differences. Its growth trend was significantly faster from 2000 to 2013, with an average annual growth rate of 8.37%, while its growth trend from 2013 to 2017 was significantly slower, with an average annual growth rate of 0.83%.

From the perspective of CO_2, CH_4, and N_2O, the emissions of the three are different from 2000 to 2017. The share of CO_2 emissions in total GHG emissions has remained at 99.7–99.8% over the 2000–2017 period, making it clearly the most important source of GHG emissions, while the share of CH_4 and N_2O in total GHG emissions after conversion to CO_2 equivalent is smaller and stable at approximately 0.03 and 0.2%, respectively. Therefore, although N_2O emissions are second only to CO_2, there is a huge difference between N_2O emissions and CO_2 emissions from specific values. From 2000 to 2013, N_2O emissions were in the growth stage, with an average annual growth rate of 7.75%, while from 2014 to 2017, N_2O emissions showed an obvious downward trend, especially in 2016. Among the three greenhouse gases, CH_4 has the smallest emission. From 2000 to 2009, CH_4 emissions were in a rapid growth stage, with an average annual growth rate of 9.08%. From 2009 to 2010, CH_4 emissions decreased significantly. From 2010 to 2017, CH_4 emissions were in slow growth stage, with an average annual growth rate of 1.70%. In short, among the three greenhouse gas emissions, only N_2O emissions have obviously decreased in recent years, while

Fig. 4 GHG emissions of China



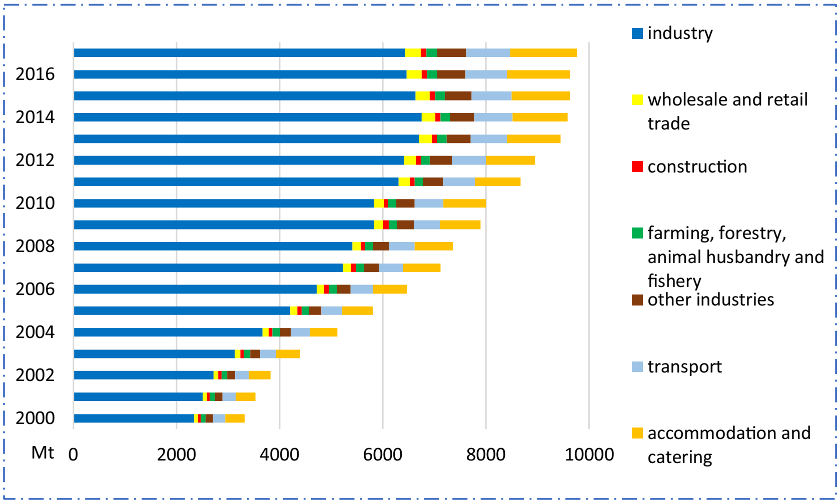


Fig. 5 Total GHG emissions from different industries in China

CO_2 and CH_4 emissions are still increasing, but the growth rate has been slow.

Figure 5 shows the total GHG emissions from the energy consumption of different industries in China. From the perspective of industrial structure, in 2000, the proportion of GHG emissions from seven industrial sectors in the annual GHG emissions ranked from high to low: industry (70.44%); accommodation and catering (11.33%); transport (7.21%); other industries (4.23%); farming, forestry, animal husbandry, and fishery (2.89%); wholesale and retail trade (2.34%); and construction (1.55%). Although the proportion of GHG emissions in industry has decreased in 2017, its proportion has remained at a high level of 65.90%. The proportion of GHG emissions from wholesale and retail trade has increased to 3.05%, ranking fifth. The proportion of GHG emissions from farming, forestry, animal husbandry, and fishery has dropped to 2.89%, ranking sixth. The ranking of the other four sectors remained unchanged, but only the proportion of GHG emissions from construction decreased first and then increased from 2000 to 2017, which was 1.16% in 2017. The proportions of GHG emissions in transport, accommodation and catering, and other industries have maintained an upward trend, increasing by 1.5%, 1.91%, and 1.76% respectively. On the whole, among the seven industries that consume energy, the industry sector has the largest proportion of GHG emissions, but the proportion of GHG emissions in industry has not always shown an increasing trend. The proportions of GHG emissions in transport, accommodation and catering, and wholesale and retail trade have increased significantly. This is clearly related to industrial restructuring in China. Industry has long been the leading sector of national economic development, but with China in the process of transitioning to post-industrialization, high-technology industries and services are increasingly becoming important industries of national economic development.

Analysis of the relationship between GHG emissions and industrial structure

This paper selects China's GHG emissions from 2000 to 2017 as the GHG emissions variables, selects the ratio of value added to GDP as industry structure variables, and uses PLS to implement the expanded STIRPAT model to explore the impact of industrial structure on GHG emissions. The calculation results are shown in Table 3.

According to Table 3, the estimation equation can be expressed in the following form:

$$\begin{aligned}\ln GHG = {} & 5.87-0.92\ln F+1.20\ln I \\ & +0.89\ln C-0.57\ln W-0.88\ln T-0.37\ln H \\ & +0.72\ln \end{aligned} \tag{7}$$

Table 3 Parameter estimation results of STIPART model

Variable	GHG	CO_2	CH_4	N_2O
Constant	5.87	5.87	− 2.30	− 1.23
ln*F*	− 0.92	− 0.93	− 0.82	− 0.87
ln *I*	1.20	1.20	1.27	1.77
ln *C*	0.89	0.88	0.71	1.00
ln *W*	− 0.57	− 0.57	− 0.72	− 0.65
ln *T*	− 0.88	− 0.88	− 0.75	− 0.94
ln *H*	− 0.37	− 0.37	− 0.18	− 0.42
ln *O*	0.72	0.72	0.61	0.29

$$\begin{aligned}\ln CO_2 = {} & 5.87-0.93\ln F + 1.20\ln I \\ & + 0.88\ln C - 0.57\ln W - 0.88\ln T - 0.37\ln H \\ & + 0.72\ln O \end{aligned} \tag{8}$$

$$\begin{aligned}\ln CH_4 = {} & -2.30-0.82\ln F + 1.27\ln I \\ & + 0.71\ln C - 0.72\ln W - 0.75\ln T - 0.18\ln H \\ & + 0.61\ln O \end{aligned} \tag{9}$$

$$\begin{aligned}\ln N_2O = {} & -1.23-0.87\ln F + 1.77\ln I \\ & + 1.00\ln C - 0.65\ln W - 0.94\ln T - 0.42\ln H \\ & + 0.29\ln O \end{aligned} \tag{10}$$

From the above results, the impacts of different industries on GHG emissions are different. The proportions of the value added of industry and construction to GDP are positively correlated with total GHG emissions and CO_2 emissions, that is, as the proportion of industry and construction increases, China's total GHG emissions growth rate will increase. The proportion of the value added of accommodation and catering; transport; farming, forestry, animal husbandry, and fishery; and wholesale and retail trade are negatively correlated with total GHG emissions and CO_2 emissions. The sector that has the greatest impact on total GHG emissions and CO_2 emissions is industry, for 1% increases in the proportion of the value added of China's industry in GDP, total GHG emissions and CO_2 emissions will increase by 1.2%. The reason is that among China's industrial enterprises, there are a large number of high energy consumption enterprises, which leads to large energy consumption, causing significant negative environmental effects, and these are caused by the specific attributes of the industry (Yuan et al. 2016). The sector that has the least impact on the total GHG emissions and CO_2 emissions is the accommodation and catering: for every 1% increase in the proportion of output value, the total GHG emissions and CO_2 emissions will decrease by 0.37%. Since 2011, the proportion of coal consumption in China has been declining significantly, and the proportion of natural gas, hydropower, wind power, and other clean energy consumption has increased. As of 2019, China's clean energy consumption accounted for 23.4% of total energy consumption (National Statistical Bulletin of 2019). Clean energy is now more widely used in the daily lives of residents; coal and other highly polluting energy sources are gradually being eliminated. Accommodation and catering is closely related to people's clothing, food, and housing. Therefore, even if the output value increases year by year, it consumes more clean energy and reduces the use of highly polluting energy, and can effectively reduce GHG emissions.

For CH_4 and N_2O emissions, the proportions of the value added of industry, construction, and other industries are positively related to them; the proportions of output value of farming, forestry, animal husbandry, and fishery; wholesale and retail trade; transport; and accommodation and catering are negatively correlated with CH_4 and N_2O emissions. However, the ranking of the impact of various industrial sectors on CH_4 and N_2O emissions is different from that of CO_2 emissions, for CH_4 emissions: industry > farming, forestry, animal husbandry and fishery > transport > wholesale and retail trade > construction > other industries > accommodation and catering; for N_2O emissions: industry> construction > transport >farming, forestry, animal husbandry and fishery > wholesale and retail trade > accommodation and catering > other industries. Farming, forestry, animal husbandry, and fishery is the second largest source of CH_4 emissions, energy consumption and agricultural activities are the main sources of CH_4 emissions, and in agricultural activities, CH_4 emissions come from livestock manure management, animal rumination, and crop cultivation (Zhang, 2012). However, industry has the greatest impact on CO_2, CH_4, and N_2O emissions; the GHG emissions from industry are the primary factors affecting China's GHG emissions.

Analysis of the relationship between GHG emissions and economic growth

Analysis of the economic growth trends of various industries in China

With the deepening of China's reform and opening up and the continuous improvement of the market economic system, China's achievements in economic development have attracted worldwide attention. As shown in Fig. 6, China's GDP has increased annually, from 10 trillion yuan in 2000 to 45.5 trillion yuan in 2017 (constant price in 2000), which is an increase of 4.55 times during this period. During the "11th Five-Year Plan" from 2006 to 2010, the average growth rate of GDP reached 10.96%. From 2000 to 2017, the average annual growth rate of China's GDP was approximately 9.32%. On the whole, despite the slowdown in GDP growth, total GDP is growing annually, indicating that China's economy is developing well and that the country and its people are becoming richer.

The output value of China's industries is ranked as follows: industry > other industries > wholesale and retail trade > farming, forestry, animal husbandry, and fishery > construction > transport > accommodation and catering. The output value of these seven industrial sectors is increasing annually, which is also in line with the trend in total GDP, indicating that all industries are in a stage of rapid development. In addition,

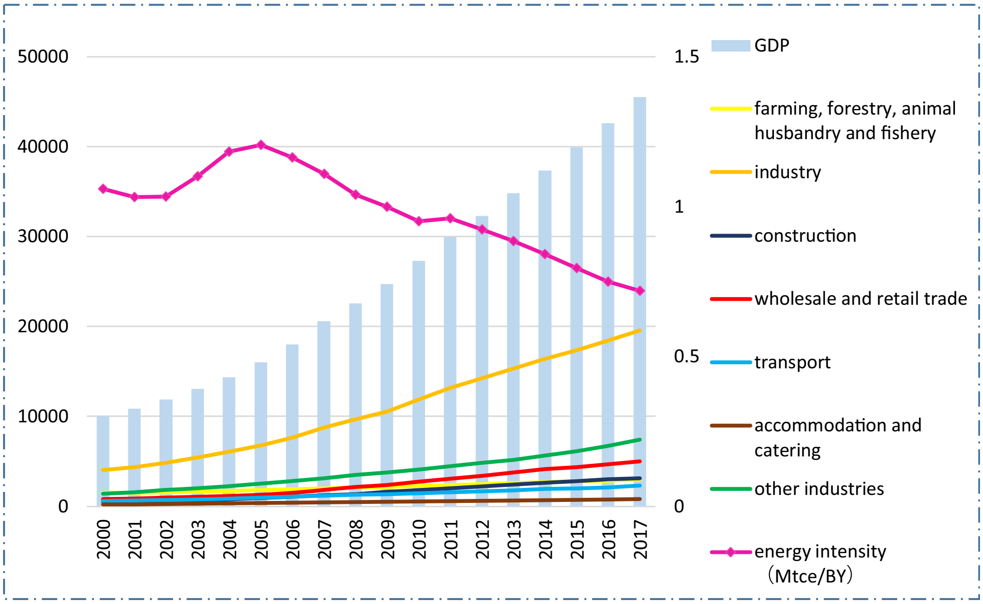


Fig. 6 Economic growth trends of various industries and overall energy intensity

China's large population base, relatively cheap labor force, huge potential market, and deepening openness to the outside world have led increasingly more manufacturing enterprises worldwide to invest and produce in China, resulting in the great development of the Chinese industry. The GDP of industry grew from 4 trillion yuan in 2000 to 19.6 trillion yuan in 2017, the growth trend is very obvious, and the gap with the GDP of other six industries is very obvious. From 2000 to 2017, the GDP of wholesale and retail trade; farming, forestry, animal husbandry, and fishery; construction; and transport increased by 4.2 trillion yuan, 1.5 trillion yuan, 2.6 trillion yuan, and 1.7 trillion yuan, respectively. It can be seen that during this period, wholesale and retail trade; transport; and farming, forestry, animal husbandry, and fishery developed rapidly. With the advancement of urbanization in China, cities of all sizes have accelerated their development, which makes the GDP growth of construction equally obvious. The GDP of accommodation and catering only increased by 0.62 trillion yuan from 2000 to 2017, which is the smallest change in GDP compared with that of other six industries. Overall, industry remains the focus of China's economic development, and industries belonging to tertiary industry have received attention.

Energy intensity is usually expressed as total energy consumption per unit of GDP, which can indicate the economic efficiency and utilization efficiency of energy, and the smaller the value, the higher the energy utilization efficient. As shown in Fig. 6, China's overall energy intensity maintained a growing trend over the period 2000–2005, with an increase of 0.15 Mtce/BY. China's overall energy intensity has shown a rapid decline after 2005, with a decline of 0.49 Mtce/BY. On the one hand, because of the adjustment of China's industrial structure, the proportions of light industry and heavy industry have changed significantly, and technological progress has greatly improved energy efficiency. On the other hand, since 2005, China strictly controlled high energy consumption enterprises, eliminated backward production methods, developed and promoted new energy sources, and formulated a series of policies related to energy conservation and emission reduction. The government's strong measures have made the declining trend of China's energy intensity very obvious in recent years.

Analysis of the decoupling state of GHG emissions and economic growth

According to Eq. (6), the decoupling results of China's GHG emissions and economic growth are shown in Figs. 7 and 8. Figure 7 shows the decoupling relationship between China's GHG emissions (including total GHG emissions and CO_2, CH_4, N_2O emissions) and economic growth. Figure 8 shows the decoupling relationship between the total GHG emissions of various industries and their economic growth in China.

From 2000 to 2006, the decoupling coefficients between China's total GHG emissions and economic growth all exceed 0.8, which did not show a decoupling state, especially in 2003–2004, which was a state of expansive negative decoupling. It means that the growth rate of total GHG emissions is greater than the economic growth rate, and the extensive economic growth model has caused severe environmental damage. With the increasing damage caused by GHG emissions to the environment, countries have come to realize the seriousness of global warming. On February 16, 2005, the Kyoto Protocol, the first regulation to limit GHG emissions in human history, came into effect. As one of the major emitters of greenhouse gases, China has also introduced relevant

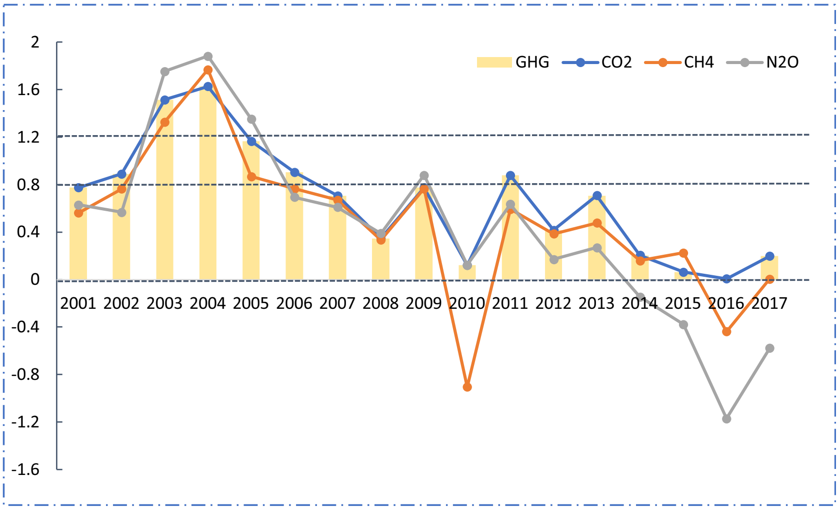


Fig. 7 Overall decoupling state from 2000 to 2017

measures for energy conservation and emission reduction, and vigorously promoted the development of a green economy during the "11th Five-Year Plan." Therefore, in the period 2006–2017 (except 2011), the decoupling coefficients between China's total GHG emissions and economic growth were in the range of 0–0.8, showing a weak decoupling state. The world financial crisis in 2008 had a large impact on China's economy. China launched the "four trillion plan" to reduce the impact and stimulate economic growth. Some high energy consumption enterprises have put into production again, which explains the expansive link between total GHG emissions and economic growth in 2011. By 2016, the decoupling coefficients between China's total GHG emissions and economic growth were close to 0, but they increased in 2017. On the whole, the control effect of China's overall GHG emission is good, and China is gradually achieving the ideal state of sustainable economic development.

Since CO_2 is a major contributor to GHG, the decoupling of CO_2 emissions and economic growth in China is consistent with the decoupling of total GHG emissions and economic growth. The decoupling coefficients between CH_4 emissions and economic growth in China exceeded 0.8 from 2003 to 2005. In the remaining years, except for 2010 and 2016, the decoupling coefficients between CH_4 emissions and economic growth in China were in the range of 0–0.8, showing weak decoupling state. In 2010 and 2016, China showed the strong decoupling state between CH_4 emissions and economic growth. CH_4 leakage during coal mining and oil and natural gas mining is the source of

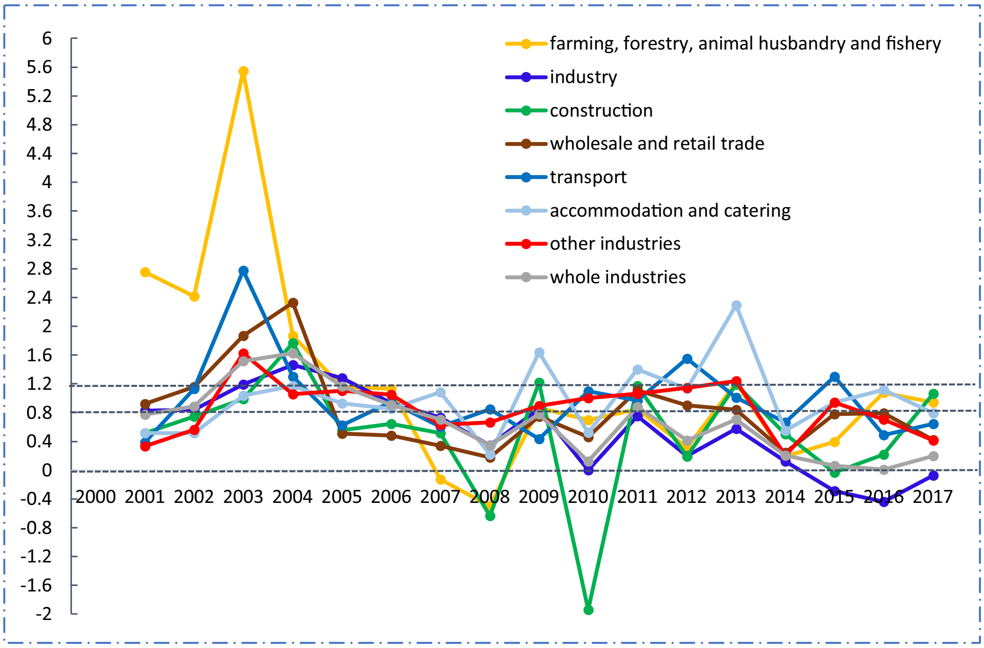


Fig. 8 Seven industries' decoupling state from 2000 to 2017

CH_4 escape emissions, of which coal mining is the largest CH_4 escape emissions source (Zhang et al. 2012). China's demand for coal is still rigid, but at the same time, China is also actively developing and promoting new energy, and gradually reducing the use of coal in some industries, which is the main reason why the decoupling coefficients between CH_4 emissions and economic growth have decreased annually. For N_2O emissions, the decoupling coefficients between China's N_2O emissions and economic growth exceeded 1.2 from 2003 to 2005, showing an expansive negative decoupling state. In 2006–2013 (except 2009), it showed a weak decoupling state. In 2014–2017, the decoupling coefficients of China's N_2O emissions and economic growth were less than 0, showing a strong decoupling state for four consecutive years. Fossil fuel combustion and biomass combustion are the main sources of N_2O emissions in the field of energy. Although its emissions are far less than natural sources such as soil and water body, they are the main sources of N_2O emissions caused by human behavior. The transition from the expansive negative decoupling to the strong decoupling state between China's N_2O emissions and economic growth shows that the adjustment in energy consumption and use in China can effectively control N_2O emissions. Compared with CO_2 and CH_4, N_2O has reached the best decoupling state, which shows that the control effect of N_2O emission reduction is the best in the energy field.

Because the GDP of various industries is increasing annually, the decoupling state between total GHG emissions and the economic growth of various industries is shown as strong decoupling, weak decoupling, expansive link, and expansive negative decoupling.

For industry, the total GHG emissions and economic growth have experienced the process of expansive link-expansive negative decoupling-expansive link from 2000 to 2006. During this period, China's economic growth was based on an extensive approach, with high energy consumption, inefficient utilization, and serious pollution, and the growth rate of GHG emissions is greater than the economic growth rate of industry. From 2007 to 2014 (except 2009), the decoupling state has always remained weak decoupling. With the entry into force of the Kyoto Protocol in 2005, China issued a series of regulations and policies, such as the "Renewable Energy Law" and the "Energy Conservation Law," abandoning the crude economic development approach and proposing to build a "resource saving and environment friendly" society, thereby reducing GHG emissions annually. In 2009, the decoupling state shifted, mainly due to the impact of the world financial crisis. To stimulate economic development, the industrial economy needed to be encouraged to recover. After 2009, the decoupling state changed into weak decoupling. From 2015 to 2017, the decoupling state of total GHG emissions and economic growth showed a strong decoupling state because China regards reducing GHG emissions as a binding indicator of national economic and social development. Under the background of a migration in industrial structure from secondary industry to tertiary industry, industrial technology has been comprehensively upgraded, and the number of high energy consumption and high pollution enterprises has been reduced. Industry has maintained the decoupling state between GHG emissions and economic growth for 3 years, showing the best state of strong decoupling.

For farming, forestry, animal husbandry, and fishery, the decoupling coefficients between GHG emissions and economic growth were above 0.8 from 2000 to 2006 and even reached as high as 5.5 in 2003. During this period, it showed the expansive negative decoupling state or expansive link state. Subsequently, total GHG emissions and economic growth showed a strong decoupling state from 2007 to 2008. During the period 2009–2017, the decoupling state was scattered, mainly weak decoupling, and expansive link. Before 2007, China's agriculture was still underdeveloped, and its productivity was low. In addition, livestock breeding technology was generally not advanced, and livestock manure was not handled properly. All of the above factors caused the growth rate of GHG emissions to be higher than the growth rate of economic growth. After 2007, the GHG emissions from farming, forestry, animal husbandry, and fishery were unstable. On the one hand, the mechanization of the planting and breeding industries was well popularized, production technology was greatly improved, and the generated waste received better treatment. All these factors have slowed the growth rate of total GHG emissions from farming, forestry, animal husbandry, and fishery (Wei et al., 2018). On the other hand, the advancement of the urbanization process has shifted the rural labor force to the city, which has also affected the economic development of farming, forestry, animal husbandry, and fishery to a certain extent. Therefore, the decoupling state of farming, forestry, animal husbandry, and fishery fluctuated greatly in the later period.

For transport, during the period from 2000 to 2017, its decoupling state was scattered: weak decoupling, expansive link, and expansive negative decoupling occur alternately. The energy consumption of transport accounts for 10.01% of total energy consumption, making it the second largest energy consumption sector in China after industry. Despite China's commitment to the use of new energy sources in transport, it remains more dependent on traditional energy sources. The GHG emissions and economic growth of the transport have reached a decoupling state in 2017; overall, the total GHG emissions from transport and economic growth have not been decoupled, so China needs to increase the emission reduction of transport.

For construction, from 2000 to 2008, total GHG emissions and economic growth have reached a decoupling state. In the period 2009–2013, the decoupling state between GHG emissions and economic growth was scattered. And then construction has been in a state of decoupling for 3 years, but the GHG emissions and economic growth showed an expansive link state in 2017. This pattern is closely related to the urbanization process in China. Before 2009, the construction developed slowly. But after 2009, the construction developed rapidly, with a significant increase in GHG emissions, which is the reason for the scattered decoupling state from 2009 to 2013. Although the decoupling state was not achieved in 2017, overall, the decoupling effect of the construction is obvious, but the emission reduction efficiency of the China's construction still needs to be improved.

For wholesale and retail trade, the GHG emissions were not decoupled from economic growth in 2000–2004 or 2011–2013, while the GHG emissions and economic growth showed a weak decoupling state in the remaining years. GHG emissions from wholesale and retail trade increase with economic growth, but its growth rate is far less than economic growth rate. The energy consumption of wholesale and retail trade accounts for only 2.18% of total energy consumption. The proportion of energy consumed is relatively small, GHG emissions are lower, and the growth rate is below economic growth rate. In general, the total GHG emissions from wholesale and retail trade have been decoupled from economic growth, and the effect of emission reduction is obvious, but it has not reached the optimal state of strong decoupling.

For accommodation and catering, expansive link, expansive negative decoupling, and weak decoupling appeared alternately from 2000 to 2017. From 2003 to 2007, the total GHG emissions and economic growth showed continuous expansive link state. Other industries showed continuous expansive link state from 2003 to 2006 and from 2009 to 2013. Overall, regardless of whether accommodation and catering or other industries, total GHG emissions and economic growth have not reached the decoupling state, and their emission reduction efficiency needs to be improve.

For China's overall economy, with the reform of the industrial structure and the development of a low-carbon circular economy, the total GHG emissions have decoupled from economic growth. The impact of economic growth on GHG emissions is gradually being mitigated, but the decoupling level has been maintained in a weak decoupling state. The pressure to reduce GHG emissions is still greater, and the efficiency of energy utilization needs to be improved.

Conclusions

China's total GHG emissions showed a year-on-year growth trend from 2000 to 2017, but the growth rate in different periods showed obvious differences. Sort the GHG emissions from energy consumption in different industries: industry > accommodation and catering > transport > other industries > farming, forestry, animal husbandry, and fishery > wholesale and retail trade > construction. The proportion of the value added of secondary industry to GDP is positively correlated with GHG emissions. The proportions of the value added of primary industry and tertiary industry are negatively correlated with GHG emissions. China's GHG emissions are decoupled from the overall economic growth, and the control effect of N_2O emission reduction is the best. Overall, China's control of GHG emissions is reasonable. Therefore, China can incorporate the remaining greenhouse gases except CO_2 into the GHG emission reduction strategy, formulate emission reduction indicators accordingly, and implement various GHG emissions reduction programs together. And China needs to adjust the structure of energy consumption, develop and introduce new and renewable energy, give financial, tax, and policy preference to clean energy, and formulate reasonable policies and regulations to ensure the effective allocation of resources. In addition, there are obvious differences in economic development and energy reserves in different regions of China. It is necessary to make appropriate adjustments according to local policies, establish an environmental protection fund, and provide special support to local economic losses that may be caused by environmental protection.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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