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Co-benefits of policies to reduce air pollution and carbon emissions in China

Botong Xian, Yalin Xu, Wei Chen, Yanan Wang *, Lu Qiu

College of Economics and Management, Northwest A&F University, Yangling 712100, China

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ABSTRACT

Coordinated efforts to reduce pollution and carbon emissions have become an inevitable choice for China's comprehensive green transformation of economic and social in the new stage of development. However, the co-benefits of policies to reduce air pollution and carbon emissions in different departments has not been effectively evaluated. This study uses the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC) to calculate the carbon and major air pollutants emission tracks at the provincial and sectoral levels in China from the bottom to up. We evaluate the synergies between current pollution reduction policies and carbon reduction policies in the power, industry, transport, resident and agriculture sector. The results show that the implementation of current emission reduction policies has significantly reduced major air pollutants and slowed down the growth rate of CO_2 emissions. The synergistic effects of the carbon reduction policy and pollution reduction policies are various in different sectors, and pollution reduction policies have a greater inhibitory effect on controlling air pollution and carbon emission. Under the cooperative control scenario, CO_2 emissions will peak in 2028 and basically achieve the carbon emission target of 2 °C in 2050. SO_2, NO_X, CO, $PM_{2.5}$, and NH_3 emissions will reach 3.7 Mt., 4.9 Mt., 50.3 Mt., 0.9 Mt., and 2.7 Mt. in 2050, respectively.

1. Introduction

In recent decades, climate change in China has become increasingly obvious (Wang et al., 2021; Sun et al., 2023), and the greenhouse effect has also increased year after year (Wang et al., 2019). As the world's largest CO_2 emitter, China's CO_2 emissions account for 28.7% of the world's total (International Energy Agency (IEA), 2019). To implement the Paris Agreement on climate change, China has made a solemn commitment to "double carbon" targets, striving to achieve a carbon peak by 2030 and carbon neutrality by 2060 (Li et al., 2022a; Wang et al., 2022a). At the same time, the current situation of air pollution in China is severe, and regional air environment problems are becoming increasingly prominent (Liu et al., 2023). In 2021, 35.7% of cities still fail to meet the air quality standards, which damages the health of the people and impedes the sustainable development of cities (China Ministry of Ecology and Environment, 2022). For a long time, the Chinese government has treated meeting its climate commitments and improving air quality as two separate issues, each with different strategies (Zhao et al., 2021). In fact, air pollutants and greenhouse gases are homologous, and pollution reduction and carbon reduction are highly consistent in terms of control ideas and management measures (Yi et al., 2022; Li et al., 2017a; Rafaj et al., 2013). In June 2022, the Chinese government issued the Implementation Plan for Synergic Efficiency in Reducing Pollution and Carbon, giving preliminary instructions on coordinated emissions reduction. It is expected that by 2025, a coordinated work pattern for pollution reduction and carbon reduction will be basically formed, and the collaborative capacity to reduce pollution and carbon will be significantly improved by 2030 (China Ministry of Ecology and Environment, 2022b). At present, China's collaborative governance of pollution reduction and carbon reduction is entering a substantial stage of promotion, with the space for emission reduction gradually narrowing, and the difficulty of emission reduction in the end treatment becoming increasingly greater. The focus of work has shifted to the source treatment (China Ministry of Ecology and Environment, 2022b). Therefore, the composition and distribution characteristics of pollutants and carbon emissions should be described in detail, as well as the synergistic characteristics and implementation path of emission reduction policies should be further analyzed. This will not only provide action guidelines for the comprehensive coordinated promotion of pollution reduction and carbon reduction, but also point out the

* Corresponding author at: College of Economics and Management, Northwest A&F University, No. 3 Taicheng Road, Yangling, Shaanxi, China.
E-mail address: wyn3615@nwafu.edu.cn (Y. Wang).

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direction for China's economy to achieve comprehensive green transformation in the post-COVID-19 era.

Existing studies have verified the existence of synergy between greenhouse gases and air pollutants by studying the distribution characteristics of their emissions. Wang et al. (2023) found that the local accumulation characteristics of SO_2, dust, and $PM_{2.5}$ were highly similar to carbon emissions, and the evolution path was similar, which verified the possibility of collaborative management. The synergy between air pollution and carbon emissions per unit of GDP can also be verified by constructing the synergy index, and the synergy is more significant in eastern and southern China. However, due to the continued high dependence on coal, the per capita carbon intensity of the northern region is higher, and the synergy between air pollution control and carbon emission reduction is poor (Xue et al., 2023). However, in key areas such as the Beijing-Tianjin-Hebei region and the northern part of the Yangtze River Delta, there is a significant synergistic effect between pollutants, mainly $PM_{2.5}$ and CO_2, and it is actively driven by the CO_2 emission-related social costs and $PM_{2.5}$-related health impacts (Guan et al., 2023). At the same time, existing studies have further analyzed the factors that may influence the degree of synergy between greenhouse gases and air pollutants. Coal consumption, the added value of the secondary industry, population size, total import and export trade, etc. are effective drivers of the CO_2 mitigation and air pollution control synergy degree, while GDP, innovation, urbanization, energy consumption intensity, environmental protection investment and other factors hinder the improvement of the degree of synergy between the two (Yi et al., 2022; Tang et al., 2022). Some scholars believed that the implementation of relevant emission reduction policies is the root cause of the change in the degree of synergy between them. For example, the promulgation of Environmental Protection Tax Law (Gao et al., 2022), low-carbon city pilot (Li et al., 2022b), carbon pricing policy (Li et al., 2018), clean energy policy (Tibrewal and Venkataraman, 2021), optimization of energy structure (Lu et al., 2019), promotion of electric vehicles (Alimujiang and Jiang, 2020) and other emission reduction policies and measures have synergistic emission reduction effect, significantly improve the degree of synergy between air pollutants and carbon emissions. In addition, some scholars further predicted China's future collaborative emission reduction trend based on policy driving. Shu et al. (2022) believed that the Three-year Action Plan for Blue Skies will significantly promote coordinated emissions reduction, and predicted that by 2030, $PM_{2.5}$, SO_2, NO_x, NH_3, and CO_2 will be reduced by 17%, 25%, 21%, 3%, and 1%, respectively, compared with the base year. Yuan et al. (2022) found that the energy transition had different emission reduction effects on different air pollutants and industries. With the strengthening of the control level at the end of the pipe in 2025, the concentration of $PM_{2.5}$ and O_3 could be reduced nationwide.

Although current studies have discussed the synergy of pollution and carbon reduction from different perspectives, there are still some deficiencies. At the beginning, scholars mainly discussed the synergy between greenhouse gases and air pollutants and their influencing factors (Xue et al., 2023; Yi et al., 2022; Li et al., 2022c; Sawlani et al., 2021), but rarely analyzed the reasons for the synergy change from the policy level, ignoring the important driving force of emission reduction policies. Since 2013, the Chinese government has rolled out a series of emission reduction policies to improve air quality and the climate environment. Some scholars only evaluated the emission reduction effect of a single policy (Gao et al., 2022; Li et al., 2022a; Li et al., 2018; Zhu et al., 2022; Yang et al., 2022; Tong et al., 2023). In fact, policy measures are usually package plans. These plans are issued and implemented at the same time, and their effects are also synergistic. However, there are few researches on the synergistic effect of policy combinations, and the emission reduction effect of these policy combinations is unknown. In addition, the policy prediction is only carried out in a certain sector or a certain city (Zeng and He, 2023; Yu et al., 2020; Wang et al., 2022a), which failed to put forward overall emission reduction action guidance at the national level.

Herein, the purpose of this study is to examine the synergistic effect of pollution reduction policies and carbon reduction policies in multiple sectors, and to predict the implementation effects of the combination of emission reduction policies in the future. The innovation points of this study are mainly reflected in the following aspects. First of all, there is a certain degree of synergy and combination effect between pollution reduction policies and carbon reduction policies, but the implementation effect of the policy combination is still unclear. We select representative pollution reduction policies and carbon reduction policies from the package to assess the synergy between the two emission reduction policies. Secondly, considering the practical differences between different departments, the effectiveness of emission reduction policies varies among different sectors, resulting in heterogeneity in the implementation effects of different policy combinations among sectors. By adjusting the policy mix, we predict the implementation effects of pollution and carbon reduction in various sectors of China under different policy combinations in the future, providing reference for policy optimization in various sectors.

The rest of the paper is arranged as follows. Section 2 describes the methods and data of this study in detail. Section 3 presents the results and discussions of the emission trajectories of CO_2 and air pollutants, the synergies of pollution reduction and carbon reduction policies, endogeneity and robustness test of the model, and scenario prediction. The conclusions and related policy implications are given in Section 4.

2. Methods and data

2.1. Estimate of CO_2 emissions and major air pollutants

The historical trends of CO_2 and air pollutants emissions in China from 2006 to 2020 were estimated by using the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC). The MEIC model is an anthropogenic emissions simulation platform based on bottom-up approach by Tsinghua University, which has the characteristics of long time series, high spatiotemporal resolution and dynamic updating (Li et al., 2017b; Zheng et al., 2018a).

In this study, we select five typical air pollutants, namely SO_2, NO_x, CO, $PM_{2.5}$, NH_3, and anthropogenic sources were divided into five sectors, namely power, industry, transport, resident and agriculture. Therefore, emissions of CO_2 and major air pollutants originating from fossil fuel combustion and cement production process were estimated separately for provinces and sectors:

$$E = \sum_{i}^{n} A_i \times EF_i \tag{1}$$

where E denotes CO_2 or five air pollutants emissions, A denotes fuel consumption and industrial production, EF denotes CO_2 and air pollutants emission factors obtained from Liu et al. (2015), i denotes emission sources.

2.2. Quantification of mutual co-benefits

The fixed effects panel regression model is adopted in this study to measure the synergistic effects of pollution reduction and carbon reduction policies (Zhang et al., 2022). Specifically, the carbon reduction effects of pollution reduction policies and the pollution reduction effects of carbon reduction policies are modeled respectively under the same data set.

According to Kaya identity, CO_2 emissions can be decomposed as follows:

$$CO_2 = \frac{CO_2}{Energy} \times \frac{Energy}{GDP} \times \frac{GDP}{Pop} \times Pop \tag{2}$$

where CO_2 is CO_2 emissions, $Energy$ is total energy consumption, GDP is gross domestic product, *Pop* is total population. Because $\frac{CO_2}{Energy}$ has a strong positive correlation with the proportion of coal consumption in total energy consumption (i.e., energy consumption structure), it is often replaced by energy consumption structure. Therefore, CO_2 emissions are affected by the following four variables: energy consumption structure, energy consumption per unit of GDP (i.e., energy intensity), per capita GDP and population.

Yuan and Pan (2013) pointed out that although Kaya identity is the main method for analyzing driving factors of CO_2 emission at present, it can only explain the change of CO_2 emission flow, but cannot explain the change of stock. Therefore, we combine other factors in the study of CO_2 emission, such as the level of scientific and technological innovation ability (Pui and Othman, 2019), air temperature (Gurriaran et al., 2023), etc. In addition, policy variables related to pollution reduction and carbon reduction are included to fit research themes. Here we make a more detailed explanation of selected co-beneficial measures in our assessment. The carbon market is one of the important policy tools for China to achieve the goal of "double carbon". Beijing, Shanghai, Guangdong, Shenzhen, Hubei, Tianjin and Chongqing launched the pilot carbon emission trading market in 2013, which has achieved remarkable carbon reduction results so far. Therefore, this study defines "whether to carry out carbon emission rights trading market" as a dummy variable, as a substitute variable for carbon reduction policy. Considering the consistency and availability of data and the reliability of reflecting the intensity of pollution reduction policies, we select five representative policy measures from the Air Pollution Prevention and Control Action Plan (China State Council, 2013), which can comprehensively evaluate the implementation effect of pollution reduction policies from the four levels of government, enterprises, market and the public. As shown in Table 1, only these measures that were implemented for the first time or strengthened since 2013 are selected and measured with appropriate indicators. Finally, the regression equation of CO_2 is constructed as follows:

$$lnCO_2it = \alpha_0 + \beta_0 RCP_{it} + \beta_1 RPP1_{it} + \beta_2 RPP2_{it} + \beta_3 RPP3_{it} + \beta_4 RPP4_{it} + \beta_5 RPP5_{it} + \beta_6 lnPop_{it} + \beta_7 lnPGDP_{it} + \beta_8 ES_{it} + \beta_9 EI_{it} + \beta_{10} RD_{it} + \beta_{11} T_{it} + \varepsilon_i + \varepsilon_{it} \tag{3}$$

where *RCP* denotes carbon reduction policy, *RPP*1-*RPP*5 denotes five representative pollution reduction policies, *Pop* denotes total population, *PGDP* denotes GDP per capita, *ES* denotes energy consumption structure, *EI* denotes energy intensity, *RD* denotes ratio of R&D expenditure to GDP, *T* denotes annual mean temperature. *i* denotes province, the value ranges from 1 to 30, *t* denotes year, and the value ranges from 2013 to 2020. ε_i denotes individual fixation effect, ε_{it} denotes random error. The notation ln is taking the natural log of a variable. The coefficients β_1-β_5 respectively reflect the carbon reduction effects of different pollution reduction policies, also known as the degree of coordination between RCP and RPP. If the coefficient is significantly negative, it means that the pollution reduction policy can promote the reduction of carbon emissions.

Due to the same root homology of air pollutants and CO_2, the emission of air pollutants is also affected by precipitation (Zheng et al., 2019). Similarly, the regression equation of air pollution emissions can be established as shown in Eq. (4).

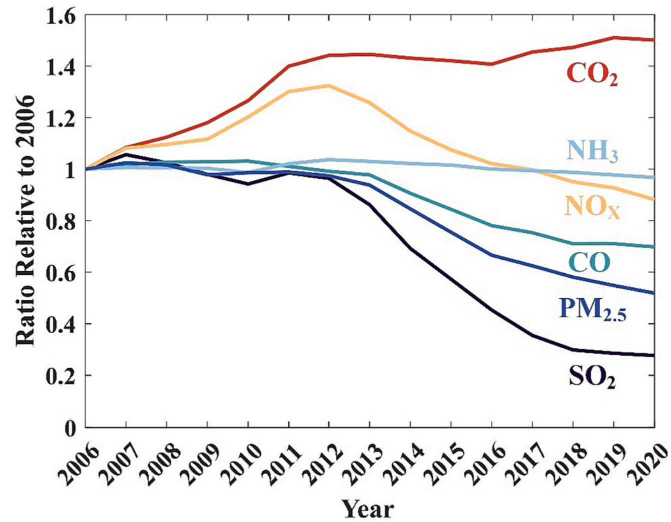

Fig. 1. Trends of CO_2 and five air pollutants emissions in China from 2006 to 2020.

$$lnPollution_{it} = \rho_0 + \gamma_0 RCP_{it} + \gamma_1 RPP1_{it} + \gamma_2 RPP2_{it} + \gamma_3 RPP3_{it} + \gamma_4 RPP4_{it} + \gamma_5 RPP5_{it} + \gamma_6 lnPop_{it} + \gamma_7 lnPGDP_{it} + \gamma_8 ES_{it} + \gamma_9 EI_{it} + \gamma_{10} RD_{it} + \gamma_{11} T_{it} + \gamma_{12} lnRainfall_{it} + \varepsilon_i + \varepsilon_{it} \tag{4}$$

where *Pollution* denotes the emission of a certain air pollutant, *Rainfall* denotes annual mean precipitation. Therefore, the co-benefits of pollution reduction of RCP are estimated by γ_0.

2.3. Data sources

CO_2 and five air pollutants emissions of provinces and departments are obtained from the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC), and the missing part was calculated using data on fuel consumption from China Energy Statistical Yearbook. The data about pollution reduction policies, such as the green coverage rate of built-up areas and the number of heavily polluting enterprises, are all from China Environmental Statistical Yearbook. Data related to population, GDP and R&D expenditure are from the China Statistical Yearbook, data on various energy consumption are from the China Energy Statistical Yearbook, and data on temperature and precipitation are from the China Climate Bulletin.

Table 1
Definition of pollution reduction policy variables adopted in the study.

Variables	Policy measure	Index selection
RPP1	Expand the scale of green space in urban built-up areas	Green coverage rate of built-up areas
RPP2	Promote cleaner production	Number of heavily polluting enterprises
RPP3	Promote the clean use of coal	Raw coal entry rate
RPP4	Improve energy efficiency	Energy processing and conversion efficiency
RPP5	Perfect environmental and economic policies	Investment in environmental pollution control

3. Results and discussion

3.1. Emission trajectory of CO_2 and major air pollutants

China's anthropogenic emissions of CO_2 and major air pollutants from 2006 to 2020 were estimated based on the MEIC model. As shown in Fig. 1, CO_2 emissions increased rapidly from 2006 to 2013, with a maximum growth rate of 10.6%. In 2011, The State Council issued the "Notice on carrying out the Pilot Work of Carbon Emission Trading", all sectors became aware of environmental protection and began to take relevant measures to reduce carbon emissions. The growth rate slowed down significantly and reached a small peak in 2013. Since 2013, with the official launch of carbon emission rights trading markets in seven pilot cities, the trend of carbon emissions has turned to decline. However, with the increase of anthropogenic emission sources due to economic development, the carbon emissions have not been timely supplemented with other policies to adapt, and the carbon emissions have rebounded after 2016 and finally reached 11.5 Gt in 2020, which is 1.5 times the CO_2 emissions in 2006. This also reflect the effectiveness and necessity of fully launching the carbon emission rights trading market.

Contrary to the rising trend of CO_2 emissions, the emissions of SO_2, NO_x, CO, $PM_{2.5}$, and NH_3 decreased by 72.3%, 11.8%, 30.2%, 48.1%, and 3.2%, respectively during the same period. Since the 11th Five-Year Plan listed the reduction of total pollutants as a binding target, all sectors have implemented protection in the course of development and effectively promoted emission reduction in accordance with the principle of coordinated development and mutual benefit. Remarkable emission mitigation has been identified as the major driver of national air quality improvements during the clean air action period. However, it is worth mentioning that emissions of these air pollutants, especially NO_X, rebounded around 2010, which is due to the delayed impact of the financial crisis (Wang et al., 2022b; Pacca et al., 2020). On the one hand, the gloomy macroeconomic situation has prompted companies to make environmental protection a priority sacrifice to stay afloat. On the other hand, to stimulate the economy, the government increased enterprise investment and blindly pursued GDP growth, ignoring environmental protection and ecological construction. In 2010, only 3.6% of cities at or above the county level met first-class air quality standards, according to China's State of the Environment Bulletin.

China is a vast country with huge differences in economic development and environmental conditions among different regions. The middle part of Fig. 2 shows the distribution of average CO_2 and air pollutants emissions from 2006 to 2020 for 30 provinces. Obviously, there is significant regional heterogeneity among Chinese provincial cities, and CO_2 and air pollutants mainly come from North China and East China in terms of geographical administrative division. The Beijing-Tianjin-Hebei (BTH) region known as the "capital economic circle", has been one of the fastest-growing economic zones in the world, and also faced severe carbon and air pollution problems (Wu et al., 2023). Although the government has introduced relevant policy measures to stop this trend (e.g., Action Plan to Comprehensive Control Autumn and Winter Air Pollution in Beijing-Tianjin-Hebei and Surrounding Regions 2017–2018), the fragmentation of government due to administrative and fiscal decentralization hinders regionally coordinated emission reduction, Hebei is still a major emitter of CO_2 and major air pollutants, accounting for 75.0% and 79.0% of the BTH, and 6.9% and 8.8% of the national total. As typical resource-based provinces with rich coal reserves, Shanxi and Inner Mongolia are important energy-heavy chemical bases in China (Yan and Peng, 2016; Zheng et al., 2018b). Industries such as thermal power, chemical engineering and metallurgy imposed a heavy burden on air quality. At the same time, local enterprises for a long-term of private and indiscriminate mining, not only brought benefits to the local economic, but also caused serious damage to the atmospheric environment. Thus, SO_2 and NO_X emissions seriously exceeded the standard over the years. After reaching the peak in 2011, the air pollutants emissions in the two provinces decreased slowly at a rate of 6.3% and 4.3% respectively, which indicates that the effect of current policies is not ideal in this region and there is still a large potential for emission reduction. East China is one of the fastest-developing regions in China, especially the Yangtze River Delta, where urbanization is advancing rapidly. However, the rapid urbanization also brings tremendous pressure on the ecological environment through high population density, large energy consumption, heavy industrial structure and increased traffic expansion. Notably, Shandong Province within the region is China's largest contributor to carbon emissions, producing

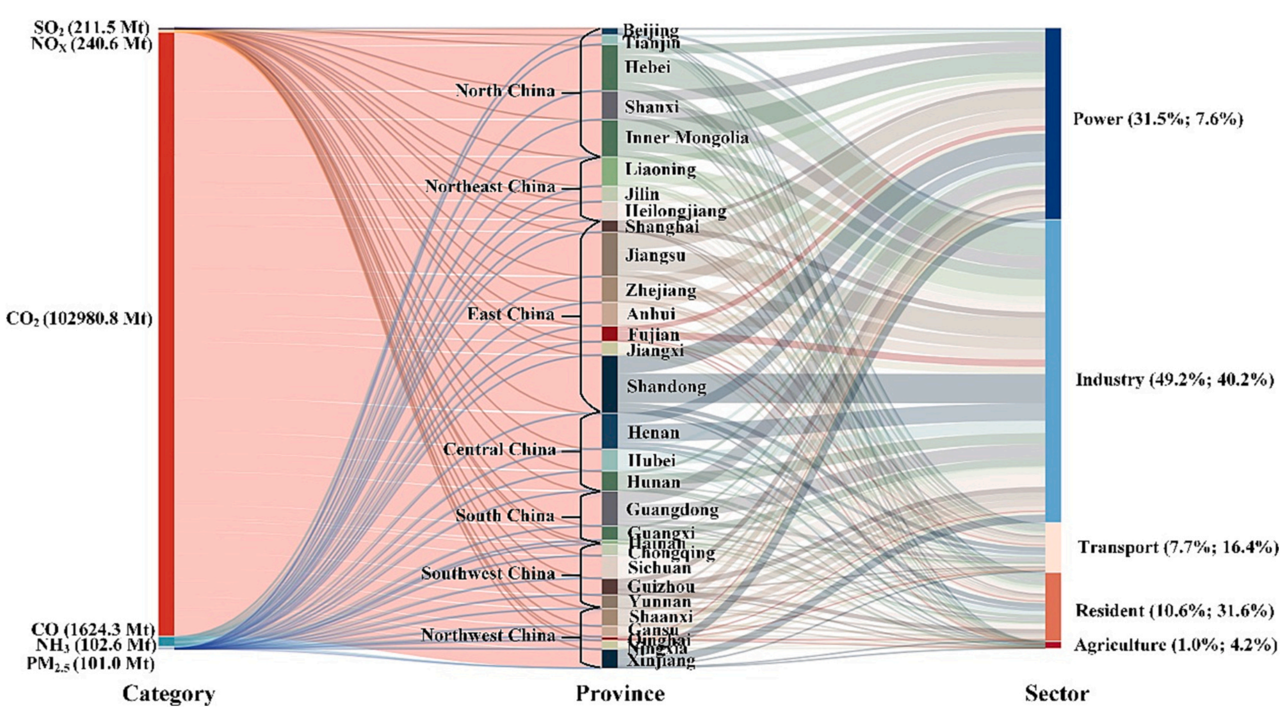

Fig. 2. Emission trajectory of provinces and sectors in China from 2006 to 2020.

15.0% of the country's total in the study range. In 2021, 28.9% of the days in Shandong exceeded the standard of air quality, and the annual average $PM_{2.5}$ concentration was 39 μg/m^3, much higher than the national average concentration of 30 μg/m^3 (Fan et al., 2020). Various types of greenhouse gases and air pollutants continue to increase in recent years, and has become the primary bottleneck restricting the green sustainable development of this region.

At the sector level, as the right part of Fig. 2 shows, according to estimation, power and industry are the main sources of CO_2 emissions, contributing 31.5% and 49.2% respectively to China's total emissions from 2006 to 2020. China's power generation structure has long been dominated by thermal power, heavily dependent on coal, coal-fired power is responsible for more than 90% of the power's carbon emissions. Although the government has actively invested in the development of nuclear, wind, solar and other clean energy sources for power generation, thermal power is still the primary form of power generation in China. During the 12th Five-Year Plan period (2011–2015), the annual use of coal for thermal power generation in the power sector accounted for about 63% of the country's total coal consumption. As a pillar industry of national economic growth, the industrial sector continues to develop rapidly for decades in China. China has long been the largest producer of industrial sources all over the world, such as cement, iron and steel (Wu et al., 2023). However, industrial boilers, metal smelters, paper mills, cement plants and so on are major sources of anthropogenic emissions of air pollutants. The results show that the industry sector is also the biggest contributor to air pollution, accounting for 40.2% of China's emissions of air pollutants, especially in 2009, accounting for nearly half of the total. Sustained GDP growth and the severity of air quality may indicate that economic growth has not yet decoupled from air pollution in the industry sector. The agricultural sector is both a carbon source and a carbon sink, which is an important sector in reducing carbon and air pollution. Although farmland soils have significant carbon sequestration capacity, the use of agricultural inputs such as fertilizers, pesticides and agricultural machinery can produce large amounts of CO_2 and NH_3. Therefore, the transformation of agricultural ecosystem can be realized through adopting conservation tillage measures, expanding paddy field planting area, increasing straw returning to the field and increasing the application of organic fertilizer.

3.2. Co-benefits between pollution and carbon reduction policies

By reviewing national policy packages, five representative pollution reduction policies were summarized, and the reduction effects of CO_2 and air pollutant emission were respectively evaluated when the pollution reduction policies were combined with the carbon reduction policy. The results are shown in Fig. 3, the numbers in the squares are the coefficients of policies in the regression results, representing the effectiveness or synergy of the policy implementation. The significance level and standard error of each coefficient are shown in the Appendix (Tables A1–6). Obviously, different policy combinations have different effects on different sectors and different air pollutants. In general, the synergistic effect of the carbon reduction policy and the pollution reduction policies is remarkable. In terms of the emission reduction effect of the carbon reduction policy, the carbon reduction policy based on the carbon emission rights trading market not only significantly suppressed CO_2 emissions but also synergistically reduced the emission of

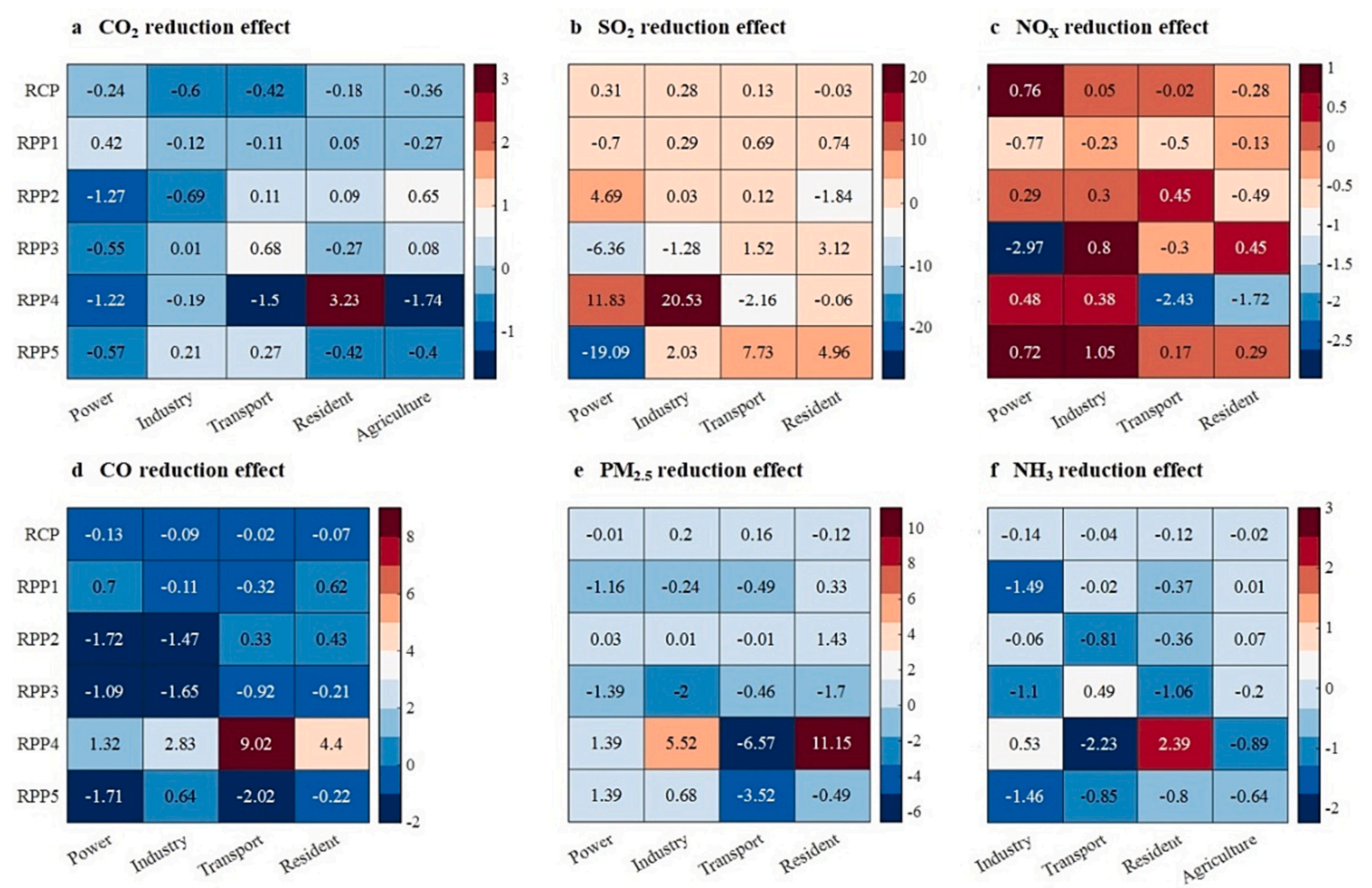

Fig. 3. Synergistic effects of different policies on CO_2 and air pollutants. RCP is the implementation of a carbon emission trading market, RPP1 is expanding the scale of green space in urban built-up areas, RPP2 is promoting cleaner production, RPP3 is promoting the clean use of coal, RPP4 is improving energy efficiency, RPP5 is perfecting environmental and economic policies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

major air pollutants, especially for CO and NH_3. As shown in the first line of Figs.3a-f, the carbon reduction effects of RCP are significant and similar across all sectors, but its pollution reduction effect varies in different sectors. To be specific, the current RCP has positive estimated coefficients in reducing SO_2 emissions and lacks synergies, except in the resident sector. Similarly, the RCP has only significantly promoted the reduction of NO_X and $PM_{2.5}$ emissions in part sectors, and both air pollutants can be reduced in the industrial sector only through pollution reduction policies. Since the associated estimated coefficients are all significantly negative, RCP has an important mitigation effect on the emission of CO and NH_3 in all sectors, which is coordinated with pollution reduction policies to jointly reduce emissions. The results show that the pilot project of the carbon emission trading market is successful, and the effect of carbon emission reduction is significantly higher than that of pollution reduction, which lays a good foundation for the launch of the national carbon emission rights trading market in the future.

In terms of the emission reduction effect of the pollution reduction policies, pollution reduction policies have significantly reduced the emission of air pollutants, and also inhibited CO_2 emissions to varying degrees in different sectors. As shown in lines 2 through 6 of Figs.3a-f, the effect of each pollution reduction policy is different, but all of them focus on pollution reduction, and the effect of carbon reduction is auxiliary. Expanding the scale of green space in urban built-up areas can not only do a good job in urban landscaping, promote the green and low-carbon transformation of the city, but also promote high-quality sustainable development of the city. RPP1 contributes to reducing the emissions of CO_2 and most air pollutants, and has the effect of inhibiting NOx emissions in all sectors, but fails to reduce SO_2. In Fig. 3d, the estimated coefficients of RPP2 in the power sector and industry sector are −1.72 and −1.47 respectively, and both are negative at the significance level of 1%, indicating that RPP2 significantly reduces the emission of NOx. This is because the implementation of cleaner production is a fundamental change to the traditional terminal pollution control method, emphasizing the control of pollutants from the source and the whole process, and "desulfurization, denitrification, dust removal transformation" as its main implementation approach, can play a direct role in the power sector and the industry sector. Moreover, the absolute values of the estimated coefficients are greater than those of the RPP2 on CO_2 respectively (1.27 and 0.69), indicating that the pollution reduction effect of RPP2 is greater than its carbon reduction effect. Promoting the clean use of coal has been remarkably effective and synergistic in the power sector which is dominated by thermal power generation, mainly through the high-quality development and utilization of coal resources. As one of the main sources of pollution discharge in the civil sector, with the technological transformation of industrial boilers, the pollution sharing rate of civil coal is increasing year by year. However, the implementation of RPP3 effectively hinders the emission of carbon and air pollutants from this emission source, except for SO_2, which is due to the lower utilization rate of sulfur fixers (Hu et al., 2022). Theoretically speaking, as an important measure of energy conservation and emission reduction, the effectiveness and synergy of RPP3 should be significantly present in various sectors, but in practice it does not. Among the five pollution reduction policies selected in this study, the implementation effect of RPP4 is the least ideal, probably because the coexistence of RPP4 and RCP leads to problems such as repeated management and multiple supervision, which causes related departments and enterprises to increase their operation, management and ecological costs, and weakens the emission reduction effect. Since improving environmental and economic policies focus on increasing investment in environmental pollution control, including increasing support for air pollution control in key industries and regions, such as urban environmental infrastructure, industrial pollution sources and so on. Therefore, RPP5 can perform well in all aspects, especially in reducing the emissions of CO_2, CO, and NH_3. As studied by Shi et al. (2022), supporting the "promote clean fuels in the residential sector" to reduce CO_2 emissions by 120.8 Mt. in 2020, which strongly contributed to the transformation of the national energy system. In addition, due to the long implementation time, rich experience and strong implementation of China's pollution reduction policy, its inhibition effect on the emissions of air pollutants and CO_2 is greater than that of the carbon reduction policy.

3.3. Endogenous and robustness tests

3.3.1. Endogenous test

The reason for the possible occurrence of endogeneity is that in the benchmark regression, there is reverse causality between the emission reduction policies and the emission of CO_2 and air pollutants (that is, the more CO_2 and air pollutants are discharged, the more intensive the emission reduction policies are). Therefore, this study adopts the commonly used instrumental variable method to deal with the endogeneity problem. Specifically, the first-order lag term of RCP is selected as the instrumental variable in Eq. (3), and the first-order lag term of RPPs are selected as the instrumental variables in Eq. (4). The lagging term is highly correlated with its current term, but it is lowly correlated with other variables in the model. Then, the instrumental variable panel model is used to estimate Eqs. (3) and (4) respectively. Considering the length of the article, only the results of the endogenous test of the synergistic effects of pollution reduction and carbon reduction policies on CO_2 and SO_2 in the power sector are presented, and the full results of the endogenous test will be presented in the Supplementary Information (Tables S1–6). Columns (1) and (2) in Table 2 show that the size and significance of the estimated coefficients of RCP and RPPs are not much different from the estimated coefficients of the benchmark model, indicating that the model in this study does not have serious endogeneity.

3.3.2. Robustness test

This study attempts to use the following methods to test the robustness.

First, change the calculation method of dependent variables. In the benchmark model, the value of each dependent variable is expressed in terms of its total emissions. This part uses emission intensity (emissions per unit of GDP) as the value of the dependent variable. Similarly, only the results of the robustness test of the synergistic effects of pollution reduction and carbon reduction policies on CO_2 and SO_2 in the power sector are presented, and the full results of Method 1 of the robustness test will be presented in the Supplementary Information (Tables S7–12). The results in columns (3) and (4) in Table 2 show that the value of the coefficient of each variable changes slightly, but the direction remains unchanged. These show that the emission indicators constructed in this study are reasonable to a certain extent, and the estimated results of the benchmark model have strong robustness, and will not produce different results due to the different selection of emission indicators.

Second, add control variables. In the process of urbanization development, the economic scale effect, agglomeration effect and energy consumption characteristics of urban residents have an important impact on carbon emissions and air pollution (Zhao and Wang, 2022; Qi et al., 2023). Therefore, this part takes the urbanization rate as a control variable to supplement the panel model. Similarly, only the results of the robustness test of the synergistic effects of pollution reduction and carbon reduction policies on CO_2 and SO_2 in the power sector are presented, and the full results of Method 2 of the robustness test will be presented in the Supplementary Information (Tables S13–18). The results in columns (5) and (6) of Table 2 show that the coefficients of the explanatory variables remain significant and in the same direction. Therefore, it can be concluded that the robustness of the model is high.

3.4. Analysis of policy-level simulation results

3.4.1. Scenario design

With the purpose of exploring the potential evolution of air pollution

Table 2
The results of the endogenous test and robustness test of the synergistic effects of pollution reduction and carbon reduction policies on CO_2 and SO_2 in the power sector.

Variable	Consider endogeneity		Change dependent variables		Add control variables	
	$lnCO_2$ (1)	$lnSO_2$ (2)	$lnCO_2$ (3)	$lnSO_2$ (4)	$lnCO_2$ (5)	$lnSO_2$ (6)
RCP	−0.0755***	0.2657*	−0.1525**	0.3707*	−0.1337*	0.3661*
	(0.0132)	(0.1435)	(0.0821)	(0.2368)	(0.0829)	(0.2322)
RPP1	0.3627*	−0.6807	0.4175**	−0.7007	0.2890*	−0.1776
	(0.2829)	(0.7876)	(0.2698)	(0.7858)	(0.1832)	(0.7962)
RPP2	−1.1631*	4.1795	−1.2726**	4.6868	−1.1904**	4.0227
	(0.4578)	(5.2218)	(0.4451)	(5.2888)	(0.4474)	(4.2606)
RPP3	−0.5808*	−5.3306*	−0.5485*	−6.3603*	−0.5176*	−6.6631*
	(0.2836)	(3.6775)	(0.2367)	(3.6970)	(0.2370)	(3.6798)
RPP4	−0.9597**	9.7812	−1.2230***	11.8258	−1.9766**	17.1836
	(0.0666)	(13.6985)	(0.0917)	(14.0381)	(1.1493)	(14.0193)
RPP5	−0.5993*	−24.6887*	−0.5657*	−19.0874*	−0.5010*	−27.2454*
	(0.2081)	(12.2130)	(0.4382)	(14.1994)	(0.1611)	(16.6120)
lnPop	1.2399**	−5.4524**	1.3605***	−4.2147***	1.2818**	−2.5780*
	(0.4276)	(1.0427)	(0.4088)	(1.1841)	(0.4112)	(1.1592)
lnPGDP	0.2391*	−0.9673*	0.8308***	−1.3238***	0.1342*	−0.3742*
	(0.1016)	(0.1210)	(0.1043)	(0.3010)	(0.1068)	(0.2990)
ES	0.0387*	0.2187*	0.0562*	0.2315**	0.0497*	0.2798***
	(0.0251)	(0.1078)	(0.0264)	(0.0761)	(0.0268)	(0.0748)
EI	0.0472***	−0.0076	0.0509***	−0.0005	0.0499***	−0.0055
	(0.0067)	(0.0486)	(0.0072)	(0.0208)	(0.0072)	(0.0202)
RD	1.2722*	−0.7540	1.1967	−0.2354	1.5494**	−4.6287*
	(0.9377)	(1.7570)	(0.9065)	(2.6253)	(0.5178)	(2.8541)
T	0.0005*	0.0024*	0.0006**	0.0019*	0.0006*	0.0018*
	(0.0001)	(0.0019)	(0.0001)	(0.0017)	(0.0001)	(0.0016)
lnRainfall		−0.0287		−0.0341		−0.0273
		(0.3349)		(0.1119)		(0.1096)
U					0.9896*	−7.2332***
					(0.3610)	(1.9288)
-cons	9.2400	−14.6788*	19.7450*	−18.2113*	14.0223*	−42.1137*
	(8.4282)	(6.7222)	(9.2186)	(6.6241)	(9.5010)	(26.6105)
N	240	240	240	240	240	240
R^2	0.4903	0.6376	0.8526	0.8853	0.4131	0.8292
F-statistic	96.45***	10.12***	76.04***	19.00***	75.16***	20.68***

Notes: *** indicates that the statistical value is significant, at a significance level of 1%; ** indicates that the statistical value is significant, at a significance level of 5%; * indicates that the statistical value is significant, at a significance level of 10%. Values in () are standard errors.

and CO_2 emissions under the synergistic effects of pollution reduction policies and carbon reduction policies, this section sets the following scenarios according to the combination of emission reduction policies and the intensity of implementation: no carbon and pollution reduction policy scenario (NCP), business as usual scenario (BAU), carbon and pollution reduction policy scenario (CP1-CP5), cooperative control scenario (CC).

In NCP, the development during 2013–2050 would follow the trend in 2006–2012, without any emission reduction policy. BAU is based on the trend from 2013 to 2020, reflecting the continuation of existing policies under the promise of nationally determined contribution. Since the national carbon emission trading market has been launched online in July 2021, the RCP index in each scenario will all be 1 from 2021, except NCP. The CP1-CP5 scenarios are the combination of carbon reduction policies and five pollution reduction policies, which means that when implementing RCP and RPP together, one pollution reduction policy is emphasized in turn, while other pollution reduction policy indicators are the same as those in BAU. CC is the optimal policy combination, which selects the optimal emission reduction policies in each sector and combines them according to the synergistic effects of various policies obtained in Section 3.2 and the study of Tong et al. (2020), to achieve the best emission reduction effect. A detailed description of the prospective change of each pollution reduction policy indicator in each scenario is provided in Table 3. To emphasize the impact of policy variables on the emissions of CO_2 and air pollutants, control variables were kept consistent in all scenarios. The energy consumption structure

Table 3
Setting of the prospective change of each pollution reduction policy indicator in each scenario compared to 2020 (%).

Scenario		2030					2050				
		RPP1	RPP2	RPP3	RPP4	RPP5	RPP1	RPP2	RPP3	RPP4	RPP5
NCP				None					None		
BAU		2.28	−1.08	4.68	0.32	5.24	7.01	−3.18	15.39	0.96	16.34
CP1		8.03	−1.08	4.68	0.32	5.24	28.16	−3.18	15.39	0.96	16.34
CP2		2.28	−9.56	4.68	0.32	5.24	7.01	−26.03	15.39	0.96	16.34
CP3		2.28	−1.08	10.95	0.32	5.24	7.01	−3.18	17.48	0.96	16.34
CP4		2.28	−1.08	4.68	3.61	5.24	7.01	−3.18	15.39	11.64	16.34
CP5		2.28	−1.08	4.68	0.32	10.48	7.01	−3.18	15.39	0.96	34.81
CC	Power	2.28	−9.56	10.95	0.32	10.48	7.01	−26.03	17.48	0.96	34.81
	Industry	8.03	−9.56	10.95	0.32	5.24	28.16	−26.03	17.48	0.96	16.34
	Transport	8.03	−9.56	4.68	0.32	5.24	28.16	−26.03	15.39	0.96	16.34
	Resident	2.28	−1.08	10.95	0.32	10.48	7.01	−3.18	17.48	0.96	34.81
	Agriculture	2.28	−1.08	4.68	3.61	10.48	7.01	−3.18	15.39	11.64	34.81

and energy intensity were calculated by referring to the coal consumption and total energy consumption in the study of Yuan et al. (2022). SSPs are used to quantitatively describe the relationship between climate change and socioeconomic development pathways (Jiang et al., 2022). The estimated values of China's population and GDP in 2020–2022 under the SSP2 scenario (Middle of the Road) in the SSPs Population and Economic Projections database are consistent with the actual situation. Meanwhile, since emission reduction policies are the key variables in the scenario simulation, to prevent the influence of control variables on them, the relevant data of the SSP2 scenario in the database were used in the simulation of different scenarios in this study. And the temperature and precipitation of each future year are from the WorldClim database.

3.4.2. *Prediction analysis of CO_2 and major air pollutants emissions*

Combined with the regression coefficient obtained in Section 3.2, the values of relevant variables of each sector in each future year were substituted into Eqs. (3) and (4) respectively to predict the emissions of CO_2 and air pollutants under different policy scenarios up to 2050. Fig. 4a shows the trend of CO_2 emissions from 2012 to 2050 under different policy scenarios. In NCP, CO_2 emissions rise exponentially and have yet to peak, reaching 3434.1 Mt. in 2050, which is 8.5 times more than the carbon emissions under the 2.0 °C temperature control target (4.05 Gt). In other words, if no mitigation measures are taken, China's carbon emissions will not meet the Paris Agreement. If a series of emission reduction measures based on the carbon emission trading market are implemented, as the BAU shows, although CO_2 emission is still on an upward trend, it has been significantly reduced 6.9 Gt and 21.9 Gt compared with the NCP, respectively in 2030 and 2050. It is worth noting that due to the implementation of a basket of emission reduction policies in 2013, CO_2 emissions have been effectively controlled or even reduced through the adjustment of energy structure, the utilization of clean energy, and the change of enterprises' environmental awareness. However, after 2032, because the policies have not been updated in time to adapt to the new situation, CO_2 emissions rebounded again, growing at an average rate of 0.6% a year. Especially in the power sector, CO_2 emissions have been increasing or even exceeding the NCP (Fig. 4g), indicating that the current policy mix is

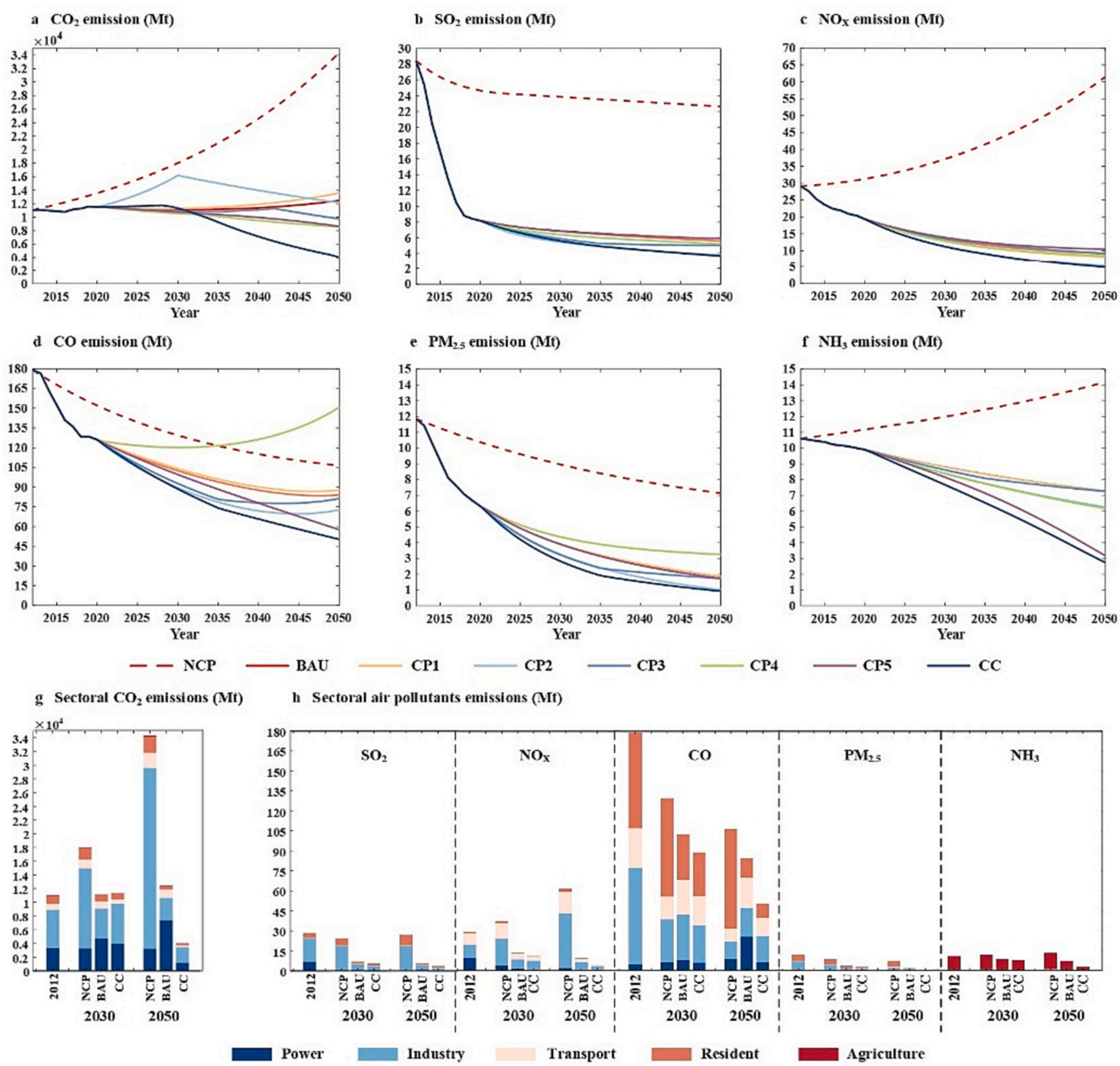

Fig. 4. Prediction of CO_2 and air pollutants emissions under different policy scenarios.

ineffective for it. The prediction of CO_2 emissions in CP1-CP5 scenarios is consistent with the results in Section 3.2, and the pollution reduction policy has played an ideal role, but there is little difference from the situation in BAU. This shows that the unified adjustment of the implementation of a single pollution reduction policy in China can only maintain the status quo and cannot achieve the goal of "double carbon".

Figs.4b-f respectively show emission trajectories of five major air pollutants in different future scenarios up to 2050. Before 2012, there were already policies aimed at reducing air pollution, such as the Technical Policy on Prevention and Control of Vehicle Emission Pollution, and the Tenth Five-Year Plan for National Environmental Protection. However, only the implementation of pre-2012 policies will not counteract the NOx and NH_3 emissions arising from the growing demand for people's life and industry. Therefore, in NCP, the two will continue to grow according to the previous trend, reaching 61.4 Mt. and 14.2 Mt. respectively in 2050. In BAU and CPs, emissions of major air pollutants would decline with the strengthening of pollution reduction and carbon reduction policies, which shows that these emission reduction policies still have considerable potential for the reduction of air pollution in the future. For SO_2, its emissions drop precipitously at an average rate of 14.2% per year from 2012 to 2018, and then turn into a steady decline with the installation of end-of-pipe control devices such as flue gas desulfurization are relatively saturated. For NO_X, emissions in BAU would fall from their peak in 2012 to a gap of 52.3 Mt. from the NCP by 2050, with industry and transport sectors being the main contributors. In addition, the emissions of SO_2 and NO_X in CPs are nearly the same as that in BAU, mainly because both of them are not emphasized enough in existing pollution reduction policies and their complex composition and integrated sources also cause difficulties in emission reduction. Therefore, in the case that the carbon emission reduction policy based on the carbon trading market remains unchanged, only strengthening the implementation of a single pollution reduction policy cannot significantly reduce air pollution. Unlike other air pollutants, CO pollution is more difficult to control, its emissions will rebound in the future in most scenarios, and even its emissions in CP4 will exceed those in NCP in 2035. This indicates that too much emphasis on improving energy efficiency is detrimental to CO emissions, which is also consistent with the results in Section 3.2, and that additional emission reduction policies should be supplemented in time to counter the rebound in CO emissions. For $PM_{2.5}$, with more stringent pollution reduction and carbon reduction policies, emissions would decline in BAU and CPs by different rates. In particular, the emission reduction effect in CP1 is the same as that in BAU, and both emissions will reach 1.8 Mt. in 2050, indicating that the expansion of the scale of green space in urban built-up areas needs to cooperate with other policies to further play its role in reducing pollution. For NH_3, the combined implementation of pollution reduction and carbon reduction policies reversed its development direction, but the emission reduction is small. In BAU and CPs, the reduction is only 3.3 Mt. to 7.4 Mt. compared with 2012, indicating that the implementation effect of the emission reduction policies would not reach their upper limits, and there is the possibility of further adjustment.

However, due to the different sources and proportions of CO_2 and air pollutants in each sector, emissions from different sectors show diverse variation tendencies in the future. Therefore, according to the synergy results, we constantly adjust the way of policy mix to design a combination of emission reduction policies for different sectors to minimize CO_2 and air pollutants emissions in CC. Figs.4g-h respectively show the distribution of CO_2 and five air pollutants emissions in five sectors under NCP, BAU, and CC scenarios. In the power sector, CO_2 and CO emissions increase substantially in BAU, and the severity of the form is greater than that in NCP scenario. So we adjusted the policy, put more emphasis on cleaner production, promoting the use of new energy and improving the environmental economic policy, and finally, the emissions of the two in CC will reduce by 6192.5 Mt. and 19.1 Mt. more than that in BAU, respectively in 2050. In the industry sector, although CO_2 and five air pollutants show various sensitivities to emission reduction policies, compared with the NCP scenario, their emissions are effectively curbed in BAU. Based on maintaining the emission reduction trend, we combine RPP1 to RPP3 and cooperated with RCP to reduce emissions, especially for CO. CO emissions in the industry sector will reach 28.3 Mt. in 2030 and 19.9 Mt. in 2050, 17.5% and 8.7% less than that in BAU, respectively. In the transport sector, emissions of CO_2 and all air pollutants greatly depend on the end-control, for which we assume improving the quality of diesel and gas used in vehicles, taking older cars off the road and expanding the greening area of roads, and eventually emissions would be cut by 13.1% to 75.6% of the BAU scenario by 2050. Due to the low combustion efficiency of civil stoves and stoves, the resident sector is the primary contributor to CO pollution. Therefore, we focus on promoting civilian clean fuels and issuing clean energy subsidies to maximize CO emissions control in CC. CO emissions will decline at an average rate of 4.9% from 2021 to 11.0 Mt. in 2050. In the agriculture sector, the emission reduction of NH_3 in BAU is not strong enough, with only 1.3 Mt. less in 2050 than in 2030. Therefore, we adapt two long-term effective policies of enhancing energy utilization and increasing investment in pollution control, resulting in a reduction of 4.9 Mt. from 2030 to 2050 in CC. On a national level, CO_2 emissions will peak at 11.7 Gt in 2028 and then decrease to 4.05 Gt in 2050 in the CC scenario, basically meeting the carbon target under 2 °C. And SO_2, NO_X, CO, $PM_{2.5}$, and NH_3 emissions are estimated to reach 3.7 Mt., 4.9 Mt., 50.3 Mt., 0.9 Mt., and 2.7 Mt. in 2050, respectively under the optimal scenario.

4. Conclusions and policy implications

In this study, we estimated CO_2 and major air pollutants emissions of each sector and province from 2006 to 2020 based on the MEIC model, and used the panel regression model to evaluate the effectiveness and synergy of carbon reduction policies and representative pollution reduction policies, then eight future scenarios were designed to predict CO_2 and major air pollutants emission trends under different policy combinations until 2050. Our results reveal that CO_2 emissions show a continuous growth trend from 2006 to 2020, and due to the trial of the national carbon emission trading market, it briefly dropped in 2013. On the contrary, SO_2, NO_X, CO, $PM_{2.5}$, and NH_3 emissions peaked in succession during the same period, and then decreased by 23.0 Mt., 9.7 Mt., 60.1 Mt., 5.7 Mt., and 0.4 Mt. by 2020. At the same time, the air pollution situation in North China and East China spatially and in power and industry at the sector level was more severe. The above change in emissions is attributed to the implementation of emission reduction policies, among which carbon reduction policies and pollution reduction policies have remarkable effectiveness and synergy in the integrated treatment of air pollutants and greenhouse gases in different sectors and different air pollutants. In addition, since China's current pollution reduction policies have been implemented for a long time and the system is relatively complete, its emission reduction effect is better, and it can provide experience and support for the current unstructured carbon reduction policies. According to the effect of emission reduction, the carbon reduction policy is combined with different pollution reduction policies. Under the condition of constantly adjusting the intensity of the policy, we designed the optimal plan for different sectors, to achieve the maximum reduction of the emission of CO_2 and major air pollutants, and to promote the realization of the "double carbon" goal and the coordinated goal of pollution reduction and carbon reduction. It is estimated that CO_2 emissions will reach 4.05 Gt in 2050 in the CC scenario, and the emission of SO_2, NO_X, CO, $PM_{2.5}$, and NH_3 will decrease to 3.7 Mt., 4.9 Mt., 50.3 Mt., 0.9 Mt., and 2.7 Mt. in 2050, respectively under the optimal scenario.

The above results provide implications for addressing the challenges presented at the beginning. Firstly, both carbon reduction policies and pollution reduction policies are effective and synergistic, and their combination will greatly promote the process of emission reduction.

Therefore, a collaborative control system for greenhouse gas and air pollutant emissions should be established and improved as soon as possible. Given China's top-down environmental governance system, it is necessary to coordinate the work related to carbon peaking and ecological environmental protection from the legal level, to ensure the implementation of the target of carbon reduction and pollution reduction. The government should improve the management system, raise the requirements for emission reduction, promote pollution and carbon reduction at the same time, and form effective incentives and constraints. For example, increasing the tax burden on heavy energy-consuming enterprises, and giving incentives to enterprises that use clean energy or technology. At the same time, the coordination mechanism of pollution prevention and control at the provincial levels should be improved to avoid resource waste caused by inter-regional planning conflicts.

Secondly, due to the different effects of emission reduction policies in different sectors, there should be a differentiated mix of emission reduction policies that are most suitable for each sector. In the power sector, which is dominated by thermal power generation, new energy sources such as solar, wind and nuclear energy should be developed and utilized as soon as possible to gradually improve the energy structure. In the industry sector, the key is to focus on both prevention and control at the source and treatment at the end. At the source, the government should step up efforts to eliminate outdated production capacity and strictly control the entry of energy-intensive, high-polluting and resource-based enterprises into the market. At the end, the government should upgrade industrial boilers, raise standards for pollutant discharge, and strengthen supervision over enterprises' emissions. In the transport sector, mobile sources are the main culprits of greenhouse gases and air pollution, so the government should focus on phasing out old vehicles as soon as possible, improving the quality of gasoline and diesel for vehicles, and subsidizing the purchase of new energy vehicles. In the resident sector, it is necessary to accelerate the transformation of coal into electricity and gas and the use of clean energy, increase the publicity of pollution reduction and carbon reduction policies and cultivate the awareness of the people of environmental protection and emission reduction. The agricultural sector is the main source of NH_3 emission, so it is necessary to reduce the agricultural capital input in the crop planting process, optimize the way of fertilization, and improve the utilization rate of fertilizer. Finally, the whole sector should optimize the energy consumption structure, reduce energy intensity across all sectors and encourage green technology innovation. The government should also vigorously promote the concept of collaborative governance of pollution reduction and carbon reduction, and raise the environmental awareness of the whole people.

However, our study contained some uncertainties and limitations. Firstly, five indicators were selected to quantify the implementation intensity of five representative pollution reduction policies. But in fact, the effect of policy implementation is reflected in many aspects, which can not be expressed by a single indicator, and it is better to build a comprehensive index system to evaluate. Secondly, the carbon reduction policy is regarded as the carbon emission trading market in this study, but the emission reduction effect of other carbon reduction policies cannot be ignored. When setting the future policy scenario, we assumed that the carbon reduction policy is the national carbon emission trading market and remains unchanged, the accuracy of the forecast results would be affected.

CRediT authorship contribution statement

Botong Xian: Formal analysis, Writing – original draft, Visualization. **Yalin Xu:** Data curation, Visualization. **Wei Chen:** Supervision, Writing – review & editing, Funding acquisition. **Yanan Wang:** Supervision, Funding acquisition, Writing – review & editing. **Lu Qiu:** Data curation.

Declaration of Competing Interest

We declare that we have no conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

Data will be made available on request.

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Appendix A. Appendix

Table A1

The results of the synergistic effects of pollution reduction and carbon reduction policies on CO_2.

Variable	Power	Industry	Transport	Resident	Agriculture
RCP	−0.2415***	−0.6206***	−0.4235***	−0.1794**	−0.3627***
	(0.0821)	(0.0421)	(0.0231)	(0.0583)	(0.0423)
RPP1	0.4175**	−0.1208***	−0.1142*	0.0465*	−0.2738*
	(0.2698)	(0.0368)	(0.0800)	(0.0087)	(0.1381)
RPP2	−1.2727**	−0.6929**	0.1099**	0.0891*	0.6456**
	(0.4451)	(0.2241)	(0.0167)	(0.0027)	(0.2329)
RPP3	−0.5485*	0.0121*	0.6840***	−0.2693*	0.0789*
	(0.2367)	(0.0009)	(0.0815)	(0.1250)	(0.0322)
RPP4	−1.2230***	−0.1881	−1.5018*	3.2255*	−1.7442***
	(0.0917)	(0.1874)	(0.6396)	(1.7871)	(0.2157)
RPP5	−0.5657*	0.2074*	0.2681*	−0.4243*	−0.4031*
	(0.4382)	(0.1880)	(0.1145)	(0.3469)	(0.3561)
lnPop	1.3605***	0.6667**	0.0911	−0.1633	−0.2937*
	(0.4088)	(0.2137)	(0.1198)	(0.2898)	(0.2129)
lnPGDP	0.1692**	−0.0260*	0.0246	0.0774*	0.0699*
	(0.1043)	(0.0067)	(0.0274)	(0.0400)	(0.0322)
ES	0.0562*	−0.0275*	0.0005	0.0299**	−0.0001
	(0.0264)	(0.0140)	(0.0012)	(0.0102)	(0.0049)

(*continued on next page*)

Table A1 (*continued*)

Variable	Power	Industry	Transport	Resident	Agriculture
EI	0.0509*** (0.0072)	0.2230*** (0.0368)	0.0009 (0.0277)	−0.1683 (0.2817)	0.5090*** (0.1288)
RD	1.1967* (0.9065)	0.1653 (0.2129)	−2.3481*** (0.4853)	−0.1373 (0.1477)	−0.8553** (0.2767)
T	0.0006** (0.0001)	0.0003* (0.0001)	0.0001 (0.0002)	−0.0001 (0.0004)	0.0004* (0.0003)
-cons	10.5347* (9.2186)	10.1878** (5.5353)	10.8396*** (2.7896)	−4.4715 (8.2354)	12.2333* (4.9001)
N	240	240	240	240	240
R^2	0.4068	0.2899	0.7510	0.3834	0.5258
F-statistic	76.04***	146.13***	299.92***	257.29***	280.77***

Notes: *** indicates that the statistical value is significant, at a significance level of 1%; ** indicates that the statistical value is significant, at a significance level of 5%; * indicates that the statistical value is significant, at a significance level of 10%. Values in () are standard errors.

Table A2
The results of the synergistic effects of pollution reduction and carbon reduction policies on SO_2.

Variable	Power	Industry	Transport	Resident
RCP	0.3107* (0.2368)	0.2837** (0.1147)	0.1326* (0.0746)	−0.0300*** (0.1462)
RPP1	−0.7007 (0.7858)	0.2855* (0.2136)	0.6913** (0.2611)	0.7431* (0.5057)
RPP2	4.6868 (5.2889)	0.0278 (0.6805)	0.1190* (0.0791)	−1.8435* (1.0219)
RPP3	−6.3603* (3.6970)	−1.2815* (0.6040)	1.5183*** (0.2690)	3.1226* (1.8185)
RPP4	11.8258 (14.0381)	20.5274 (23.5743)	−2.1552* (1.0650)	−0.0627 (4.5206)
RPP5	−19.0874* (14.1994)	2.0282*** (0.5657)	7.7308 (8.0049)	4.9644 (4.1211)
lnPop	−3.2147** (1.1841)	0.7532* (0.6434)	0.4094* (0.3900)	−1.1166* (0.7363)
lnPGDP	−0.3238* (0.3010)	−0.5173** (0.1702)	−0.0486 (0.0884)	−0.1705* (0.1352)
ES	0.2315** (0.0761)	0.1136** (0.0422)	0.0049 (0.0040)	0.0711** (0.0261)
EI	−0.0005 (0.0208)	0.1162* (0.0704)	−0.0862 (0.0895)	0.3996** (0.3760)
RD	−0.2354 (2.6253)	−1.6108* (0.6416)	−9.2003*** (1.5717)	−1.0586** (0.3760)
T	0.0019* (0.0017)	0.0009* (0.0005)	−0.0005* (0.0001)	0.0006 (0.0010)
lnRainfall	−0.0341 (0.1119)	−0.0993* (0.0600)	0.0471* (0.0351)	0.0162 (0.0803)
-cons	−17.4216* (6.6242)	−80.1742*** (16.6685)	−1.7856 (9.0066)	2.4232 (20.7944)
N	240	240	240	240
R^2	0.8170	0.8858	0.3149	0.7037
F-statistic	19.00***	64.19***	24.69***	154.29***

Notes: *** indicates that the statistical value is significant, at a significance level of 1%; ** indicates that the statistical value is significant, at a significance level of 5%; * indicates that the statistical value is significant, at a significance level of 10%. Values in () are standard errors.

Table A3
The results of the synergistic effects of pollution reduction and carbon reduction policies on NOx.

Variable	Power	Industry	Transport	Resident
RCP	0.7614*** (0.1459)	0.0565*** (0.0086)	−0.0172** (0.0034)	−0.2781*** (0.0838)
RPP1	−0.7696* (0.4842)	−0.2255* (0.1846)	−0.4973*** (0.1169)	−0.1271* (0.0894)
RPP2	0.2911** (0.0941)	0.2983* (0.1036)	0.4528** (0.1698)	−0.4929* (0.2807)
RPP3	−2.9672*** (0.4295)	0.7967** (0.2695)	−0.2961* (0.1205)	0.4540* (0.2690)
RPP4	0.4758* (0.2704)	0.3849*** (0.0547)	−2.4300** (0.9247)	−1.7202* (1.5730)
RPP5	0.7169* (0.5875)	1.0472*** (0.2524)	0.1656* (0.0978)	0.2915*** (0.0421)
lnPop	0.1199*** (0.0296)	0.0253 (0.2871)	−0.3703* (0.1746)	0.3158* (0.2188)

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Table A3 (*continued*)

Variable	Power	Industry	Transport	Resident
lnPGDP	0.1277*	−0.1295*	0.0147	−0.1856*
	(0.0855)	(0.0759)	(0.0396)	(0.1006)
ES	0.0169	−0.0356*	0.0266**	0.0645***
	(0.0469)	(0.0188)	(0.0018)	(0.0149)
EI	0.0273*	0.1279**	0.0266**	0.3040
	(0.0128)	(0.0493)	(0.0038)	(0.4049)
RD	−2.8259*	−0.8775**	−0.9864*	−0.4652*
	(1.6176)	(0.2862)	(0.7038)	(0.2142)
T	0.0010*	0.0004*	−0.0001	−0.0002
	(0.0004)	(0.0001)	(0.0002)	(0.0006)
lnRainfall	−0.0615	0.0217	0.0093**	0.0259*
	(0.0689)	(0.0268)	(0.0007)	(0.0193)
-cons	12.8364	−1.3812	16.5067***	9.4630***
	(16.4045)	(7.4368)	(4.0331)	(1.8585)
N	240	240	240	240
R^2	0.7584	0.5559	0.7167	0.5569
F-statistic	23.09***	124.68***	178.31***	168.68***

Notes: *** indicates that the statistical value is significant, at a significance level of 1%; ** indicates that the statistical value is significant, at a significance level of 5%; * indicates that the statistical value is significant, at a significance level of 10%. Values in () are standard errors.

Table A4
The results of the synergistic effects of pollution reduction and carbon reduction policies on CO.

Variable	Power	Industry	Transport	Resident
RCP	−0.1317*	−0.0908*	−0.0168*	−0.0713*
	(0.1120)	(0.0417)	(0.0061)	(0.0522)
RPP1	0.7009*	−0.1073	−0.3161*	0.6165*
	(0.3715)	(0.2669)	(0.1263)	(0.2838)
RPP2	−1.7157**	−1.4738***	0.3312**	0.4276
	(0.6094)	(0.4391)	(0.1834)	(0.5695)
RPP3	−1.0913***	−1.6460***	−0.9164***	−0.2106
	(0.3295)	(0.3897)	(0.1301)	(0.4600)
RPP4	1.3211*	2.8324*	9.0166	4.3996*
	(0.8548)	(2.3061)	(7.9988)	(2.5235)
RPP5	−1.7111*	0.6389*	−2.0166*	−0.2217**
	(0.9855)	(0.3650)	(0.9698)	(0.0298)
lnPop	1.5757**	1.4427***	−0.1507	−0.5551*
	(0.5599)	(0.4151)	(0.1886)	(0.4107)
lnPGDP	0.0914	0.1520*	0.1373**	−0.0303
	(0.1423)	(0.1098)	(0.0427)	(0.0986)
ES	0.1119**	−0.0795**	0.0007	0.0274*
	(0.0360)	(0.0272)	(0.0019)	(0.0146)
EI	0.0233*	0.3636***	−0.1103*	−0.0163
	(0.0098)	(0.0713)	(0.0433)	(0.3971)
RD	1.9472*	0.3096	−0.3876	−0.5515**
	(1.2412)	(0.4139)	(0.7602)	(0.2100)
T	0.0008**	0.0006*	−0.0001	−0.0003
	(0.0001)	(0.0002)	(0.0003)	(0.0006)
lnRainfall	−0.0729*	0.0289	−0.0304**	−0.0436*
	(0.0529)	(0.0387)	(0.0170)	(0.0385)
-cons	−3.8894	−3.9627	−31.0903***	−12.6361*
	(12.5878)	(10.7543)	(4.3565)	(6.6306)
N	240	240	240	240
R^2	0.2338	0.7159	0.6706	0.6245
F-statistic	46.45***	57.94***	108.82***	204.63***

Notes: *** indicates that the statistical value is significant, at a significance level of 1%; ** indicates that the statistical value is significant, at a significance level of 5%; * indicates that the statistical value is significant, at a significance level of 10%. Values in () are standard errors.

Table A5
The results of the synergistic effects of pollution reduction and carbon reduction policies on $PM_{2.5}$.

Variable	Power	Industry	Transport	Resident
RCP	−0.0121*	0.2134*	0.1605*	−0.1249*
	(0.0083)	(0.0625)	(0.0508)	(0.0823)
RPP1	−1.1546**	−0.2424*	−0.4874**	0.3257*
	(0.3593)	(0.1042)	(0.1776)	(0.2842)
RPP2	0.0300*	0.0122	−0.0069*	1.4303*
	(0.0193)	(0.0360)	(0.0002)	(0.5704)

(*continued on next page*)

Table A5 (*continued*)

Variable	Power	Industry	Transport	Resident
RPP3	−1.3873***	−1.9982***	−0.4579*	−1.7013***
	(0.3187)	(0.2982)	(0.1832)	(0.4606)
RPP4	1.3869*	5.5224	−6.5715*	11.1481
	(0.7608)	(4.7645)	(3.4066)	(8.5271)
RPP5	1.3893*	0.6784*	−3.5221*	−0.4857*
	(0.9201)	(0.2793)	(1.3657)	(0.2307)
lnPop	0.3288	0.6261*	0.0718	0.5976*
	(0.5414)	(0.3176)	(0.2656)	(0.4113)
lnPGDP	0.0261	0.0548	0.0733*	0.4423***
	(0.1376)	(0.0840)	(0.0602)	(0.0988)
ES	0.0293	−0.0293	0.0062*	0.0321*
	(0.0348)	(0.0208)	(0.0027)	(0.0146)
EI	0.0235*	0.0144	−0.0963*	1.4561***
	(0.0095)	(0.0545)	(0.0610)	(0.3976)
RD	−3.2359**	−1.4114***	1.7549*	−2.0120***
	(1.2004)	(0.3167)	(1.0706)	(0.2103)
T	0.0008	0.0004	0.0005*	−0.0002
	(0.0008)	(0.0004)	(0.0004)	(0.0006)
lnRainfall	0.0306	−0.0404*	0.0181	−0.0718**
	(0.0512)	(0.0296)	(0.0239)	(0.0386)
-cons	2.1628	−16.1380*	30.8981***	−55.3104***
	(12.1735)	(8.2286)	(6.1352)	(11.6470)
N	240	240	240	240
R^2	0.7063	0.9109	0.2631	0.8246
F-statistic	54.34***	71.01***	93.97	201.00***

Notes: *** indicates that the statistical value is significant, at a significance level of 1%; ** indicates that the statistical value is significant, at a significance level of 5%; * indicates that the statistical value is significant, at a significance level of 10%. Values in () are standard errors.

Table A6
The results of the synergistic effects of pollution reduction and carbon reduction policies on NH_3.

Variable	Industry	Transport	Resident	Agriculture
RCP	−0.1447*	−0.0358**	−0.1177*	−0.0188*
	(0.1190)	(0.0050)	(0.0664)	(0.0057)
RPP1	−1.4877***	−0.0249	−0.3719**	0.0089*
	(0.4110)	(0.2275)	(0.2291)	(0.0016)
RPP2	−0.0577	−0.8101*	−0.3584*	0.0666*
	(0.6994)	(0.3303)	(0.2598)	(0.0072)
RPP3	−1.1012**	0.4889*	−1.0586**	−0.1970***
	(0.6602)	(0.2344)	(0.3713)	(0.0506)
RPP4	0.5249*	−2.2314*	2.3866*	−0.8887*
	(0.4950)	(1.7992)	(1.0374)	(0.4518)
RPP5	−1.4589*	−0.8469	−0.7982*	−0.6352***
	(0.6235)	(1.7469)	(0.5084)	(0.1356)
lnPop	0.4000	0.7134*	0.6075**	0.0029
	(0.6604)	(0.3398)	(0.3316)	(0.0796)
lnPGDP	−0.3743*	−0.4071***	−0.2751***	−0.0484*
	(0.1660)	(0.0770)	(0.0796)	(0.0232)
ES	0.1275*	−0.0091**	−0.0020	0.0051**
	(0.0564)	(0.0035)	(0.0118)	(0.0018)
EI	−0.1432*	0.1710*	0.2495	−0.0414
	(0.1061)	(0.0780)	(0.3206)	(0.0479)
RD	0.6237	1.3790***	−0.1951*	0.0482
	(0.6428)	(0.3694)	(0.1696)	(0.1037)
T	−0.0283**	0.0005*	0.0001	0.0001
	(0.0028)	(0.0003)	(0.0005)	(0.0001)
lnRainfall	−0.0193*	0.0282	−0.0329*	−0.0001
	(0.0094)	(0.0305)	(0.0311)	(0.0075)
-cons	9.4241	9.1486*	−3.0640	8.0082***
	(16.2517)	(7.8476)	(9.3898)	(1.8205)
N	240	240	240	240
R^2	0.4224	0.2698	0.6746	0.5966
F-statistic	137.49***	88.26***	92.19***	739.61***

Notes: *** indicates that the statistical value is significant, at a significance level of 1%; ** indicates that the statistical value is significant, at a significance level of 5%; * indicates that the statistical value is significant, at a significance level of 10%. Values in () are standard errors.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2023.107301.

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