Improving the regional deployment of carbon mitigation efforts by incorporating air-quality co-benefits: A multi-provincial analysis of China

Hong-Dian Jiang[a,b], Pallav Purohit [d], Qiao-Mei Liang[b,c,e,*], Li-Jing Liu[b,c], Yu-Fei Zhang[b,c]

[a] School of Economics and Management, China University of Geosciences (Beijing), Beijing, 100083, China

[b] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

[c] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China

[d] Energy, Climate, and Environment Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

[e] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing 100081, China

E-mail: bitjhd@163.com (H.D. Jiang), purohit@iiasa.ac.at (P. Purohit), liangqiaomei@bit.edu.cn (Q.M. Liang), liulijing1993@gmail.com (L.J. Liu), zyfi369@163.com (Y.F. Zhang).

**Corresponding author: liangqiaomei@bit.edu.cn (Q.M. Liang)*

Author addresses: No.5, Zhongguancun South Street, Haidian District
Beijing 100081, China

Abstract: It is critically important to include the co-benefits of abated air pollution when sharing carbon mitigation efforts among provinces. Therefore, using a Chinese multi-regional computable general equilibrium model, this study incorporated the pollutant co-benefits into the carbon marginal abatement cost curves and evaluated the inter-provincial abatement effort sharing for China's provinces to achieve the Nationally Determined Contribution target. Results show that the more developed eastern economies face higher abatement costs under the same abatement level compared to the less developed central and western provinces. Second, in the composition of total co-benefits among provinces, the co-benefits of SO_2 reductions exceed 60% followed by the co-benefits of NO_X and $PM_{2.5}$ reductions. Finally, the provincial abatement costs will be offset by 4.3% to 18.9% after considering the co-benefits. Specifically, provinces with high per capita GDP and energy-intensive industries (e.g. Shandong, Liaoning, and Jilin) and some provinces with energy production bases (e.g. Inner Mongolia, Shanxi, and Xinjiang) have higher co-benefits and offset the more abatement costs; therefore, they can consider raising abatement efforts. Moreover, provinces with high economic levels but fewer co-benefits (e.g. Beijing, Tianjin, and Shanghai) can consider providing climate funding or transferring abatement technologies to support the abatement work of less developed provinces.

Keywords: Marginal abatement cost; Air pollution; Co-benefits; Multi-regional; Computable general equilibrium

JEL classification: C68; E61; P28; Q52

1. Introduction

The period prior to 2030 is critical for countries to achieve carbon neutrality goals (IPCC, 2022), and they accordingly need to undertake substantial planning and deployment in the coming years. In particular, while emission reduction targets are usually proposed at the national level, specific tasks and measures need to be implemented by various regions and sectors within a country. Therefore, one of the first steps of importance will be to reasonably share abatement efforts at the sub-national level.

Compared to other countries, it is more arduous and complex for China to reach carbon neutrality. On the one hand, China needs to reduce the current 30.6% (BP, 2021) of global carbon emissions to net zero in less than 40 years. On the other hand, as a large country with a vast territory, obvious differences in climate conditions, resource endowment, economic development, and industrial structure exist among the different regions in China. Meanwhile, China emphasizes the balanced development of various regions and has formulated corresponding regional development strategies such as the Western Development and Northeast Region Revitalization Plan. Therefore, the deployment of abatement efforts at the regional level is particularly complicated for China, and it is necessary for a targeted regional low-carbon development plan to be formulated according to local conditions. To this end, a region-scale analysis covering the vast majority of the country is needed.

In the research on the cross-regional sharing of abatement efforts in a large developing country like China, a special point of concern is the co-benefits of abated air pollution. Given the many shared anthropogenic sources of greenhouse gas and air pollutants, mitigation policies aimed at carbon reductions could bring co-benefits from abated air pollution. For developing countries, it is more important to pursue co-benefits because they are in a rapid stage of economic development, usually accompanied by high carbon emissions and large amounts of air pollutants, thus the carbon abatement costs could be offset to a greater extent by the co-benefits of air pollution (Cai et al., 2016; Mittal et al., 2015). Moreover, the benefits of climate change mitigation are usually a long-term process. Air quality and health co-benefits can be seen in the near-term and have the characteristics of being definite, immediate, and effective (Deng et al., 2017; West et al., 2013), which can help developing countries coordinate the relationship between carbon emission reduction and economic development. Therefore, incorporating the co-benefits of abated air pollutants could help each region more accurately grasp the costs and benefits of their own emission reduction, and more effectively coordinate the relationship between the whole and its parts.

Currently, the research on China's regional low-carbon development policies can be divided into two categories (Lin and Jia, 2019; Liu et al., 2020): first, to explore the direction of low-carbon policy choices through the analysis of influencing factors; second, to simulate the abatement effects of different low-carbon policies. Regarding research scale, due to the strong data availability of the research on the influencing factors, there are extensive studies at various levels such as economic circle (Cai et al., 2018), provincial (Zhang et al., 2016), city (Liu et al., 2020), industry (Lindner et al., 2013), and even enterprise level (Zhang et al., 2015). There are obviously fewer studies on the simulation of low-carbon policy measures at the regional level. Most of these studies either consider the whole province or several provinces as the research object (Liu et al., 2017; Xie et al., 2018), and a few focus on a specific industry in specific regions (Lin and Jia, 2019). In particular, studies on abatement effort sharing that cover most provinces in China from an economy-wide perspective are lacking.

Studies on influencing factors or policy simulations at the regional level mainly focus on carbon dioxide, and there are still few analyses involving the co-benefits of greenhouse gases and pollutants. The existing studies mainly focus on the additional impact of implementing regional or industrial low-carbon policies on regional pollutant emissions and economic benefits (Chang et al., 2020), and how to design low-carbon policies with the goal of maximizing synergistic emission reduction benefits or minimizing synergistic emission reduction costs (Yang and Teng, 2018; Yang et al., 2018). Some studies that do address co-benefits at the regional level mainly focus on specific regions (Alimujiang and Jiang, 2020; Cao et al., 2021) or specific industries such as electricity and transportation (Tian et al., 2018; Zhang and Zhang, 2020). In addition, most of these studies adopt bottom-up engineering models for assessment, which are carried out within a partial equilibrium framework. Although substantial detailed technical characteristics are described in the bottom-up models, such models ignore the effects of input and output prices and resource allocation in the economic system. The general equilibrium effects of marginal abatement costs (MACs) should not be ignored while aiming to significantly reduce carbon and air pollutant emissions (Bergman, 1991; Conrad and Schröder, 1991).

Given the identified knowledge gap, using a Chinese multi-regional computable general equilibrium (CGE) model, this study aims to incorporate the co-benefits of carbon abatement policies into the carbon marginal abatement cost curves (MACCs) and to evaluate total abatement costs and inter-provincial abatement effort sharing for China and its provinces in achieving the latest Nationally Determined Contribution (NDC) target. This study intends to answer the following three questions: (1) What are the revised carbon MACCs of China and its provinces if co-benefits (mainly referring to the effects of carbon abatement policies in reducing sulphur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$)) are considered? (2) What will the total abatement cost be for China and its provinces to achieve the NDC target before and after considering the co-benefits? (3) How will the inclusion of the air pollution co-benefits of carbon abatement policies affect the sharing of abatement efforts among provinces?

This study contributes to the literature in the following three respects. First, this study is the first to comprehensively evaluate and compare the carbon MACCs among provinces from an economy-wide perspective based on covering the vast majority of provinces in China. Second, this study adopts the MACCs of multiple pollutants to quantify the co-benefits and their components from abated air pollution in each province and explores the inter-provincial differences in co-benefits through cluster analysis combining economic development level and industrial structure, thereby compensating for the lack of general equilibrium effects in bottom-up models. Third, this study combines the inter-provincial differences between co-benefits and carbon abatement costs to complement and improve the limitation of most studies that rely only on carbon abatement costs as a single indicator to break down abatement efforts, thereby providing support for the decision to deploy provincial abatement effort sharing that considers both the whole and its parts as well as the short and long terms.

The remainder of this study is structured as follows: the model and data are outlined in Section 2; the results, along with the discussion, are presented in Section 3; finally, the conclusions and policy recommendations are presented in Section 4.

2. Methodology

2.1 Basic model framework

The Multi-Regional China Energy and Environmental Policy Analysis model of China's Climate Change Integrated Assessment Model (C^3IAM/MR.CEEPA), which is a Chinese multi-regional dynamic recursive CGE model (Wei et al., 2018), is employed in this study. The multi-region CGE model not only has the basic characteristics of the single-region model but also describes the inter-regional economic relations, including inter-regional commodity trade and factor flow. Therefore, the MR.CEEPA can capture the direct and indirect interactions between different agents in different regions and, thus, can simulate the regional characteristics of policy effects, as well as the ripple effects and feedback effects of regional policies on other regional economies by affecting inter-regional commodity and factor flows (Bhattacharyya, 1996; Zhang et al., 2013). Moreover, the MR.CEEPA pays special attention to the detailed description of the current situation of Chinese multi-regional energy and environment, including a variety of greenhouse gas and air pollutant emissions. As the model covers 31 provinces and municipalities (without Hong Kong, Macao, and Taiwan), as shown in Table S1 of the Supplementary Material, it is suitable as a core analysis tool for this study. Fig. 1 shows the basic framework of the MR.CEEPA model. It is composed of five basic modules: production, income, expenditure, investment, and foreign trade. For detailed descriptions of each sub-module, please refer to Wei et al. (2018) and Liang et al. (2014).

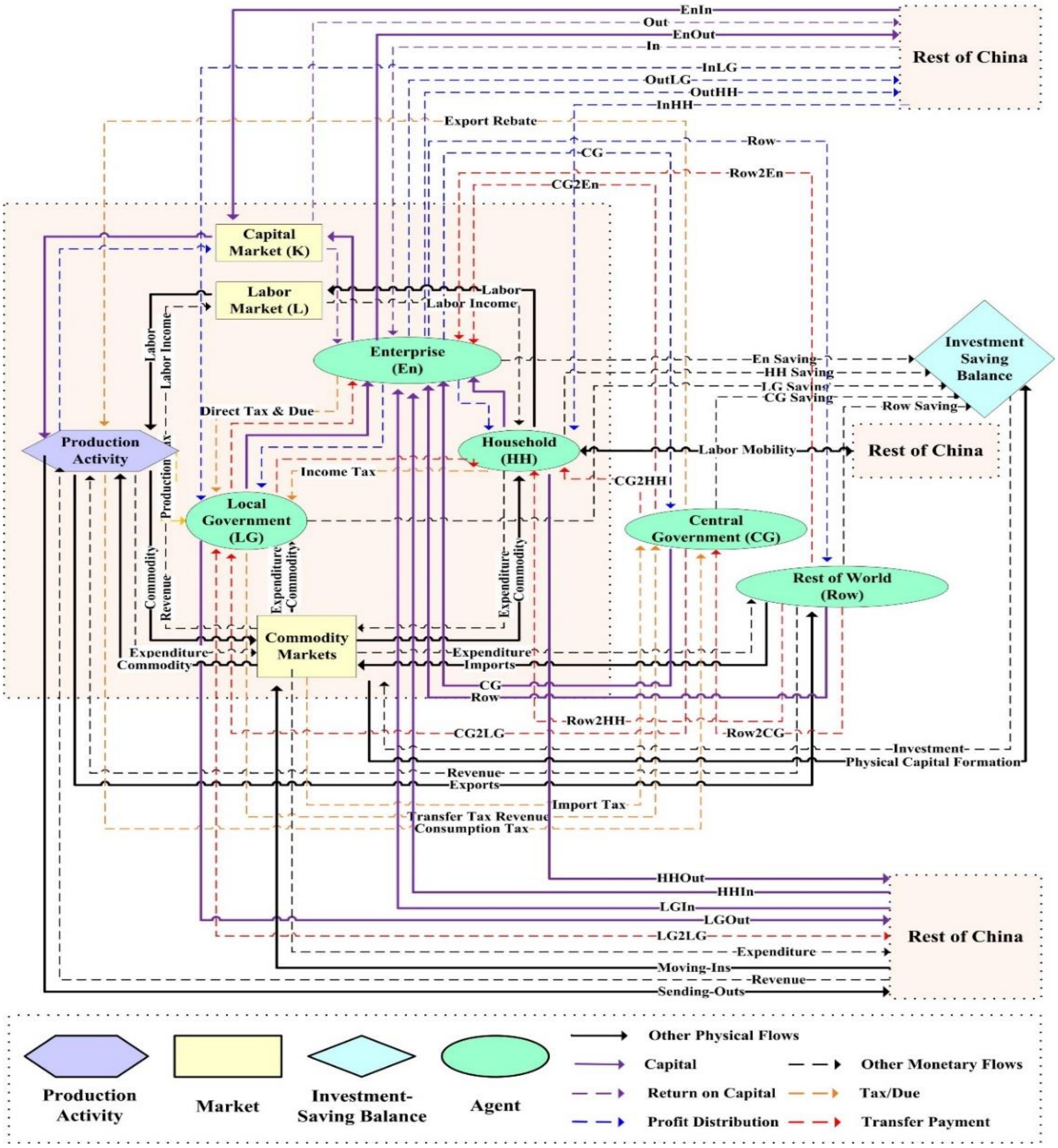


Fig. 1. The basic framework of the MR.CEEPA (Wei et al., 2018)

It is worth noting that inter-regional commodity flows are slightly different from single-region model settings. Regarding inter-regional commodity flow, we referred to the studies of Zhang et al. (2013) and Wang et al. (2020). The commodities produced by a certain region not only supply their regional consumption demand but also supply other regions in the country and foreign markets. This study employs a three-layer nested constant elasticity of transformation function to describe the optimal allocation of commodities between domestic regions and exports, as shown in Fig. 2. In addition, the commodities consumed in a given region partly come from local production, inter-regional transfer, and imports from abroad. Therefore, this study adopts the Armington assumption (Armington, 1969) and assumes that there is imperfect substitutability among commodities from different regions in the market. The commodity that is supplied domestically is composed of domestic and imported commodities following a CES function, as shown in Fig. 2. In addition, the inter-regional capital transfers are also different from single-region model settings, see the Supplementary Material S2.

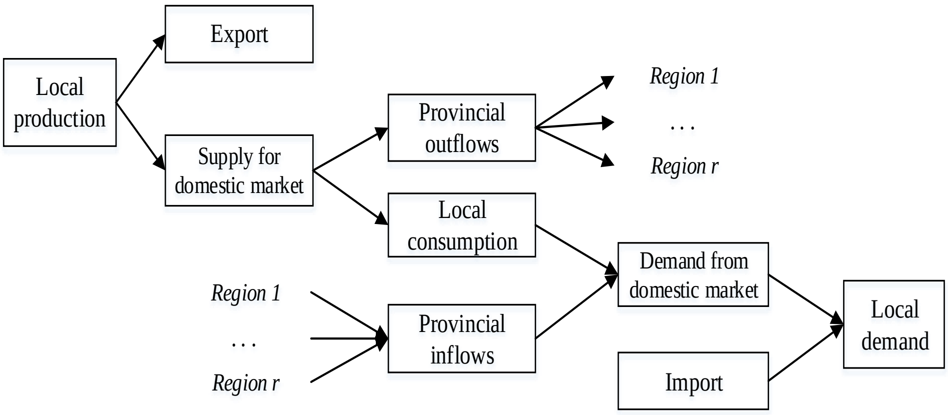


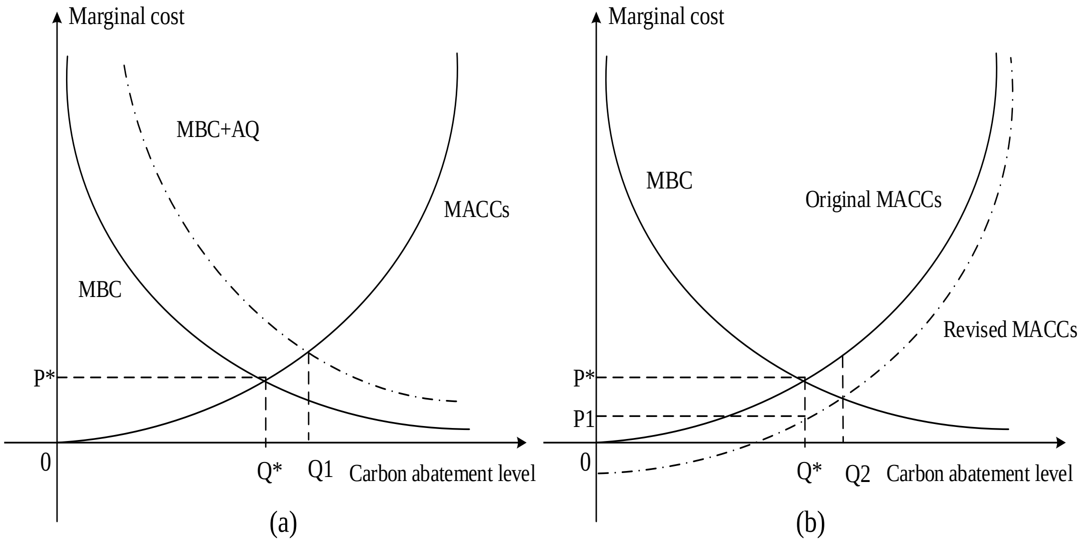
Fig. 2. The nested structure of the trade module

2.2 Simulating the original MACCs and revised MACCs in the MR.CEEPA

The MACCs reflect the relationship between the marginal costs and carbon mitigation potential of abatement measures, which have become a standard tool for analysing the cost-effectiveness of different abatement strategies (Jiang et al., 2020;

2022b; Kesicki and Strachan, 2011). In the CGE model, the MAC is the equilibrium price of carbon when carbon emission constraints are imposed (Klepper and Peterson, 2006). In this study, we follow a method that is popular in existing studies (Jiang et al., 2022b; Klepper and Peterson, 2006; Yang et al., 2018), whereby the carbon price level required to achieve a specific emission reduction reflects the MAC at that emission reduction level.

Fig. 3 indicates the effect of the co-benefits from abated air pollutants on the original MACCs. The intersection of the original MACCs and marginal benefit curve (MBC) shows the optimal abatement level Q*. If the co-benefits from abated air pollutant are considered, then the MBC will shift upwards so that its intersection with the original MACCs moves to the right, and thus the optimal level of mitigation will increase from Q* to Q1, see Fig. 3(a). In practice, however, the MBC is difficult to describe due to model features and data availability, especially for a model with sector classification as detailed as the CGE; moreover, policy makers focus more on changes in the abatement cost because they aim to limit emissions to a point at which marginal costs increase rapidly (Whitesell, 2011). Thus, many studies portray the effects of co-benefits by offsetting the degree of abatement costs (Eory et al., 2013; Groosman et al., 2011; Jiang et al., 2022a; Yang et al., 2018). In addition, like a tax wedge, whether the co-benefits are used to add the MBC (see Fig. 3a) or offset the MAC (see Fig. 3b), both will have the same optimal abatement level under the new equilibrium. Overall, this approach can not only provide decision makers with an intuitive view of the extent to which abatement costs are affected but can also provide support for adjusting optimal abatement level according to cost-benefit analysis.



(a) (b)

Fig. 3. Effects of co-benefits from abated air pollutants on the carbon MAC (Eory et al., 2013; Jiang et al., 2022a; Yang et al., 2018).

Accordingly, this study also follows the principle adopted in most literature and incorporates the co-benefits from abated air pollutants into the original MACCs; it investigates to what extent the co-benefits can offset the abatement costs. Meanwhile, for simplicity and following the conventions used in the existing literature (Guo et al., 2016; Muller, 2012; Yang et al., 2018), this study adopts “revised MAC” to indicate changes in relative relationship between cost and benefit, see Eq. (1).

$$MAC_r = MAC_0 - \sum_i CB_i \Big/ \Delta Q_{CO_2} \tag{1}$$

where MAC_r is the revised MAC; MAC_0 is the original MAC without considering co-benefits; CB_i is the co-benefits of the *i-th* pollutant under a specific carbon emission reduction amount; ΔQ_{CO_2} is the carbon emission reduction amount under MAC_0; and $CB_i \big/ \Delta Q_{CO_2}$ is the co-benefits of the *i-th* pollutant per unit CO_2.

Regarding evaluating the co-benefits of each pollutant, first, we utilize a similar carbon tax method to tax various pollutants and employ MR.CEEPA model to obtain a set of combinations of MAC and emission reductions for SO_2, NO_x, and $PM_{2.5}$. Notably, tax revenue recycling is not considered and all tax revenue is included in government income. Second, curve fitting is performed on the obtained pollutant MACCs. In this study, all MACCs are in the form of third-order functions based on existing studies (Bernard et al., 2008; Morris et al., 2008) and a series of tests, see Eq. (2):

$$MAC_i = \alpha q_i^3 + \beta q_i^2 + \gamma q_i \tag{2}$$

where MAC_i is the MAC of the i-th pollutant; q_i is the emission reduction amount of the i-th pollutant; and α, β, and γ are the regression coefficients.

Third, the co-benefits in this study are considered as averted abatement costs of pollutants and as equal to the area under the pollutant MACCs (Klepper and Peterson, 2006), which can be obtained by integrating Eq. (2), see Eq. (3).

$$CB_i = {}^1\!/_4 \cdot \alpha q_i^4 + {}^1\!/_3 \cdot \beta q_i^3 + {}^1\!/_2 \cdot \gamma q_i^2 \tag{3}$$

The revised MACCs can then be obtained by substituting the corresponding reductions of various pollutants under a specific carbon abatement amount into Eq. (3), and then substituting the estimated results into Eq. (1).

Finally, based on Eqs. (2) and (3), the original and revised MACCs are used to calculate the total abatement costs to achieve the given target with and without co-benefits.

2.3 Data sources and parameter calibration

The Social Accounting Matrix (SAM) is the key database in a CGE model, which can fully describe the income distribution in the economic system of a country or region over a given period. For the MR.CEEPA, the 2012 SAM table is built based on the 2012 China multi-regional input–output (IO) table compiled by the State Information Center[1], combined with miscellaneous yearbooks and literature including the China Statistical Yearbook (2013, 2014) (NBS., 2013b, 2014), the China Financial Yearbook (2013) (MOF, 2013), the China Energy Statistics Yearbook (2013) (NBS, 2013a), and the China Customs Statistical Yearbook (2013) (GAC, 2013). Furthermore, considering the research needs and the efficiency of model solving, this study merged 42 sectors in the IO table into 18 sectors, including the main macro-economic sectors and high energy-consuming sectors, as shown in Table S2 of the supplementary materials. In addition, we refer to the 2012 Energy Balance databases of the International Energy Agency (IEA) to convert the monetary quantity of energy data into physical quantity (IEA, 2012).

The greenhouse gas and air pollutant emissions data in the base year are taken from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2020; Klimont et al., 2017). The GAINS model contains a database on country-, sector-, and fuel-specific emission factors for a range of air pollutants and greenhouse gases from energy production and consumption. We have estimated a sectoral emission factor using total energy-related emissions divided by corresponding energy consumption or total non-energy-related emissions divided by corresponding gross output (Wei et al., 2018) for the < ECLIPSE_V6b_CLE_base>[2] scenario (Klimont et al., 2021). The ECLIPSE baseline scenario considers all the air pollution

---

[1] Currently, data are shared with the State Information Centre in the form of project cooperation, and the corresponding tabulation methods and data are expected to be published within this year.

[2] Further description of the ECLIPSE baseline scenario is available in GAINS 4.0 (see: http://gains.iiasa.ac.at/).

control policies and measures implemented until 2018.

In addition, the model requires some endogenous and exogenous parameters. The endogenous parameters are obtained by the calibration method, whereas the exogenous parameters, such as various substitution elasticities, carbon emission coefficients, and carbon oxidation rates, are taken from the relevant literature (IPCC., 2006; Liang et al., 2014; Paltsev et al., 2005; Tian et al., 2016; Wu et al., 2019), and with our further modification, as shown in Table 1.

Table 1. Elasticity parameters in the model

Elasticities	**Value**
Elasticities for production [1]	
Between intermediate inputs and capital-energy-labour composition	0
Between resource and non-resource input composition (for agriculture and primary energy sectors)	0.6
Between labour and capital-energy composition	0.6
Between capital and energy composition	0.9
Between electricity and fossil fuel	0.5
Among fossil fuels	1
Elasticities of substitution between imports and domestic production (SigmaQ) [1]	
Agriculture	3
Energy products	4
Other products	2
Elasticities of substitution in capital regional transfer (SigmaNK) [2]	6
Elasticities of substitution between exports and domestic sales (SigmaEX) [1]	
Agriculture	4
Energy products	5
Other products	3
Local—domestic for China's provinces (SigmaDdAll) [3]	SigmaQ+2
Across China's regions for China's provinces (SigmaDd) [3]	SigmaQ+2

Data sources: [1] Refer to Liang et al. (2014); [2] Refer to Xu (2007); [3] Refer to Wu et al. (2019), and Tian et al. (2016).

3. Results and discussion

3.1 The original national MACCs and regional MACCs

Fig. 4 describes the carbon MACCs of China and of its provinces in 2030 (considering that 2030 is the target year for achieving carbon peak and NDC in China (The State Council, 2021a,b), this study will adopt it as a basis for policy target setting). It is observed that significant geographical differences are shown in the distribution of provincial MACCs, especially in high abatement percentage level. Specifically, the four provinces of eastern China (Shandong, Shanghai, Jiangsu, and Zhejiang) have the steepest carbon MACCs. Under the 20% emission reduction level (this ratio is selected to improve the display of results), the MACs of these four provinces will all exceed 1150 yuan/ton CO_2 (2012 constant price, the same hereafter; about 183 \$/ton CO_2, 2012 exchange rate, the same hereafter), see Fig. 5. Meanwhile, other eastern provinces (viz. Beijing, Tianjin, Fujian, Guangdong, and Jilin) also have a higher carbon MAC, exceeding 950 yuan/ton CO_2 (i.e. the national average MAC level; about 151 \$/ton CO_2) at the 20% emission reduction level by 2030. This demonstrates that it is relatively difficult for the above provinces to reduce emissions. The differences in the MAC in different provinces stem from the differences in energy consumption variations for provinces when given the same carbon price. The increased ratios of usage cost for fossil energy in the eastern provinces is lower than the national average level when given the same carbon price because the huge demand for fossil energy in the eastern provinces under the business-as-usual scenario drives up the price of fossil energy by 2030 and the price of fossil energy in eastern provinces rises less than the national average subject to the same carbon tax. Therefore, the change in the consumption of fossil energy in these provinces is smaller than the national average level. Ultimately, the decline ratio in these provinces' carbon emissions is less than the national average level. Therefore, the MAC of these provinces is higher than that of the whole country under the same abatement level. Moreover, regarding five provinces such as Inner Mongolia, Shanxi, Liaoning, Sichuan, and Xinjiang, their MACs are lower than the average of the whole nation as their own industrial structure is dominated by fossil energy production bases or heavy industrial bases. In addition, compared with most central and eastern provinces, the carbon MACCs of the economically underdeveloped western provinces, such as Tibet and Gansu, are much lower, where the MACs at the 20% emission reduction level are lower than 700 yuan/ton of CO_2 (i.e. about 111 \$/ton CO_2).

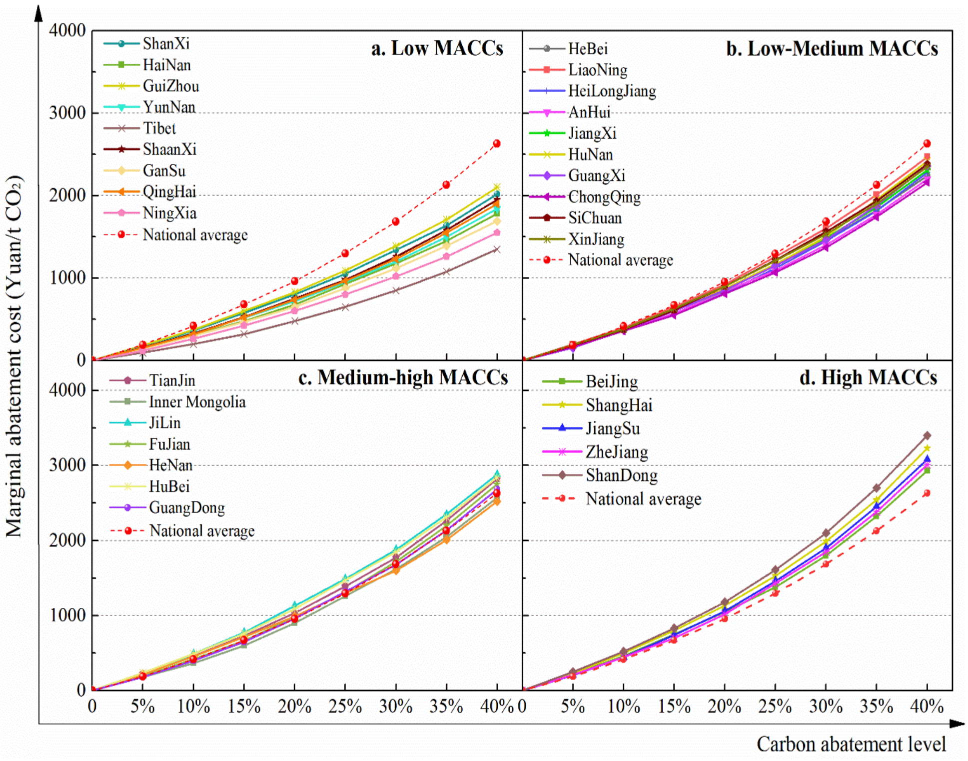


Fig. 4. MACCs for China and each province in 2030

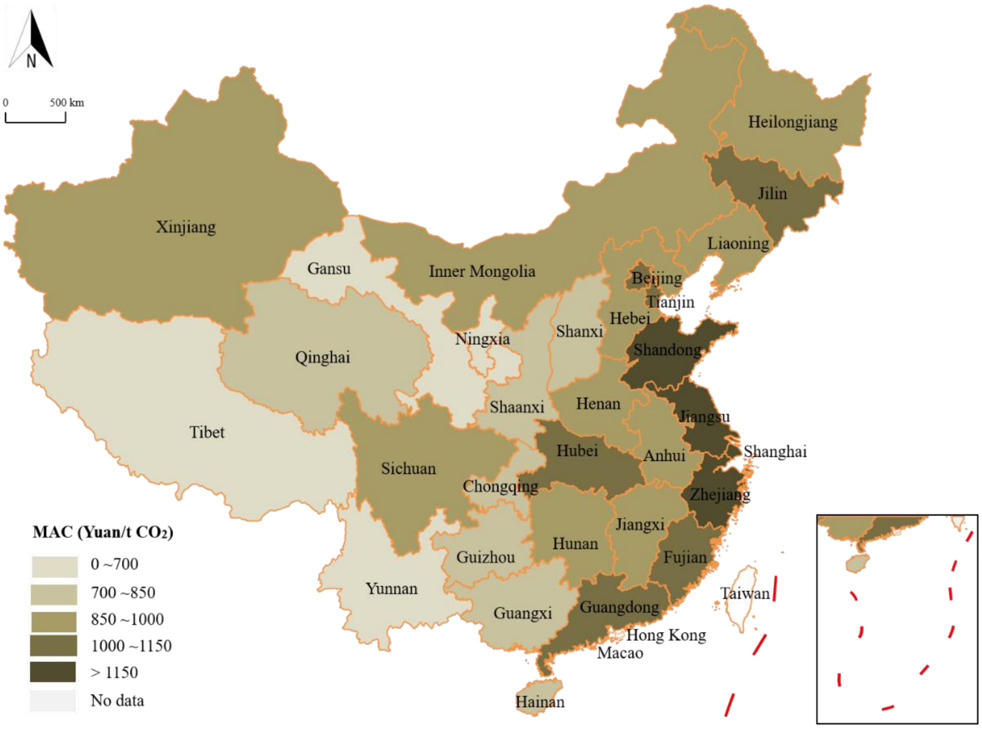


Fig. 5. MACCs with 20% emission reduction of each province in 2030

3.2 Revised MACCs for provinces

3.2.1 The MACCs for air pollutants

Similar to the carbon tax, this study also levies taxes on various pollutants including SO_2, NO_x, and $PM_{2.5}$, to obtain the relationship between the MAC and abatement rate of the three criteria pollutants in China and its provinces in 2030. The shape of pollutant MACCs in most provinces (including 21 provinces such as Beijing and Hebei) is similar to the shape of pollutant MACCs in the whole country, as shown in Fig. 6(a-b) and Fig. S1 of the Supplementary Material. For these provinces, the MAC of $PM_{2.5}$ is the highest under the same pollutant abatement level and when the abatement percentage exceeds 10%, the MAC of $PM_{2.5}$ rises sharply, indicating that the abatement cost is quite high for these provinces to achieve the deep emission reduction of $PM_{2.5}$. Moreover, the SO_2 MAC under all or most abatement percentages will be slightly higher than the NO_x MAC of the same abatement level.

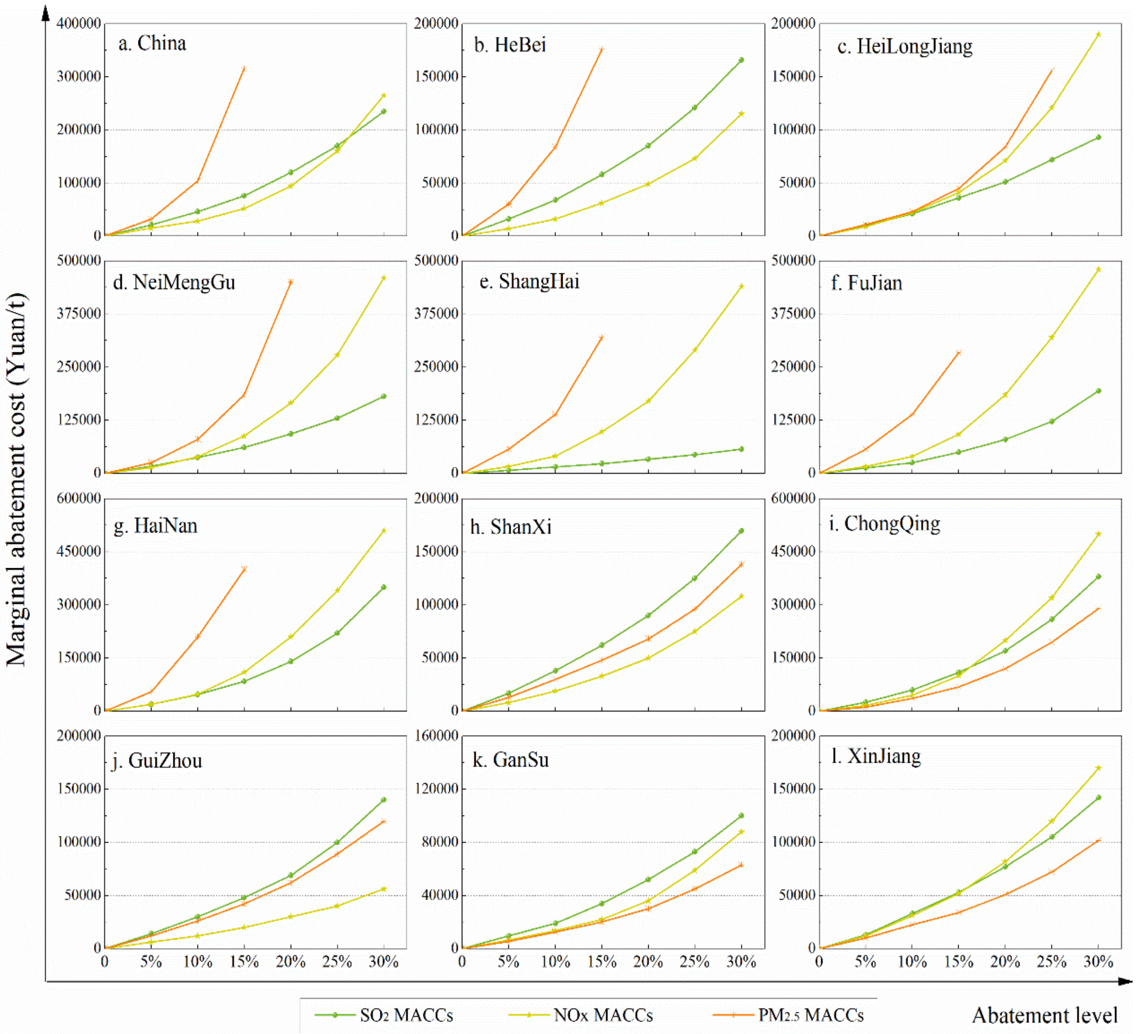


Fig. 6. MACCs for SO_2, NO_x, and $PM_{2.5}$ in China and representative provinces in 2030

Furthermore, regarding the pollutant MACCs of some provinces, such as Heilongjiang, Inner Mongolia, Shanghai, Fujian, and Hainan, the MAC of $PM_{2.5}$ is still the largest at the same abatement percentage, but the MAC of NO_x will be higher than the MAC of SO_2. Also, with the strengthening of emission reduction constraints, the gap between both becomes more obvious, as shown in Fig. 6(c-g). In addition, in some provinces, such as Shanxi, Chongqing, Guizhou, Gansu, and Xinjiang, the $PM_{2.5}$ MACCs of these provinces are relatively flat and generally lower than the SO_2 MACCs, and are even lower than the NO_x MACCs, see Fig. 6(h-l). This is mostly because $PM_{2.5}$

emissions consist of two parts: energy-related emissions and process-related emissions. According to the $PM_{2.5}$ emission factors of China's provinces calculated by the GAINS database, we found that these provinces' process-related emission factors are larger than those of other provinces so that their process-related emissions account for a larger proportion. With the improvement of abatement level, the abatement method gradually shifts from energy substitution to the decline of output scale, especially when the abatement level is very high and the production scales in all provinces have been significantly compressed. Considering that the process-related emission factors in these provinces are larger than those in other provinces, this leads to a greater reduction in these provinces' process-related emissions under the same emission price. Eventually, the $PM_{2.5}$ MACCs of these provinces are relatively flat.

3.2.2 The revised MACCs for carbon dioxide

To incorporate the co-benefits of carbon abatement policies into carbon MACCs, first, we need to monetize the co-benefits of reducing air pollutant emissions. According to Eq. (2), this study fits the MACCs in Fig. 3 and Fig. S1 to obtain the regression coefficients (α, β, γ) and the correlation coefficient (R^2) of the MACCs of various pollutants in China and its provinces in 2030. Table 2 shows the equation coefficients of pollutant MACCs for China and Beijing as an example, and for the remaining provinces, see Table S3. For each curve, R^2 is very close to 1, indicating that the result is reasonable; and all F-values are less than 0.001, indicating that the results are significant at the 0.001 level. Meanwhile, we also conduct the T-test to verify the significance of each variable coefficient (see the supplementary material S4).

Table 2. Coefficients of the approximations of the pollutant MACCs for China and Beijing in 2030 of the form: $MAC=\alpha Q^3+\beta Q^2+\gamma Q$

Pollutant MACCs	China			Beijing		
	SO_2	NO_x	$PM_{2.5}$	SO_2	NO_x	$PM_{2.5}$
α	63.5	567.1	2290.5	43818800.0	24632600.0	1318570000.0
β	444.2	-2397.4	3329.8	2814330.0	2447150.0	-15140500.0
γ	10711.6	12695.5	17600.4	635227.2	629443.5	898432.2
R^2	0.9998	0.9999	0.9998	0.9998	0.9939	0.9998
F-value	5.12E-10	4.63E-9	3.55E-8	4.14E-8	6.45E-8	1.50E-7

Note: The correlation coefficients are obtained from the Origin software.

As a next step, to assess the co-benefits of various pollutants, the pollutant reductions under a specific carbon emission reduction target are substituted into Eq. (3) and calibrated based on the parameters in Table 2. Finally, the original MACCs are subtracted from the co-benefits per unit CO_2 under a specific carbon emission reduction amount to obtain the revised MACCs. Fig. 7 shows the revised MACCs for China and Beijing in 2030 and those for all provinces are shown in Fig. S2 of the Supplementary Material. The results show that, nationally, after considering the co-benefits, the revised MACCs decline by about 7% compared to the original MACCs. At the provincial level, the revised MACCs in different provinces show a certain degree of decline, but the declining trend among provinces is different.

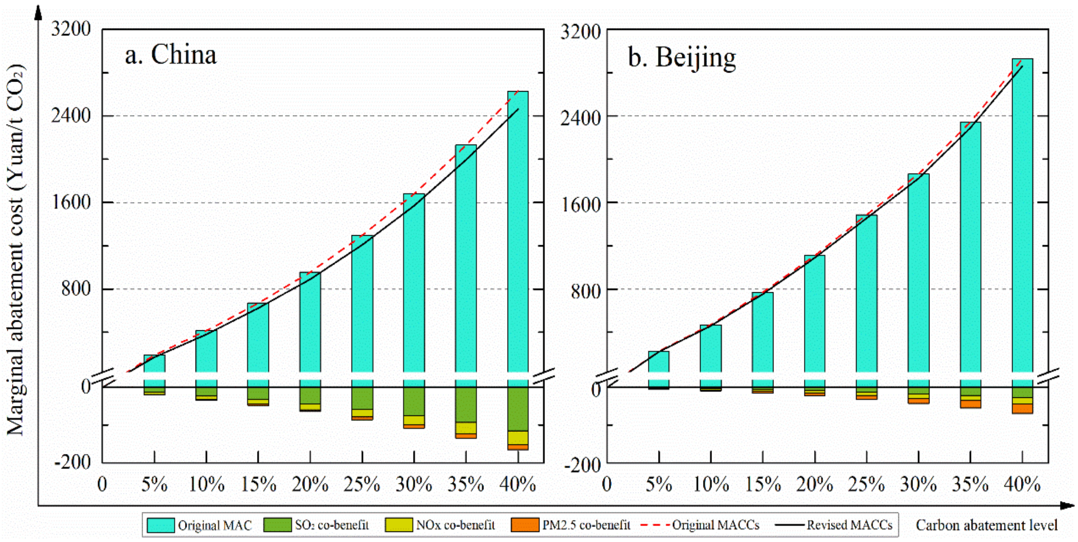


Fig. 7. Revised MACCs for China and Beijing in 2030

To further explore the differences in the co-benefits among provinces, this study selects the economic development level and industrial structure for explanation based on the relevant literature (He et al., 2018; Xian et al., 2018). Specifically, the per capita GDP of each province is used to represent the level of economic development in this study, and the proportion of the tertiary industry represents the difference in industrial structure. Generally, the higher the proportion of the tertiary industry, the lower the energy consumption per unit output value, and the corresponding carbon abatement potential is also smaller. Thus, this study divides all provinces into four regions according to whether both indicators are higher than the national average level: (I) high per capita GDP and high proportion of the tertiary industry, namely High-High; (II) high per capita GDP and low proportion of the tertiary industry, namely High-Low; (III) low per capita GDP and high proportion of the tertiary industry, namely Low-High; and (IV) low per capita GDP and low proportion of the tertiary industry, namely Low-Low. Fig. 8 shows the co-benefits of each pollutant brought by unit of CO_2 under the 20% emission reduction level in each province. It is found that the provinces located in the High-High region, especially Beijing, Shanghai, and Tianjin, have a relatively high level of economic development, and the proportions of the tertiary industry and clean energy are significantly higher than those of other provinces. Therefore, these provinces have relatively small co-benefits brought by carbon abatement policies. Moreover, two types of regions show obvious co-benefits of pollutants: one is provinces with high per capita GDP and dominated by energy-intensive industries, that is, those located in the High-Low region. In this region, the typical provinces are Shandong, Jiangsu, Liaoning, Jilin, and so on, which are mostly oil refining bases or heavy industry bases. The other type is the coal and crude oil production base with low per capita GDP, such as Inner Mongolia, Shanxi, Shaanxi, Sichuan, and Xinjiang, which are provinces that are mostly located in Low-Low areas. Additionally, some central and western provinces such as Qinghai, Gansu, Tibet, and Hainan, which are less developed, have a higher proportion of tertiary industry and light industry, and their energy structures are relatively clean. Therefore, the co-benefits of these provinces are at the bottom of the country.

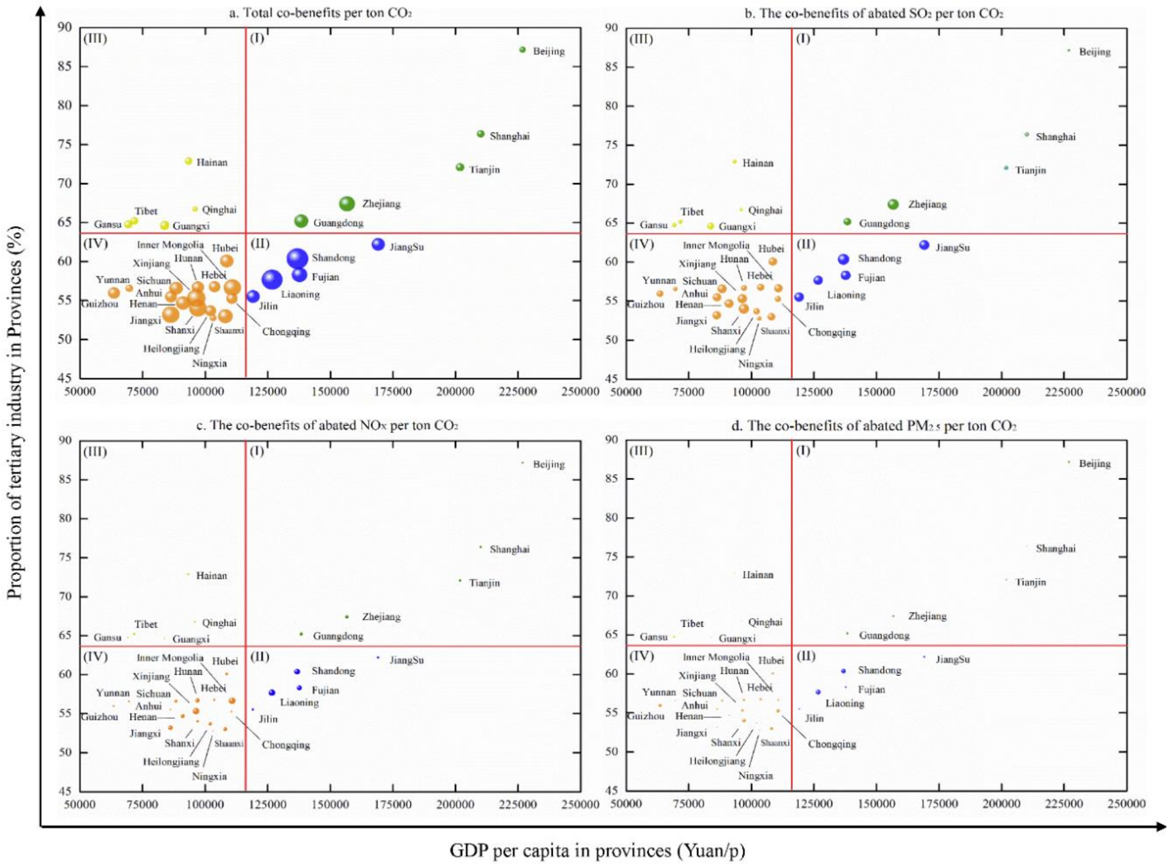


Fig. 8. Provincial differences of co-benefits per unit of CO_2 under the 20% carbon abatement level of each province in 2030

Note: The size of the circles indicates the relative size of the co-benefits in each province, and the same circle colour indicates provinces located in the same region. The red vertical line represents the national per capita GDP level, and the red horizontal line represents the proportion of the national tertiary industry.

In addition, in the composition of various pollutant co-benefits, the co-benefits of SO_2 reductions in all provinces are greater than those of the other two pollutants, exceeding 60% of the total co-benefits in each province, as shown in Fig. 8(b-d), followed by NO_x reductions and $PM_{2.5}$ reductions. Specifically, provinces with a lower per capita GDP and a high sulphur content of coal (i.e. Shanxi, Shaanxi, and Sichuan) exhibit obvious co-benefits of SO_2. Moreover, Shandong, Xinjiang, and Inner Mongolia have obvious co-benefits of NO_x reductions due to refineries, crude oil, and coal bases, which account for more than 30% of the total provincial co-benefits. The co-benefits of $PM_{2.5}$ reductions in Shanxi, Chongqing, and Liaoning are more significant due to high population density and vehicle population, accounting for more than 25% of the total provincial co-benefits.

3.3 Cost-benefit comparisons for provinces

The MACCs reflect marginal abatement costs at different abatement levels, which clearly illustrates the relative cost-effectiveness of all the abatement options. However, the government tends to focus on total abatement costs and inter-provincial abatement effort sharing under specific targets when undertaking emission reduction planning. Therefore, based on the latest NDC target proposed by the Chinese government at the Climate Ambition Summit in December 2020, namely "China's carbon intensity by 2030 will be reduced by more than 65% compared to 2005", this study investigates the total abatement costs and inter-provincial abatement effort sharing for China and its provinces to achieve the NDC target before and after considering the co-benefits. In addition, in the baseline scenario, this study assumes that China's carbon intensity in

2030 will drop by 61% compared to 2005.

To further quantify the total abatement costs of China and its provinces to achieve the NDC target before and after considering the co-benefits, we need to fit the obtained original MACCs and revised MACCs. The relevant parameters are shown in Table 3 and Table S4 (see supplementary material). For each curve, R^2 is very close to 1, indicating the result is reasonable; and all F-values are less than 0.001, indicating that the results are significant at the 0.001 level. Meanwhile, we also conduct the T-test to verify the significance of each variable coefficient (see the supplementary material S4).

Table 3. Coefficients of the approximations of the original and revised MACCs for China and Beijing in 2030 of the form: $MAC=\alpha Q^3+\beta Q^2+\gamma Q$

Coefficients	China		Beijing	
	Original MACCs	Revised MACCs	Original MACCs	Revised MACCs
α	4.0	3.2	274784.0	270076.2
β	27.3	30.7	1668.6	595.6
γ	290.3	260.5	13269.9	13069.7
R^2	0.9998	0.9998	0.9999	0.9999
F-value	6.46E-8	4.63E-8	7.48E-8	2.54E-7

Note: The correlation coefficients are obtained from the Origin software.

The carbon emission reductions for each province to achieve the NDC targets are substituted into the expression in Tables 3 and S4 to assess the total abatement costs and cost-saving effects for China and its provinces to achieve the NDC targets in 2030, as shown in Fig. 9. Our analysis indicates that the original abatement cost of each province will be offset to a certain extent after considering the co-benefits, ranging from 4.3% to 18.9%. Overall, the nationwide abatement cost is offset by 8.6%. To further examine the extent to which the co-benefits can offset the abatement cost, this study constructs an indicator for synergizing the reduction of pollution and carbon emissions

(SRPCE), that is, the ratio of the co-benefits to the original abatement cost, as shown in Fig. 10. We found that for provinces with high per capita GDP and that are dominated by energy-intensive industries (viz. Shandong, Jiangsu, Liaoning, and Jilin), and provinces with energy production bases (viz. Inner Mongolia, Shanxi, Shaanxi, Sichuan, and Xinjiang, as important coal or oil production bases in China), their SRPCE indicators exceed the national average level. In particular, Shandong has the most absolute co-benefits, offsetting the abatement cost of 4.1 billion yuan (i.e. about 651 million $). Therefore, after considering the co-benefits, the carbon abatement targets of these provinces could be more significantly increased to achieve the national "carbon peak" as soon as possible. Moreover, for some central and western provinces with relatively less developed economies and cleaner energy structures, the abatement costs they undertake are much smaller. For example, Qinghai, Gansu, Tibet, Ningxia, and Hainan have less than 1% abatement efforts and their SRPCE indicators are also lower than the national average. Thus, to balance regional economic development, their abatement targets can be considered without adjustment. Additionally, for provinces such as Beijing, Shanghai, and Tianjin, despite the fact that the level of economic development is relatively high, their abatement potential is limited due to stringent implementation of pollution control technologies and a higher proportion of tertiary industry, and their co-benefits are much smaller. These provinces can moderately increase their abatement targets or consider providing some climate funding or transferring abatement technologies to support the economic development of some central and western provinces with higher SRPCE indicators.

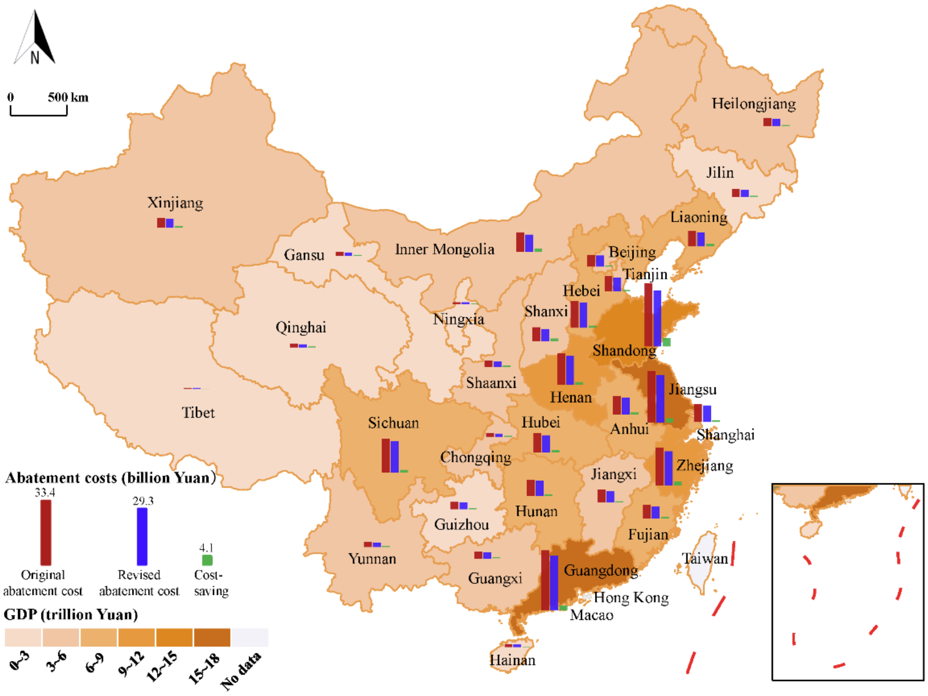


Fig. 9. The abatement costs and cost-saving effects of each province in 2030

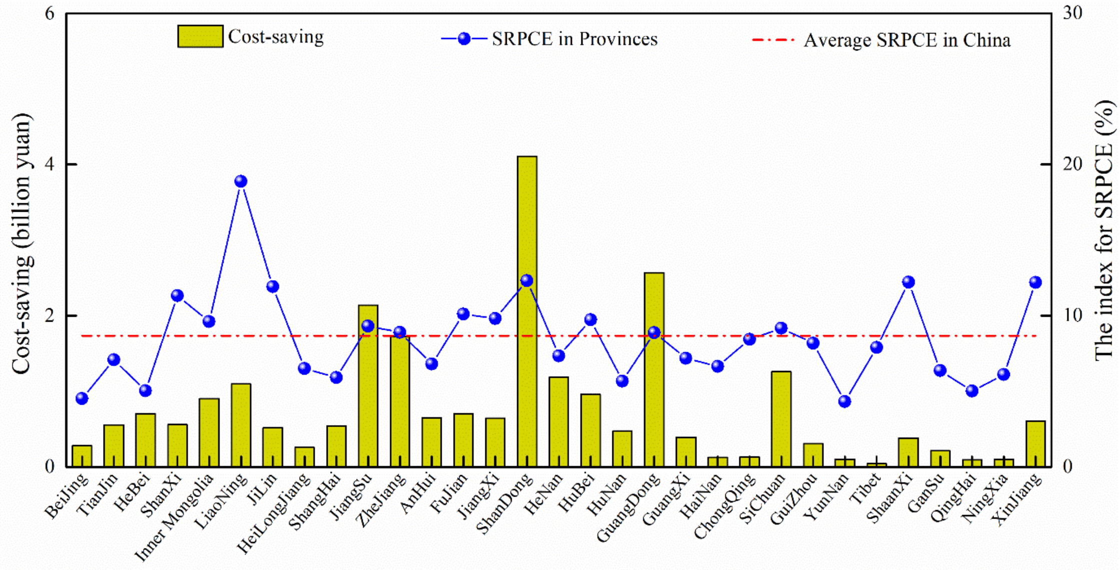


Fig. 10. The cost-saving effects and SRPCE indicator of each province in 2030

4. Conclusions and policy implications

Based on a Chinese multi-regional computable general equilibrium model, this study employed original and revised MACCs to evaluate the changes in total abatement costs and inter-provincial abatement effort sharing for Chinese provinces to achieve the latest NDC target. In addition, a sensitivity analysis including key substitution elasticities was conducted and the robustness of this study in judging the relative size of the co-benefits of each province was verified (see supplementary material for details). The following policy implications can be obtained from the results and Table 4:

Table 4. Policy deployment in key regions

Key regions	Categories	Original MACCs (High or Low) [2]	Co-benefits (High or Low) [3]	Policy deployment
High-High [1]	Beijing	High	Low	Providing climate funding and transferring abatement technologies
	Tianjin	High	Low	
	Shanghai	High	Low	
High-Low	Shandong	High	High	Raising significantly their abatement targets and increasing the policy efforts of carbon pricing such as carbon trading
	Jiangsu	High	High	
	Liaoning	High	High	
	Jilin	High	High	
Low-Low	Inner Mongolia	Low	High	
	Shanxi	Low	High	
	Shaanxi	Low	High	
	Sichuan	Low	High	
	Xinjiang	Low	High	
Low-High	Qinghai	Low	Low	Utilizing climate funding to transform and upgrade abatement technologies
	Gansu	Low	Low	
	Tibet	Low	Low	
	Hainan	Low	Low	

Note: 1. The first “High” refers to the level per capita GDP; and the second “high” refers to the level of proportion of the tertiary industry.
2. The “High” or “Low” refers to the level of regional MACCs relative to the national average MACCs.
3. The “High” or “Low” refers to the level of regional SRPCE indicator relative to the national average SRPCE indicator.

First, in the short term, after the carbon abatement targets are strengthened, the originally planned efforts of targeted abatement measures for SO_2 in all provinces can be significantly weakened, whereas the originally planned policy efforts for $PM_{2.5}$ cannot be relaxed in all provinces. The results show that in the composition of total co-benefits in all provinces, the co-benefits of SO_2 reductions exceed 60% of the total co-benefits; followed by the co-benefits of NO_x and $PM_{2.5}$ reductions. Specifically, the co-benefits of SO_2 reductions in Shanxi, Shaanxi, and Sichuan are particularly significant. Shandong, Xinjiang, and Inner Mongolia have obvious co-benefits of NO_x reductions, while the co-benefits of $PM_{2.5}$ reductions in Shanxi, Chongqing, and Liaoning are more significant. These provinces can moderately weaken the efforts of market-based policies such as environmental taxes.

Second, in the long run, if each province significantly increases its carbon abatement target to achieve “carbon neutrality”, it is likely that China and its provinces will also achieve the SO_2 and NO_x reduction targets, and the efforts put into measures for $PM_{2.5}$ can be significantly reduced. The results show that at the 40% carbon abatement level in China, the synergistic abatement rates of SO_2, $NO_{x,}$ and $PM_{2.5}$ are approximately 25%, 20%, and 10%, respectively. Therefore, under the high carbon abatement target, the co-benefits of SO_2 and NO_x reductions are obvious; thus, additional pollutant abatement measures do not need to be undertaken. Meanwhile, there is also a significant reduction for $PM_{2.5}$, which significantly weakens the corresponding policy effort.

Third, inter-provincial abatement efforts can be decomposed based on revised provincial MACCs. When co-benefits are included, the carbon abatement targets of all provinces in China can be moderately increased to achieve a “carbon peak” as soon as possible however, the resource endowment and cost-effectiveness among provinces should be considered. The results indicate that the total abatement cost of each province to achieve China's NDC target will be offset to a certain extent after considering the co-benefits, ranging from 4.3% to 18.9%. It is observed that the provinces with high per capita GDP and dominated by energy-intensive industries (e.g. Shandong, Jiangsu, Liaoning, and Jilin), and some provinces with energy production bases (e.g. Inner Mongolia, Shanxi, Shaanxi, Sichuan, and Xinjiang) have higher ratios of pollution mitigation co-benefits to the original abatement costs compared to the national average level; therefore, their abatement target can be raised more significantly. Considering the difficulties of economic development in the central and western provinces, a joint implementation mechanism could be established between developed provinces with high economic levels but less co-benefits (e.g. Beijing, Tianjin, and Shanghai) and the central and western provinces through methods such as providing climate funding and transferring abatement technologies.

Although this study incorporated the co-benefits of carbon abatement policies into the MACCs and quantified the effects of co-benefits on the abatement costs of China and its provinces in achieving the NDC's target, limitations remain. For example, this study only considered the co-benefits of air pollutant emission reduction, while health effects associated with air pollutants have not been discussed. Therefore, an important research direction is that the CGE model can build a soft-link with the atmospheric dispersion model and exposure–response function to evaluate health co-benefits, and establish the dynamic feedback of economic activities, environmental pollution, and human health. In addition, another important research direction is to explore the inter-provincial emission reduction cooperation mechanism.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [grant numbers 72074022, 72204234]; the National Social Science Foundation of China [grant number 22AZD094]; and the Fundamental Research Funds for the Central Universities (2-9-2021-020).

Declaration of competing interest

There are no conflicts of interest to declare.

References

Alimujiang, A., Jiang, P., 2020. Synergy and co-benefits of reducing CO2 and air pollutant emissions by promoting electric vehicles-A case of Shanghai. Energy Sustain. Dev. 55, 181–189.

Amann, M., Kiesewetter, G., Schöpp, W., Klimont, Z., Winiwarter, W., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Gomez-Sabriana, A., Heyes, C., Purohit, P., Borken-Kleefeld, J., Wagner, F., Sander, R., Fagerli, H., Nyiri, A., Cozzi, L., Pavarini, C., 2020. Reducing global air pollution: the scope for further policy interventions. Philos. Trans. A Math. Phys. Eng. Sci. 378, 20190331.

Armington, P.S., 1969. A theory of demand for products distinguished by place of production. IMF Staff Pap. 16, 159–178.

Bergman, L., 1991. General equilibrium effects of environmental policy: a CGE-modeling approach. Environ. Resour. Econ. 1, 43–61.

Bernard, A., Haurie, A., Vielle, M., Viguier, L., 2008. A two-level dynamic game of carbon emission trading between Russia, China, and Annex B countries. J. Econ. Dyn. Control. 32, 1830–1856.

Bhattacharyya, S.C., 1996. Applied general equilibrium models for energy studies: a survey. Energy Econ. 18, 145–164.

BP, 2021. BP statistical review of world energy. British Petroleum (BP), London., Web link: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

Cai, B., Li, W., Dhakal, S., Wang, J., 2018. Source data supported high resolution carbon emissions inventory for urban areas of the Beijing-Tianjin-Hebei region: spatial patterns, decomposition and policy implications. J. Environ. Manag. 206, 786–799.

Cai, B.F., Bo, X., Zhang, L.X., Boyce, J.K., Zhang, Y.S., Lei, Y., 2016. Gearing carbon trading towards environmental co-benefits in China: measurement model and policy implications. Glob. Environ. Change Hum. Policy Dimen. 39, 275–284.

Cao, L.B., Tang, Y.Q., Cai, B.F., Wu, P.C., Zhang, Y.S., Zhang, F.X., Xin, B., Lv, C., Chen, K., Fang, K., 2021. Was it better or worse? Simulating the environmental and health impacts of emissions trading scheme in Hubei Province. China Energy. 217, 119427.

Chang, S.Y., Yang, X., Zheng, H.T., Wang, S.X., Zhang, X.L., 2020. Air quality and health co-benefits of China’s national emission trading system. Appl. Energy. 261, 114226.

Conrad, K., Schröder, M., 1991. The control of CO2 emissions and its economic impact: an AGE model for a German state. Environ. Resour. Econ. 1, 289–312.

Deng, H.M., Liang, Q.M., Liu, L.J., Anadon, L.D., 2017. Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. Environ. Res. Lett. 12, 123001.

Eory, V., Topp, C.F.E., Moran, D., 2013. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environ. Sci. Policy. 27, 55–67.

GAC, 2013. China Customs Statistics Yearbook (2013). China Custom Magazine, Beijing.

Groosman, B., Muller, N.Z., O’Neill-Toy, E., 2011. The ancillary benefits from climate policy in the United States. Environ. Resource. Econ. 50, 585–603.

Guo, J.X., Zhu, L., Fan, Y., 2016. Emission path planning based on dynamic abatement cost curve. Eur. J. Oper. Res. 255, 996–1013.

He, W., Wang, B., Danish, Wang, Z., Danish, 2018. Will regional economic integration influence carbon dioxide marginal abatement costs? Evidence from Chinese panel data. Energy Econ. 74, 263–274.

IEA, 2012. World Energy Balances. International Energy Agency (IEA), Paris.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama, Japan.

IPCC, 2022. 2022: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Clim. Change. Cambridge, United Kingdom and New York.

Jiang, H.D., Dong, K.Y., Zhang, K., Liang, Q.M., 2020. The hotspots, reference routes, and research trends of marginal abatement costs: A systematic review. J. Cleaner Prod. 252, 119809.

Jiang, H.-D., Purohit, P., Liang, Q.-M., Dong, K., Liu, L.-J., 2022a. The cost-benefit comparisons of China's and India's NDCs based on carbon marginal abatement cost curves. Energy Econ. 109, 105946.

Jiang, H.-D., Xue, M.-M., Dong, K.-Y., Liang, Q.-M., 2022b. How will natural gas market reforms affect carbon marginal abatement costs? Evidence from China. Econ. Syst. Res. 34, 129–150.

Kesicki, F., Strachan, N., 2011. Marginal abatement cost (MAC) curves: confronting theory and practice. Environ. Sci. Policy. 14, 1195–1204.

Klepper, G., Peterson, S., 2006. Marginal abatement cost curves in general equilibrium: the influence of world energy prices. Resour. Energy Econ. 28, 1–23.

Klimont, Z., Heyes, C., Schöpp, W., Rafaj, P., Purohit, P., Cofala, J., Höglund-Isaksson, L., Wagner, F., Borken-Kleefeld, J., Gomez-Sanabria, A., Winiwarter, W., Paunu, V.V., Kiesewetter, G., Amann, M., Nguyen, B., Sander, R., 2021. Global scenarios of anthropogenic emissions of air pollutants: Eclipse.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., Schöpp, W., 2017. Global anthropogenic emissions of particulate matter including black carbon. Atmos. Chem. Phys. 17, 8681–8723.

Liang, Q.M., Yao, Y.F., Zhao, L.T., Wang, C., Yang, R.G., Wei, Y.M., 2014. Platform for China Energy & Environmental Policy Analysis: A general design and its application. Environ. Modell. Softw. 51, 195–206.

Lin, B., Jia, Z., 2019. What will China's carbon emission trading market affect with only electricity sector involvement? A CGE based study. Energy Econ. 78, 301–311.

Lindner, S., Liu, Z., Guan, D., Geng, Y., Li, X., 2013. CO2 emissions from China's power sector at the provincial level: consumption versus production perspectives. Renew. Sustain. Energy Rev. 19, 164–172.

Liu, Y., Tan, X.-J., Yu, Y., Qi, S.-Z., 2017. Assessment of impacts of Hubei Pilot emission trading schemes in China – a CGE-analysis using TermCO2 model. Appl. Energy. 189, 762–769.

Liu, Z., Wang, F., Tang, Z., Tang, J., 2020. Predictions and driving factors of production-based CO2 emissions in Beijing, China. Sustain. Cities Soc. 53, 101909.

Mittal, S., Hanaoka, T., Shukla, P.R., Masui, T., 2015. Air pollution co-benefits of low carbon policies in road transport: a sub-national assessment for India. Environ. Res. Lett. 10, 085006.

MOF, 2013. China Financial Yearbook (2013). China State Finance Magazine, Beijing.

Morris, J., Paltsev, S., Reilly, J., 2008. Marginal Abatement Costs and Marginal Welfare Costs for Greenhouse Gas Emissions Reductions: Results from the EPPA Model. MIT Press Joint Program on the Science and Policy of Global Change.

Muller, N.Z., 2012. The design of optimal climate policy with air pollution co-benefits. Resour. Energy Econ. 34, 696–722.

NBS, 2013a. China Energy Statistical Yearbook (2013). China Statistical Press, Beijing.

NBS, 2013b. China Statistical Yearbook (2013). China Statistics Press, Beijing.

NBS, 2014. China Statistical Yearbook (2014). China Statistics Press, Beijing.

Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J.R., Sarofim, M.C., Asadoorian, M.O., Babiker, M.H., 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model, version 4. MIT Press Joint Program on the Science and Policy of Global Change, Cambridge.

The State Council, 2021a. Carbon peak action plan by 2030, number 23. Of the State Council of the People’s Republic of China. http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.htm.

The State Council. (2021b). Opinions on the Accurate and Comprehensive Implementation of the New Development Concept to Achieve Carbon Peak and Carbon Neutrality. The State Council of the People's Republic of China. Web link: http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm.

Tian, X., Dai, H.C., Geng, Y., Wilson, J., Wu, R., Xie, Y., Hao, H. (2018) Economic impacts from PM2.5 pollution-related health effects in China’s road transport sector: a provincial-level analysis. Environ. Int. 115, 220–229.

Tian, X., Geng, Y., Dai, H.C., Fujita, T., Wu, R., Liu, Z., Masui, T., Yang, X., 2016. The effects of household consumption pattern on regional development: a case study of

Shanghai. Energy. 103, 49–60.

Wang, F., Liu, B.B., Zhang, B., 2020. Exploring the impacts of carbon market linkage on sectoral competitiveness: a case study of Beijing–Tianjin–Hebei region based on the CEECPA model. Clim. Change Econ. 11. DOI:10.1142/S2010007820410055.

Wei, Y.M., Han, R., Liang, Q.M., Yu, B.Y., Yao, Y.F., Xue, M.M., Zhang, K., Liu, L.J., Peng, J., Yang, P., Mi, Z.F., Du, Y.F., Wang, C., Chang, J.J., Yang, Q.R., Yang, Z.L., Shi, X.L., Xie, W., Liu, C.Y., Ma, Z.Y., Tan, J.X., Wang, W.Z., Tang, B.J., Cao, Y.F., Wang, M.Q., Wang, J.W., Kang, J.N., Wang, K., Liao, H., 2018. An integrated assessment of INDCs under Shared Socioeconomic Pathways: an implementation of C(3)IAM. Nat. Hazards. 92, 585–618.

West, J.J., Smith, S.J., Silva, R.A., Naik, V., Zhang, Y., Adelman, Z., Fry, M.M., Anenberg, S., Horowitz, L.W., Lamarque, J.F., 2013. Co-benefits of global greenhouse gas mitigation for future air quality and human health. Nat. Clim. Change. 3, 885–889.

Whitesell, W.C., 2011. Climate Policy Foundations: Science and Economics with Lessons from Monetary Regulation. Cambridge University Press, Cambridge, UK.

Wu, R., Dai, H.C., Geng, Y., Xie, Y., Tian, X., 2019. Impacts of export restructuring on national economy and CO2 emissions: a general equilibrium analysis for China. Appl. Energy. 248, 64–78.

Xian, Y., Wang, K., Shi, X., Zhang, C., Wei, Y.-M., Huang, Z., 2018. Carbon emissions intensity reduction target for China’s power industry: an efficiency and productivity perspective. J. Cleaner Prod. 197, 1022–1034.

Xie, Y., Dai, H., Dong, H., 2018. Impacts of SO2 taxations and renewable energy development on CO2, NOx and SO2 emissions in Jing-Jin-Ji region. J. Cleaner Prod. 171, 1386–1395.

Xu, Z.-Y., 2007. The Effects of Interregional Migration to Economic Growth and Regional Disparity. Peking University, Bei Jing Shi, China.

Yang, X., Teng, F., 2018. Air quality benefit of China’s mitigation target to peak its emission by 2030. Clim. Policy. 18, 99–110.

Yang, X., Teng, F., Xi, X.Q., Khayrullin, E., Zhang, Q., 2018. Cost-benefit analysis of

China's Intended Nationally Determined Contributions based on carbon marginal cost curves. Appl. Energy. 227, 415–425.

Zhang, D., Rausch, S., Karplus, V.J., Zhang, X., 2013. Quantifying regional economic impacts of CO2 intensity targets in China. Energy Econ. 40, 687–701.

Zhang, H., Zhang, B., 2020. The unintended impact of carbon trading of China's power sector. Energy Policy. 147.

Zhang, W., Li, K., Zhou, D., Zhang, W., Gao, H., 2016. Decomposition of intensity of energy-related CO2 emission in Chinese provinces using the LMDI method. Energy Policy. 92, 369–381.

Zhang, Y.-J., Wang, A.-D., Tan, W., 2015. The impact of China's carbon allowance allocation rules on the product prices and emission reduction behaviors of ETS-covered enterprises. Energy Policy. 86, 176–185.