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Exploring impact of carbon tax on China's CO_2 reductions and provincial disparities

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ABSTRACT

With fast development, it is not easy for China to achieve carbon reduction targets only by traditional command and control measures (e.g., the measures for energy-efficiency). Carbon tax is advocated as one effective complementary measure and has high possibility to be implemented for China's future low carbon development. Under such a circumstance, this paper aims at forecasting the possible impact of carbon tax on both carbon reduction and economic loss of 30 Chinese provinces. A 30-Chinese-province CGE (Computational general equilibrium) model has been developed to conduct the provincial evaluation, and seven scenarios including Business-as-Usual (BaU) scenario and six carbon tax scenarios with carbon price from 20 USD/ton to 120 USD/ton up to 2030 are set. The results show that China's industrial CO_2 will be reduced from 12.2 billion tons under BaU scenario to 10.4 billion tons, 9.3 billion tons, 8.5 billion tons, 7.9 billion tons, 7.4 billion tons and 7.0 billion tons under scenarios of TAX20, TAX40, TAX60, TAX80, TAX100 and TAX120 in 2030, respectively. Electricity, Metal and Chemicals sectors have high reduction potentials and are priority sectors for carbon tax policy. Provincial disparity analysis demonstrates that coal production/consumption and total energy consumption are key factors to affect carbon tax effect on CO_2 reduction, and Inner Mongolia, Shandong, Shanxi and Hebei have the largest industrial CO_2 reduction potentials after levying carbon tax. However, the implementation of carbon tax will impede economic development for all provinces. Therefore, the concept of carbon tax efficiency is further proposed in order to evaluate the effectiveness of carbon tax by considering both CO_2 reduction and GDP loss. Policy suggestions indicate that provinces of Shanxi, Inner Mongolia, Hebei and Anhui should be set priority when implementing carbon tax policy in China, and carbon price should be no more than 50 USD/ton.

1. Introduction

China is facing an increasing pressure to curb greenhouse gas (GHG) emissions since it surpassed the US and became the largest carbon emitter in 2007 [1,2]. In order to respond such a challenge, the Chinese government committed to reduce the intensity of carbon dioxide emissions per unit of GDP in 2020 by 40–45% compared with the level of 2005, and to increase the share of non-fossil fuels in primary energy consumption to approximately 15% by 2020 [3–5]. Considering that China is undergoing fast industrialization and urbanization, the Chinese government realizes that it may not be easy to achieve carbon reduction commitment if only traditional command and control measures (e.g., the measures for energy-efficiency) are used [6]. Thus, it is necessary to introduce market-based emission reduction measures such as carbon tax and carbon trading.

In 2013, China's National Development and Reform Commission (NDRC) launched its "pilot emission trading scheme" in seven provinces and cities [7,8]. Chinese President Xi Jinping further announced in September 2015 that China would launch a national cap-and-trade scheme in 2017 [9]. As for carbon tax policy, NDRC and the Ministry of

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Finance (MOF) had also issued their joint special report, proposing that a carbon tax should be levied in China around year 2012 [10]. However, it was postponed due to many reasons. Economists and international organizations have long advocated carbon taxes because they are easier and can generate larger carbon emission reduction with less negative impact on economic growth [11–13]. Moreover, the carbon trade scheme is a complicated and long process that cannot effectively respond current environmental problems, particularly the serious haze weather [14]. It is particularly critical to promote such a tax in China since China is facing serious challenges on responding climate change and promoting energy saving and emissions reduction [15,16]. Therefore, considering the advantages of the policy itself and the possibility of being implemented in the near future of China, this study examines the impact of future carbon tax on China so that useful policies can be released to guide its future carbon tax implementation.

Carbon tax targets to levy tax on fossil fuels (such as coal, oil, natural gas) according to their carbon contents or their carbon emissions from combustion [17]. It is an incentive-based policy instrument for controlling the carbon dioxide emissions and has received global attentions since early 1990s [18,19]. The ultimate objective of such a tax is to mitigate climate change by increasing the cost of fossil fuel usage. The implementation of this policy will result in a demand shift from carbon intensive fuels to “clean energy” (a process of optimization in energy mix) and also an industrial structure shift from energy intensive production to knowledge or service based economy [20]. The collected tax could be used to support the development of renewable energy by subsidizing the environmental protection projects or the technological development of energy saving and emission reduction [13].

Several studies have been done to evaluate the effect of carbon tax on China’s economic development, carbon reduction, living standard, social welfare, et al. For example, Liu and Lu investigated carbon tax impact on China’s economy using a dynamic CGE model, namely the CASIPM-GE model, and results showed that the carbon tax was effective to reduce carbon emissions with minor impact on China’s macro economy [21]. Liang and Wei [10] adopted a recursive dynamic CGE model to explore the impact of a carbon tax on the urban–rural gap and living standard, and found that the implementation of carbon tax under the current social welfare system would increase the income gap between urban and rural households. Li et al. [22] found that a uniform carbon tax may impede the economic development in less developed regions but will promote economic development in the more developed coastal areas. Wang and Yan [15] investigated the impacts of carbon tax on Chinese economy, energy saving and carbon emissions reduction by using one CGE model and concluded that lower carbon tax is a feasible choice under current economic situations. Yang et al evaluated the potential of China’s carbon tax policy in CO_2 mitigations from the perspective of inter-factor/inter-fuel substitution and found that nearly 3% reduction in CO_2 emissions from the 2010 level can be achieved by levying a carbon tax at 50 Chinese Yuan (RMB)/ton, particularly in the areas of East coast and Southwest China [20]. Zhu et al. investigated the impact of carbon tax on different Chinese industrial sectors and concluded that carbon tax has different impacts on different economic sectors and higher emission sectors may suffer from such a policy [23]. In addition, Zhang and Li further confirmed that carbon tax would stimulate economic development in most eastern regions but may have negative impacts on the economic development in the middle and western regions [24].

However, these published studies mainly focus on the whole China or one province or different regions. Since China is a very large country with imbalanced economic development, different resource endowments and technological levels [25], it is necessary to uncover the provincial disparities of carbon tax effect on both economic development and carbon reduction so that key provinces for carbon tax implementation can be recognized. Therefore, the main objective of this study is to predict future carbon tax impact so that valuable carbon tax policies can be raised to guide China’s low carbon development. A 30-Chinese-province CGE model has been developed for such a provincial evaluation. The whole paper is organized as below. After this introduction section, Section 2 presents the research methods, including a detailed introduction on the new 30-Chinese-province CGE model and scenarios setting, as well as data collection and treatment. Section 3 describes the research results on future industrial CO_2 reduction potentials for different industrial sectors and provinces under different carbon tax scenarios. Section 4 discusses policy implications with a special attention on carbon tax sensitivity and provincial carbon tax efficiency. Finally, Section 5 concludes the whole study and provides reasonable policy recommendations for implementing carbon tax in China.

2. Methodology and data

2.1. The 30-Chinese-province CGE model

The CGE model stems from the general equilibrium theory of Walras, in which it demonstrates that supply and demand are equalized across all of the interconnected markets in the economy. It combines the abstract general equilibrium structure formalized by Arrow and Debreu with realistic economic data to solve for the levels of supply, demand and price that support equilibrium across a specified set of markets [26]. The CGE model is widely used in analyzing impacts of policies such as taxes, subsidies, quotas or transfer instruments [27–30]. It is also a popular tool for the analysis of long-term economic implications of climate change policy [7,31–33].

The 30-Chinese-province CGE model developed in this study can be classified as a multi-sector, multi-region, recursive dynamic global CGE model that covers 22 economic commodities and corresponding sectors, and eight power generation technologies. Table A1 in supporting material shows all the details. The major model features are similar to the one-region version [34], including a production block, a market block with domestic and international transactions, as well as government and household income and expenditure blocks. Activity output for each sector follows a nested constant elasticity of substitution (CES) production function. Inputs are categorized into material commodities, energy commodities, labor, capital and resources. The technical formulation of the 30-Chinese-province CGE model has been detailed in [35], and summarized in the supporting materials. One special feature of this model is that the number of modeling regions, both internationally and within China, is highly flexible to allow for a wide range of studies. In this regard 3 regions, 7 regions or 30 provincial units of China and 1, 3, or 14 international regions could be analyzed consistently, as summarized in Table A2 in the supporting material. Tibet, Hong Kong, Macau and Taiwan are not included due to the lack of data. This CGE model is solved by the software of MPSGE/GAMS (Mathematical Programming System for General Equilibrium under General Algebraic Modeling System) [36] at a one-year time step. It has been used intensively for assessing China's climate mitigation at the national [37] and provincial levels [2,7,37–42].

2.2. Data sources

Most of the global data in this CGE model are based on the database of Global Trade Analysis Project (GTAP) 6 [43] and International Energy Agency (IEA) [IEA, 44]. The specific Chinese provincial data are based on the 2002 inter-regional input-output tables (IOT) [45] and the 2002 energy balance tables (EBT) [46]. In addition, carbon emission factors, energy prices for coal, oil and gas, and renewable energy technology costs are also required parameters. All the datasets are converted to the base year of 2002. Moreover, it is well-known that IOT and EBT are inconsistent when it comes to energy consumption across sectors, and the energy data from EBT is regarded as more reliable than IOT. A novel characteristic of this CGE model is that the

IOT of China is consistent with the sectoral energy consumption from China's EBT. In order to achieve this consistency, the linear least square method was adopted, as described in Eq. (1)–(4) below:

Minimizing:

$$\varepsilon = \sum_{f,i} (S_{f,i}^{IOT} - S_{f,i}^{EBT})^2 \quad (1)$$

Subject to:

$$S_{f,i}^{IOT} = \frac{E_{f,i}^{IOT}}{T_f^{IOT}} \quad (2)$$

$$S_{f,i}^{EBT} = \frac{E_{f,i}^{EBT}}{T_f^{EBT}} \quad (3)$$

$$\sum_i E_{f,i}^{IOT} \times P_f = \sum_i E_{f,i}^{EBT} \quad (4)$$

Where

ε	Error to be minimized.
f	Energy commodities such as coal, gas, oil, electricity.
i	Sector classification in Table A1.
$S_{f,i}^{IOT}$	Share of energy consumption across sectors in IOT (%).
$S_{f,i}^{EBT}$	Share of energy consumption across sectors in EBT (%) according to [47].
$E_{f,i}^{IOT}$	Energy consumption of f in sector i in IOT (USD).
$E_{f,i}^{EBT}$	Energy consumption of f in sector i in EBT (PJ).
T_f^{IOT}	Total energy consumption of f in IOT (USD).
T_f^{EBT}	Total energy consumption of f in EBT (PJ).
P_f	Price of energy f (USD/PJ).

2.3. Scenarios setting

Seven scenarios, including Business-as-Usual (BaU) scenario and six carbon tax scenarios, are designed to study the effects of different carbon taxes on China's industrial carbon reductions. The definitions of all the scenarios are described in details as below.

2.3.1. BaU scenario

BaU scenario follows the GDP and demographic trends of the newly developed Shared Socio-economic Pathways (SSP2) scenario, which is characterized by moderate economic growth, fairly rapid growing population and lessened inequalities between industrialized, emerging and developing regions [48]. Following this storyline, the future GDP growth rates of emerging and developing countries will be higher than those industrialized countries. As SSP2 does not provide regional economic and demographic trends for China, this study down-scales the national GDP and population scenarios of China provided by SSP2 to a regional level of China. In line with the principle of SSP2, it is assumed that the growth rates of central and western Chinese regions will be higher than those in the eastern and coastal China in the future, indicating that regional development gap within China will be narrowed. The total numbers of GDP and population of all Chinese regions are calculated by Eqs. (5) and (6). The resulting down-scaled indicators for different Chinese regions add up to the corresponding national total of the SSP2 scenario. Values in Table 1 demonstrate that per capita GDP of West and Central China will increase faster than the one in East China and the Rest of the World.

$$V(r,\ t) = V(\text{“China”},\ t) * S(r,\ t) \quad (5)$$

$$S(r,\ t) = S(r,\ t_0) * T(r)^{(t-t_0)} \quad (6)$$

Where.

V(r, t)	Values of indicator GDP or population in province r and year t;
V(“China”, t)	Values of GDP or population of SSP2 scenario for China in year t;
S(r, t)	Share ratio of province r in year t that downscales national data into provincial data. The reference year (t_0) of population and GDP are 2002 and 2010, respectively;
T(r)	Changing trend of the share of indicator population or GDP (Table 1).

On this basis, the resulting socio-economic assumptions used for the baseline scenario in this study are summarized in Table A3 in the supporting material.

2.3.2. Carbon tax scenarios

Six carbon tax scenarios considering different carbon tax prices are further set based on the BaU scenario. It assumes that the 2 °C degree can be achieved by 2050 under the largest carbon tax scenario. To study the mid-long term effect, the six carbon scenarios are named as Tax20, Tax40, Tax60, Tax80, Tax100 and Tax120, representing that carbon tax of 20, 40, 60, 80, 100 and 120 USD/ton CO_2 will be levied on all economic sectors of China in 2030, respectively. Table 2 lists the detailed carbon tax pathways for the six carbon scenarios, in which it starts from a low-level in 2020 and increase exponentially to the target values in 2030. The economic and population settings for the six carbon scenarios are exactly the same as the BaU scenario.

Twelve industrial sectors are further aggregated from 22 sectors (Table A1 in the supporting materials) to facilitate sectoral analysis. Table 3 shows the detailed classification and definitions on these sectors.

2.4. Carbon tax efficiency

Most published studies use indicators of energy demand, distributional impact, economic efficiency and CO_2 reduction efficiency to study the effect of carbon tax [49–51]. Qiao and Li also proposed the indicator of carbon tax efficiency to study the carbon reduction intensity per unit of carbon tax [52]. However, the above indicators cannot quantify the effectiveness of carbon tax by considering its impact on both carbon emission reduction and economic development. Therefore, we further extend the carbon tax efficiency concept raised by Qiao and Li, and define carbon tax efficiency (η) as the ratio of CO_2 reduction rate to absolute GDP loss (Eq. (7)).

$$\eta_j = \Delta CO_2^j / \Delta GDP^j = (CO_2^j - CO_2^0)/(GDP^j - GDP^0) \quad (7)$$

Where, η_j is the carbon tax efficiency of carbon tax scenario j. $\Delta CO_2{}^j$

Table 1
Downscaling the SSP2 scenario for China in the CGE model.

SSP2	East-China	Central-China	West-China
T(r, “GDP”)	0.998	1.002	1.003
T(r, “population”)	1	1	1

Table 2
Carbon tax pathways for different scenarios (USD/ton CO_2).

Scenarios	2020	2025	2030
Tax 20	2.71	7.37	20.00
Tax 40	3.42	11.70	40.00
Tax 60	3.91	15.33	60.00
Tax 80	4.31	18.57	80.00
Tax 100	4.64	21.54	100.00
Tax 120	4.93	24.33	120.00

Table 3
Industrial sector aggregation.

No.	Sector name	Sectors included
1	Agriculture	Agriculture
2	Mining	Coal mining+ Crude oil mining+ natural gas mining+ Other mining
3	Food	Food and Tabaco
4	Textile	Textile production
5	Chemicals	Chemicals
6	Metal	Metal smelting and processing
7	Machinery	Machinery
8	Electronic	Electronic equipment
9	Power	Electricity production
10	Other_ind	Paper + petrol oil + nonmetal products + metal products + transportation equipment + water production + other manufacturing + construction
11	Transport	Manufactured gas+ Water production
12	Service	Service

represents the carbon reduction amount of carbon tax scenario j, and equals to CO_2 emission of BaU scenario (CO_2^0) minus CO_2 emission of scenario j ($CO_2^{\,j}$). ΔGDP^j represents the absolute GDP loss of carbon tax scenario j, and equals to GDP of BaU scenario (GDP^0) minus GDP of scenario j (GDP^j).

3. Results

3.1. CO_2 emissions and GDP under all scenarios

Industry is the main source for China's energy consumption and GHG emission and therefore should be the key sector to implement carbon tax policy. This paper focuses on three industrial sectors (agricultural industry, manufacturing industry and service industry), without covering residential sector. Fig. 1 illustrates the effect of carbon tax on China's industrial carbon reductions and GDP. It shows that China's CO_2 emission will increase from 6.8 billion tons in 2010 to 12.2 billion tons in 2030 under the BaU scenario, with an almost doubled increase. However, carbon tax can effectively reduce industrial carbon emissions after 2020 due to higher carbon price. The total industrial CO_2 emissions for the year of 2030 can be reduced to 10.4 billion tons (15.2% reduction compared with BaU), 9.3 billion tons (24.1% reduction), 8.5 billion tons (30.4% reduction), 7.9 billion tons (35.4% reduction), 7.4 billion tons (39.6% reduction) and 7.0 billion tons (43.2% reduction) after levying carbon tax of 20, 40, 60, 80, 100 and 120 USD/ton CO_2, respectively.

As for the GDP growth, it will keep an increasing tendency and will not be significantly affected by carbon tax policy. The GDP will increase from 30.2 trillion RMB in 2010 to 110.7 trillion RMB in 2030 under the BaU scenario, with an average annual increase rate of 6.7%. After levying carbon tax of 120 USD, the GDP will be reduced to 105.3 trillion RMB (5% decrease) in year 2030, with an average annual GDP increase rate of 6.4%.

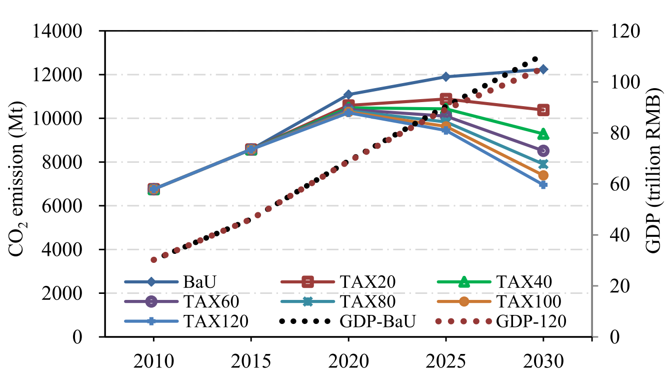

Fig. 1. Effects of carbon tax on China's industrial CO_2 emissions.

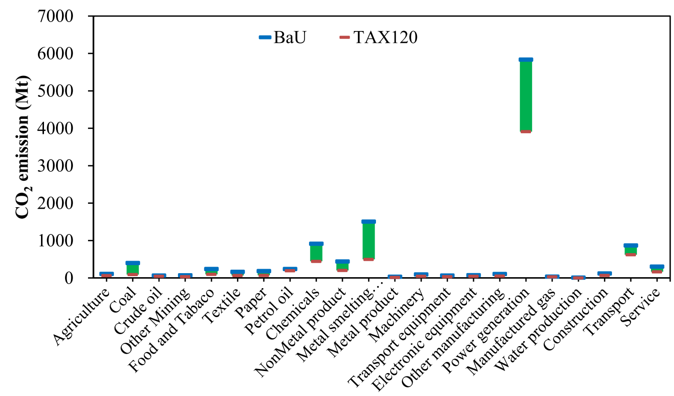

Fig. 2. Sectoral CO_2 reduction potentials under TAX120 scenario in 2030.

3.2. Estimation of CO_2 emissions from different sectors

Fig. 2 illustrates the sectoral differences of carbon reduction potential with the levy of carbon tax. Electricity production sector has both the highest carbon emissions and reduction potentials, with CO_2 emission reduced from 5.8 billion tons under the BaU scenario to 3.9 billion tons under the TAX120 scenario (1.9 billion tons reduction). Other high emission sectors include "Metal smelting & pressing" sector, "Chemical" sector and "Mining" sector. Their carbon reduction potentials will be 1.0 billion tons, 0.47 billion tons and 0.31 billion tons, respectively, under the TAX120 scenario in 2030. The aggregated carbon reductions of the top four sectors account for about 70% of the total carbon reduction.

3.3. Regional disparity of carbon emissions and reduction

Considering the imbalanced economic development and local resource endowment of different regions, regional disparity of carbon tax effect are investigated and demonstrated in Fig. 3. It is clear that CO_2 emissions and GDP values have a linear correlation, which means that provinces with higher GDP values have relatively higher CO_2 emissions. Therefore, Guangdong, Jiangsu and Shandong, the top three GDP value regions, have the largest carbon emissions with figures of 0.60 billion tons, 0.59 billion tons and 0.51 billion tons, respectively. However, GDP values are not the top factor for carbon reduction potentials caused by carbon tax. The top four provinces that have the largest carbon reduction potentials (size of the bubble) are Inner Mongolia, Shanxi, Shandong and Hebei, with values of 0.61 billion tons, 0.50 billion tons, 0.45 billion tons and 0.37 billion tons, respectively. The reason for the high reduction potential of Inner Mongolia, Shandong, Shanxi and Hebei may be that these four

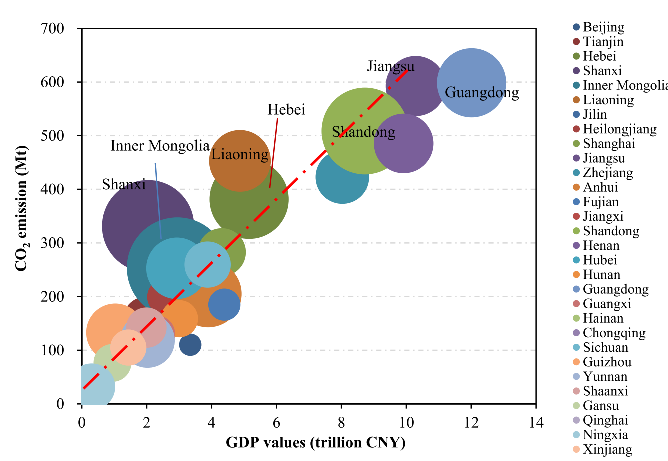

Fig. 3. Regional disparity of carbon tax effect on CO_2 emissions reduction under the TAX120 scenario in 2030 Note: The size of each bubble represents its carbon reduction.

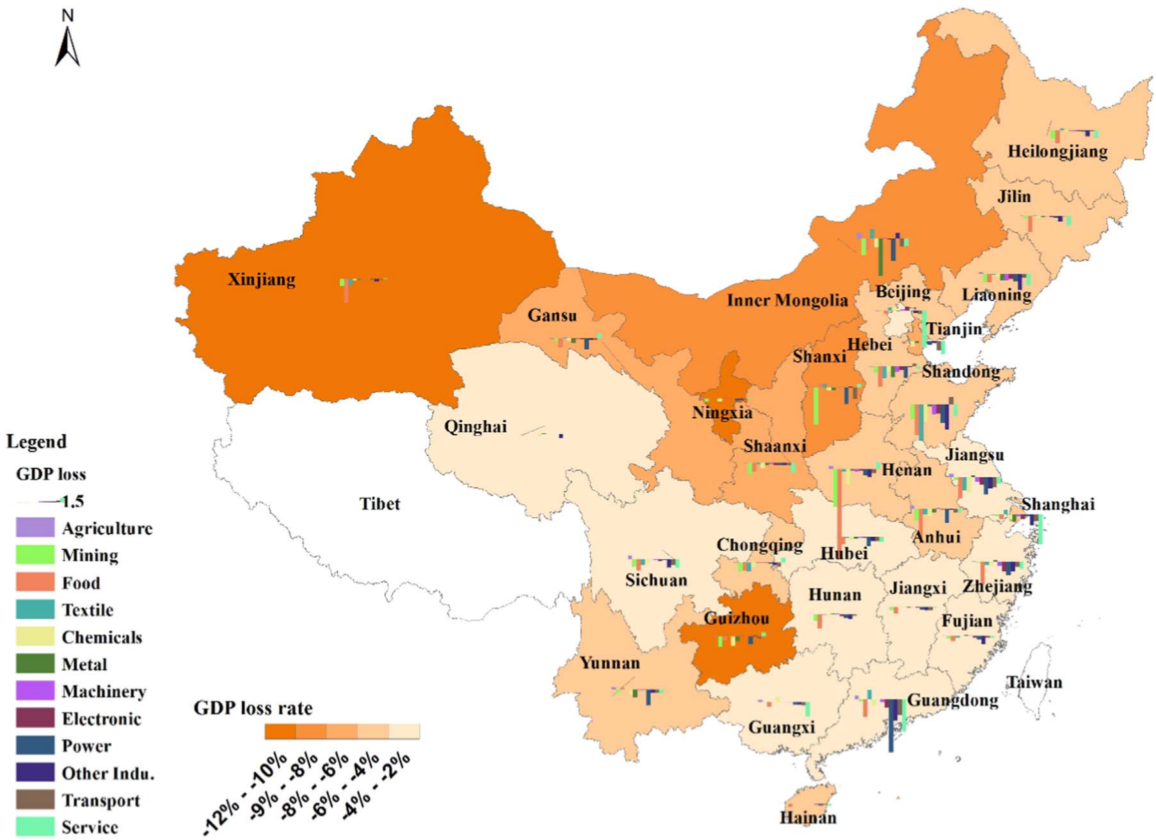

Fig. 4. Impact on GDP change by regions and sectors under TAX120 Scenario in 2030, Note: GDP loss rate is the ratio of absolute GDP loss (Δ*GDP*) to GDP of BaU scenario (GDP^0).

provinces are the regions that have the highest coal consumption. Moreover, Inner Mongolia and Shanxi are also China's two main coal production bases and have high coal ratio in their energy mix [2], and Shandong and Hebei have the top total energy consumption. Besides, Guangdong and Jiangsu also have relatively high reduction potentials because of their larger economic scales. In summary, economic scale is the key factor to affect CO_2 emissions, while coal production/consumption and total energy consumption are the most important factors that affect CO_2 reduction potential when levying carbon tax.

3.4. Impact of carbon tax on provincial economy

The impact of carbon tax on provincial economy is demonstrated in Fig. 4. It is clear that all provinces will suffer from GDP losses in 2030 under a carbon tax of 120 USD/ton CO_2. Developed eastern provinces such as Guangxi, Fujian, Zhejiang, Beijing and Jiangsu have less GDP loss rates, while less developed western provinces, particularly Ningxia, Guizhou, Xinjiang, Inner Mongolia, Shanxi and Gansu are the six provinces that have the largest GDP loss rates when levying carbon tax, although their absolute GDP loss values (bars in Fig. 4) are not so high. This demonstrates that although most less developed western regions will bear less absolute GDP losses, they will suffer from much higher GDP loss rates, namely their local economy and welfare will be more affected compared with developed eastern provinces.

The bars in different provinces further clarified the absolute economic impact (added value) and different industrial sector distributions. The economic impacts on different sectors for different provinces are quite different. Developed provinces such as Shandong, Henan, Guangdong, Jiangsu, and Inner Mongolia are the provinces to suffer from the largest absolute GDP losses. As for their sectoral distributions, sectors of Food, Mining and Chemical are the main sectors to suffer from GDP losses in *Henan*. Sectors of Electricity, Service and Food are the main sectors to suffer from GDP losses in *Guangdong*. Sectors of Food, Electricity and Chemical are main sectors to suffer from GDP losses in *Jiangsu*. Sectors of Metal and Electricity are main sectors to suffer from GDP losses in *Inner Mongolia*. With regard to *Shandong*, most of the industrial sectors will have obvious GDP losses, particularly for Textile, Food, Electricity and Mining sectors. However, one common phenomenon is that Food sector is often the dominant sector to suffer from GDP loss in most provinces, except Shanxi, Inner Mongolia, Beijing and Guangdong with *Coal mining*, *Metal smelting*, *Service* and *electricity production* as the dominant sectors for GDP loss, respectively. The reason for the GDP loss of food sector is that carbon tax will reduce income, thereby affecting consumers' expenditure, in which food is an important component. The reduction of expenditure on food will significantly affect the food demand, thus further resulting in the production decrease and GDP loss of food industry.

3.5. Impact of carbon tax on energy structure

Fig. 5 illustrates the impacts of carbon tax on energy structure, which shows the ratio changes of different fossil fuels. It is obvious that the ratio of coal in total energy mix will decrease for almost all provinces after levying carbon tax. The reason is mainly due to the fact that the carbon tax mechanism forces energy structure to shift from high carbon fossil fuels (such as coal) to low carbon fossil fuels (such as crude oil, natural gas and even renewable energy) to reduce the cost. Gansu, Sichuan, Qinghai, Jilin and Inner Mongolia will have the highest energy structure changes, with coal ratio reduced by 19.03%, 12.85%, 12.71%, 12.35% and 12.23%, respectively. Although natural gas has lower carbon content than crude oil, its high price limits its large-scale application. Therefore, the reduced coal was mainly replaced by crude oil for most provinces, particularly provinces with high economic scale, less-developed provinces and large

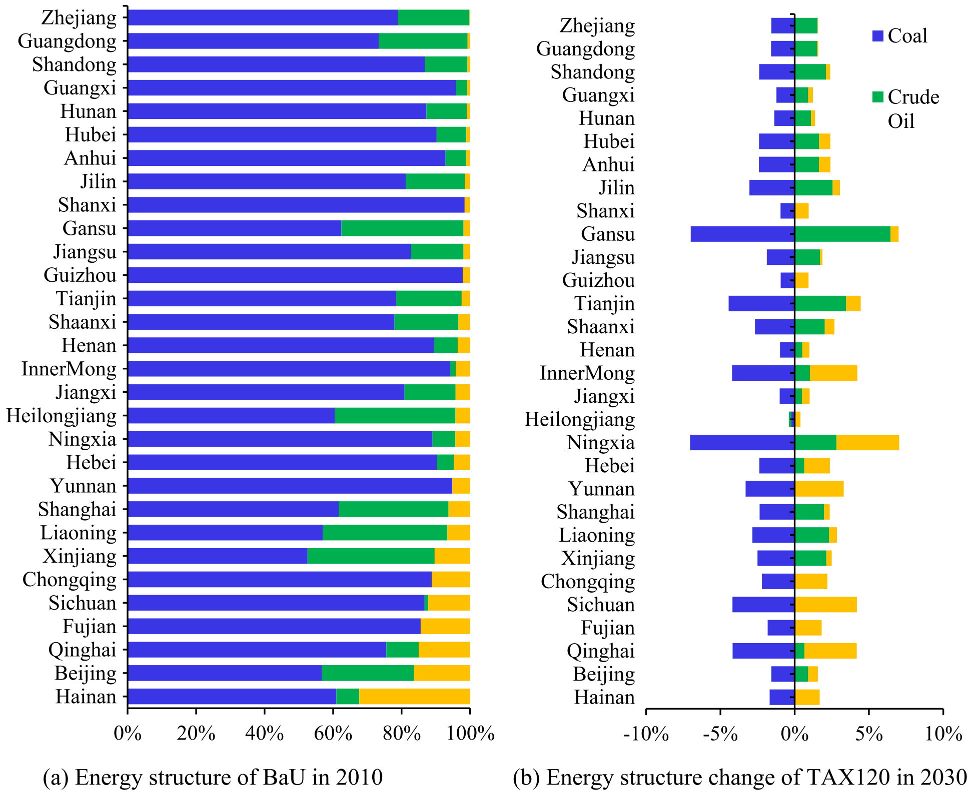

Fig. 5. Primary energy structure change under TAX120 scenario in 2030 (a) Energy structure of BaU in 2010 (b) Energy structure change of TAX120 in 2030.

industrial provinces, such as Gansu, Jilin, Shandong, Tianjin, Liaoning, Shaanxi, Xinjiang, Zhejiang, Guangdong and Jiangsu. With regard to Sichuan, Chongqing, Fujian, Hainan, Yunnan, Guizhou, Shanxi and Heilongjiang, they have relatively higher ratios of natural gas in existing energy structure and their coals will be replaced more by natural gas. The replace ratios of the top three provinces are 12.77%, 9.91% and 7.03% for Sichuan, Chongqing and Fujian, respectively. These regions locate mainly in southwestern China, and have common features of medium scale, economic-stable and non-industrial dominant. It should be noted that less developed small province Ningxia has significant energy structure change from coal to both crude oil and natural gas. In summary of the above features, economic scale, development level, industrial structure and current energy structure are main factors to influence their energy structure change pattern under the carbon tax mechanism.

4. Policy implications

4.1. Sensitivity analysis

Fig. 6 illustrates the sensitivity of CO_2 reduction and GDP loss to carbon tax, in which the regression equations have been fitted using excel. It is obvious that both CO_2 reduction and GDP loss experience increasing trends with the increase of carbon tax. However, their sensitivities to carbon tax are totally different. The relationship of carbon reduction with carbon tax can be expressed to be a polynomial equation, with correlation coefficient (R^2) being 0.9986. It demonstrates that with the increase of carbon tax, the sensitivity of carbon reduction becomes smaller. In terms of GDP loss, it exhibits a linear regression relationship with carbon tax (with the correlation coefficient (R^2) being 0.9999), particularly with the increase of carbon tax. This demonstrates that the sensitivity of GDP loss will keep stable.

4.2. Carbon tax efficiency

As defined in methodology part (Section 2), carbon tax efficiency is

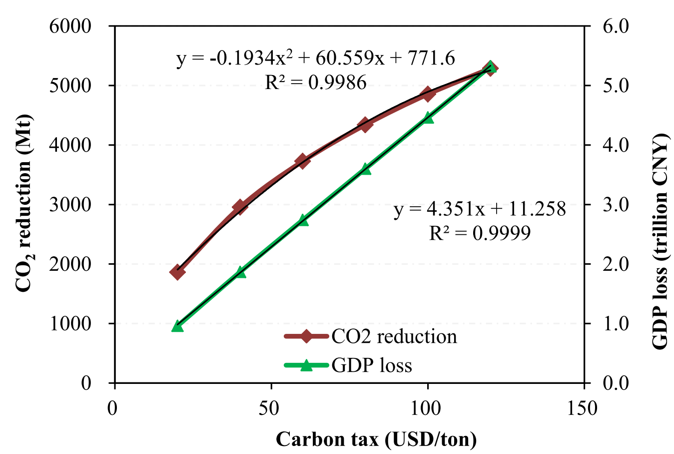

Fig. 6. Sensitivity analysis of CO_2 reduction and GDP loss under the levy of carbon tax.

the ratio of CO_2 reduction to GDP loss. It can reflect the impact of carbon tax on both carbon reduction and economic development at the same time, and therefore is suitable for evaluating the effectiveness of carbon tax. If such a value is negative, it means that carbon tax cannot only induce carbon reduction but also increase GDP, indicating a win-win situation of carbon reduction and economic development. If such a value is positive, it means that the carbon reduction can be achieved but economic development will be hindered. The bigger the positive value is, the more effective the carbon tax is, because more carbon reductions can be achieved with a less GDP loss.

The relationship between carbon tax efficiency and carbon tax for 30 Chinese provinces is demonstrated in Fig. 7. All the provinces can be classified into four types, namely special regions, high efficiency regions, medium efficiency regions and low efficiency regions. Ningxia, Inner Mongolia, Shanxi, Qinghai and Hubei are five special provinces and have the highest carbon tax efficiency, ranging from 40 to 69 under carbon tax of 20 USD/ton. By further considering that Inner Mongolia and Shanxi also

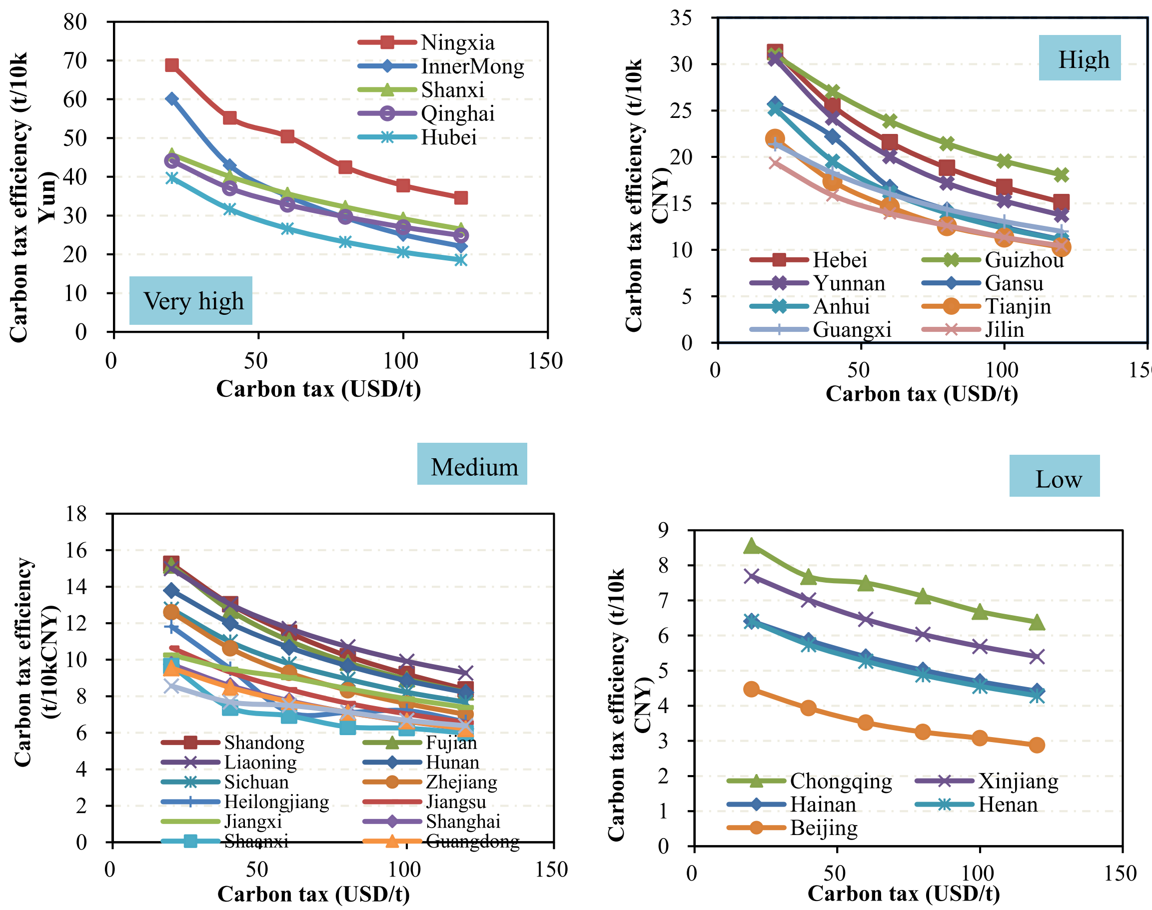

Fig. 7. Carbon tax efficiency of 30 Chinese Provinces in 2030.

have high reduction potentials while Ningxia, Qinghai and Hubei have very low reduction potentials, it is recommended that Inner Mongolia and Shanxi should be the top two priority provinces for implementing carbon tax. Hebei and Anhui also have high carbon tax efficiency and relatively higher carbon reduction potentials, and therefore should also be suggested as two priority provinces for implementing carbon tax.

Moreover, the carbon tax efficiencies are all positive and will decrease with the increase of carbon tax. Such results imply that all the provinces cannot achieve a win-win situation on carbon reduction and economic development. Lower carbon tax will lead to higher efficiency. Therefore, it is suggested that lower carbon price (less than 50 USD/ton) is better for other provinces. It can also be found that less developed western regions such as Ningxia, Qinghai, Guizhou, Gansu and Yunnan exhibit relatively higher carbon tax efficiency. However, results of Section 3.4 show that local economy and living standard of western provinces will be heavily affected after levying uniform carbon tax. Therefore, in order to solve this contradiction, it will be appropriate for China's central government to transfer more carbon taxes to western regions so that their welfare loss can be mitigated.

4.3. Research limitations

One limitation of this study is that power generation from non-fossil energy sources, which is a key low-carbon option, is not explicitly represented because of technical difficulties. Although both carbon tax and renewable energy power generation are enabled in the model, it seems that there are too many variables, and some variables related to renewable energy have very small values, leading to difficulty in finding optimal solution for this model. Consequently, this study may under-estimate carbon reduction in the power sector and overestimate the impacts of carbon tax on the macro-economy.

5. Conclusions and policy remarks

Carbon tax is a useful and prospective policy measure to mitigate China's carbon emissions. In order to examine its effect on China's industrial economy and CO_2 emissions, as well as identifying regional disparity, a novel CGE model covering 30 Chinese provinces was developed to evaluate the carbon tax effect on 30 provinces. The main conclusions and suggestions for China's carbon tax implementation include:

First, carbon tax can effectively reduce industrial carbon emissions after 2020 with the increasing carbon price. The industrial CO_2 will be reduced from 12.2 billion tons under BaU scenario to 10.4 billion tons, 9.3 billion tons, 8.5 billion tons, 7.9 billion tons, 7.4 billion tons and 7.0 billion tons in 2030 under scenarios of TAX20, TAX40, TAX60, TAX80, TAX100 and TAX120, respectively. Moreover, sectors of *Electricity*, *Metal smelting* and *Chemicals* are the three main sectors for CO_2 emission and reduction, and *should be the key sectors for implementing carbon tax policy* in China.

Second, significant regional disparity of carbon tax effect on carbon reduction exists. GDP is the top factor to affect regional CO_2 emission, while coal production/consumption and total energy consumption are the most important factors that affect CO_2 reduction potential when levying carbon tax. Therefore, *Inner Mongolia, Shandong, Shanxi and Hebei are the top four provinces to reduce China's industrial CO_2 emissions, coal production/consumption and total energy consumption.*

Third, all provinces will suffer from GDP losses after levying carbon tax. Developed eastern provinces such as Shandong, Henan, Guangdong and Jiangsu will suffer from the largest absolute GDP losses, while less developed western provinces such as Ningxia, Guizhou, Inner Mongolia, Xinjiang and Gansu will bear the most welfare losses. Moreover, energy structure will change significantly from coal to crude oil or natural gas, particularly in Gansu, Sichuan, Qinghai, Jilin and Inner Mongolia.

Finally, carbon tax sensitivity and carbon tax efficiency are investigated and discussed in order to provide appropriate carbon tax policies. Research results indicate that provinces of *Shanxi, Inner Mongolia, Hebei and Anhui should be set top priority for implementing carbon tax policy in China***.** However, carbon price should be set as less than 50 USD/ton. Moreover, in order to solve the problem that higher carbon tax efficiency may lead to more GDP loss and welfare loss, it is suggested that *the revenue from carbon tax should be reallocated and transferred more to western regions to balance their welfare losses***.**

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.04.044.

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