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Regional impacts of launching national carbon emissions trading market: A case study of Shanghai

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HIGHLIGHTS

- Initiating national carbon trading could help achieve China's INDC target.
- We investigate changes in carbon prices and carbon trading volumes under different carbon trading scenarios.
- Revenues generated through a national carbon trading program could offset macroeconomic losses.
- Sectoral output losses will decrease substantially under ETreg scenario relative to BaU scenario.

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ABSTRACT

This study investigates the impacts of launching a national carbon trade market through the IMED|CGE (Integrated Model of Energy, Environment and Economy for Sustainable Development|Computable General Equilibrium) model, between Shanghai and the Rest of China (ROC). Five scenarios are established by considering China's Nationally Determined Contributions (NDC) targets, including a baseline scenario (BaU scenario), a carbon cap on ETS participating sectors scenario (CAPsec scenario), a carbon cap on Shanghai and ROC regions scenario (CAPreg scenario), a carbon cap scenario with local carbon emissions trading among ETS participating sectors (ETsec scenario) and a carbon cap scenario with inter-regional carbon emissions trading (ETreg scenario). The results under the ETreg scenario predict a carbon price of 164.64 USD/tCO_2 and a total carbon trade volume of 189.91 Mt by 2030. The metal smelting sector will be the largest seller of emissions quotas in Shanghai, whereas the power generation sector will be the largest buyer. Due to its higher carbon mitigation cost and increasing autonomous carbon intensity, the aviation sector will face more challenges to reduce emissions among ETS participating sectors in Shanghai. The results indicate that launching a national carbon trade market could generate both economic and environmental benefits and help China achieve its NDC targets.

1. Introduction

Human-induced climate change is disrupting the health [1] and functions of ecological systems [2,3] and destabilizing social and economic systems [4–7]. Adoption of the Paris Climate Change Agreement symbolizes an international commitment to keep global average temperature rise below 2 °C, a target to avoid severe shocks to our social and economic systems [5]. To achieve this 2 °C target, the Paris agreement commits countries to reduce carbon intensity by 40–70% by the year 2050 – using 2010 levels as a standard – and to reach near-zero emissions by the end of this century [8].

As the largest carbon emitter in absolute terms, China is a critical

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signatory to this agreement. As a developing country with a population of more than 1.3 billion people, the Chinese policy leaders will be challenged to meet China's commitments while balancing rapid industrialization and urbanization. The social and economic ramifications of the required policy changes will have domestic and global implications [9]. Therefore, China's approach to meet carbon reduction targets must minimize social and economic instability.

As part of the Paris Agreement, countries put forth Nationally Determined Contributions (NDCs). China's NDCs commit to peaking carbon dioxide emissions by the year 2030 and lower its carbon dioxide emissions per unit of GDP by 60% to 65% relative to 2005 levels. Additionally, China plans to increase the share of non-fossil fuels in primary energy consumption to 20% [9].

To achieve NDC targets effectively and efficiently, China's policymakers initiated seven ETS pilots. The combined pilots account for 1.2 billion tons of CO_2 from various sectors, exceeding any other ETS pilots in the world except for the European Union's (EU) [10,11]. By establishing regional ETS pilots, including Shenzhen, Beijing, Shanghai, Guangdong, Tianjin, Hubei and Chongqing, China aimed to collect experiences and lessons for initiating a national ETS, which was implemented in 2017. Many researchers have explored not only the mechanisms of China's regional ETS pilots, but also the macroeconomic effects and environmental contributions the ETS pilots would generate. For instance, Zhao et al. [12] evaluated the efficiency of China's ETS pilots based on carbon price, trading volume, market liquidity, and information transparency. Liu et al. [13] investigated mechanisms, policy regulations and other potential obstacles hindering ETS development. Li et al. [14] explored carbon price benchmark scenarios to avoid macroeconomic destabilization. Zhang et al. [15] reviewed China's seven ETS pilots to identify theoretical and practical market mechanism challenges. In addition, several studies investigated the macroeconomic and environmental impacts of the ETS pilots. For example, Chang et al. [16], Lund [17] and Wang et al. [18] proposed carbon trade mechanisms and policies to realize both emissions reduction targets and sustainable economic development. Zhang et al. [19] assessed whether launching regional ETSs could accelerate achieving carbon emissions intensity reduction targets during 12th Five-Year Plan. Lo [20] mentioned that the pilot ETSs had been designed to prioritize economic objectives as opposed to environmental commitments. In fact, China's regional ETS pilots are confronting the dilemma that the initiatory systems contribute to problems such as carbon market failure, sluggish regulations and non-uniform emissions quota allocation [12,13].

Appling integrated assessment techniques would fill gaps in current assessments of ETS pilots and provide valuable experiences to inform China's national ETS system. Numerous studies have investigated the mechanisms and criteria of already established ETS systems in developed countries, mainly in the EU and US. Officially, EU commission rectified and modulated existing ETS mechanisms to stabilize carbon prices against macroeconomic volatility [21–23], to support climate change goals and expansion of the carbon market [24]. Salant [25], Mattoo et al. [26] and Calel et al. [27] testified that EU's ETS, the first-established and largest emission trade scheme [28], is better able to minimize the cost of capping carbon emissions and need for government intervention. Conversely, Jia et al. [29] asserted that carbon markets are vulnerable to interference based on their susceptibility as man-made markets. Gavard et al. [30] utilized a global economic model to analyze the impacts of limited carbon trade within an ETS to show the effects of limited carbon trading between EU or US and China. Shen et al. [31], Gavard [32] and Zuckerman et al. [33] reviewed differences between California's scheme and China's ETS pilots from multiple perspectives to indicate the carbon market would ultimately reach Pareto efficiency through spontaneous adjustment. Xiong et al. [34] compared the allowance mechanisms of China's ETS pilots with the EU's ETS and California's Cap-and-Trade Program to identify lessons supporting the development of national ETS. Finally, Zhang et al. [35] concluded that a multi-regional integrated ETS between China, U.S., Europe, Australia, Japan and South Korea could optimize the allocation of emissions, yield economic welfare gains for permit importing countries, and facilitate the development of clean energy in China.

Previous studies on China's regional ETS pilots have only focused on local emissions trading, and fail to investigate the macroeconomic and environmental effects at provincial and national levels. China is in a transition phase between local emissions trading and inter-regional emissions trading, and its national carbon trade market was approved at the end of 2017. To support the introduction of the inter-regional emissions trading, it is essential that policymakers understand the economic impacts of inter-regional emissions trading and impact on carbon emissions reduction targets. Under such a circumstance, this paper introduces the macroeconomic indicators with time-delay, such as inter-temporal saving and investment, to the multi-sector, multi-region, recursive- dynamic computable general equilibrium model (CGE) to transform the exogenous variables into the endogenous variables, thus restricting the predicted values of the economic variables that fluctuates with time and increasing micro-level behavior mechanisms. Therefore, the CGE model constructed in this paper is more accurate than previous methods to study the environmental and macroeconomic impacts under differently prefixed policy scenaerios. Consequently, the aim of this paper is to quantify the impacts of carbon emissions trading and macroeconomic effects on Shanghai and the rest of China (ROC) to help China achieve NDC targets with minimal economic and social disruptions. The following three questions are raised and will be answered in this study:

- What will the carbon reduction differences be between carbon trade prices and carbon abatement costs?
- What will carbon trade, trade volumes and trade values be under the following two scenarios; 1) local emissions trade among local ETS participating sectors (ETsec scenario) and, 2) inter-regional emissions trade between Shanghai and the rest of China?
- What will the effects of inter-regional emissions trading on GDP and sectoral outputs of Shanghai and the rest of China be?

The paper is organized as follows. After this introduction section, we explain the CGE model, scenarios setting and data sources in Section 2. Then we present the simulation results in Section 3, including the potential impacts of a national ETS on carbon emissions intensity, total carbon emissions, carbon market, macroeconomic indicators and sectoral outputs on Shanghai and ROC, respectively. Next we compare our results with other similar studies and discuss the policy implications on Shanghai and ROC, as well as the mechanisms of China's national ETS in Section 4. Finally, we conclude by making recommendations to inform a national ETS for China in Section 5.

2. Methods and data

2.1. The IMED|CGE model

The CGE model could capture the full range of interaction and feedback effects between different agents in the economic system. It has been widely used to assess the economic and environmental impacts of different climate policies at global [36–38] and national [39,40] levels.

The IMED|CGE (Integrated Model of Energy, Environment and Economy for Sustainable Development|Computable General Equilibrium) model applied in this study is a two-region dynamic CGE model that includes shanghai and ROC based on the provincial CGE model developed by Dai [41]. It can be classified as a multi-sector, multi-region, recursive dynamic CGE model that covers 37 economic commodities and corresponding sectors, which are classified into basic and energy transformation sectors demonstrated in Table A1. This CGE model is built using the Mathematical Programming System for General Equilibrium under General Algebraic Modeling System (GAMS/MPSGE)

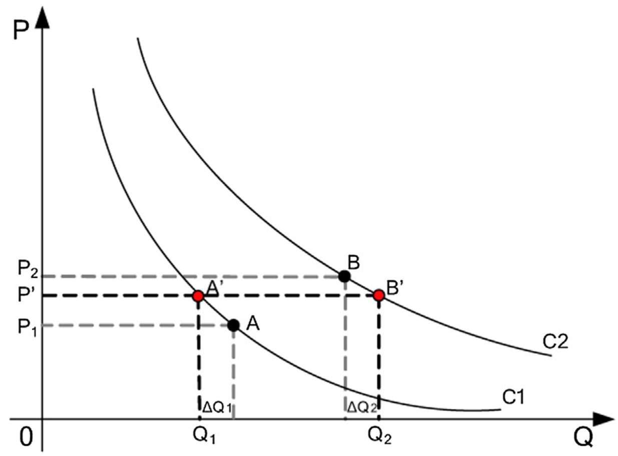

Fig. 1. Mechanism of carbon emission trade between sectors.

at a one-year time step [42]. It has been used widely for assessing China's climate mitigation strategies at the national [43–45] and provincial levels [18,41,46–51].

Major model features are similar to the one-region version [41], including a production block, a market block with domestic and international transactions, as well as government and household incomes and expenditures 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. Technical descriptions are provided in the Appendix and an up-to-date introduction to the model could be found at: http://scholar.pku.edu.cn/hanchengdai/imedcge.

For the purpose of this study, a carbon emission trade module at the sectoral level is added to the CGE model [18,47,52]. As Fig. 1 illustrates, C1 and C2 are the demand curves of carbon emission rights for sectors 1 and 2 when emission allowances Q1 and Q2 are allocated to each sector (or region) without carbon trade. The CGE model determines equilibrium points, A and B, with carbon shadow prices of P1 and P2 (P1 < P2) for sectors 1 and 2, respectively. By contrast, when free carbon trade is allowed, an identical carbon trade market will be established. Sector (or region) 1 tends to sell Q1 unit of carbon emission rights to the market while sector (or region) 2 tends to purchase Q2 unit of carbon emission rights from the market. The CGE model will find a new equilibrium point, A' and B', with identical carbon shadow price of P' that clears the carbon market by satisfying the conditions in Eqs. (1) and (2).

Carbon selling amount equals to purchasing amount, which is shown in Eq. (1):

$$\Delta Q_1 = \Delta Q_2 \tag{1}$$

Expenditure of buyers equals to revenue of sellers, which is shown in Eq. (1)

$$\Delta Q_1 P' = \Delta Q_2 P' \tag{2}$$

Correspondingly, when more sectors participate in carbon emission trade, the above conditions will keep as shown in Eqs. (3) and (4).

$$\sum_{s} \Delta Q_s = \sum_{b} \Delta Q_b \tag{3}$$

$$\sum_{s} \Delta Q_s P' = \sum_{b} \Delta Q_b P' \tag{4}$$

Where s and b represent seller and buyer (either a sector or a region) in the carbon trade market, respectively; Q represents carbon trade volume in tons; P represents carbon shadow price.

2.2. Shanghai's emissions trade scheme

Shanghai, as one of the most advanced mega-cities in China, is the economic, trade, financial and shipping center of China, as well as the leading city of the Yangtze River economic belt. Although its population accounted for only 1.7% of the national total in 2016, it consumed 1.2% of China's coal, 6.4% of petroleum, and 4.0% of natural gas, respectively. Because coal still occupies a major proportion in its energy structure, especially as the primary energy, Shanghai becomes China's largest CO_2 emitter at the city level, with a relatively high carbon abatement cost. Furthermore, the Chinese central government placed the national carbon trading platform and settlement system in Shanghai in 2017 and approved Shanghai as the national carbon trading center due to its superior financial environment and all the participated enterprises perfectly comply with the quota limits for four consecutive years. Shanghai's ETS applies to enterprises with CO_2 emissions over 20,000 tons for industrial enterprises and 10,000 tons for non-industrial enterprises. Small-scale enterprises are excluded. However, since both large and small-scale enterprises are included within one sector, almost all the emissions from participating sectors are covered in this model, only sectors of ports, hotels, malls and financial intermediation are excluded from ETS. The carbon emissions of ports, hotels, malls and financial intermediation are negligible comparing with other sectors investigated in this study so that they could be ignored without drastic emission changes. Generally, Shanghai's ETS includes 10 industrial sectors and 2 transport sectors (Table A1). In addition, this model only accounts for energy combustion related CO_2 emissions.

2.3. Scenario setting

Five scenarios are designed in this study to verify and quantify the different economic and environmental impacts on Shanghai and ROC.

The BaU scenario refers to maintaining business as usual, without carbon emissions cap and carbon emissions trade. The remaining four scenarios are divided into two categories, one is whether to permit carbon emissions trade, and the other is whether carbon emissions trade occurs within local or inter-regional emissions trade markets. The first category is to simulate the possible environmental and economic impacts when only emissions constraints policies are implemented, but without carbon emissions trade, including the CAPsec scenario which needs to set different carbon emissions constraints for each ETS participating sector, and the CAPreg scenario which implements the whole cap for Shanghai and the ROC to stimulate how many carbon emissions can be reduced with the lowest costs. The other category permits carbon emissions trade, including the ETsec scenario, which is corresponding to the CAPsec scenario and to determine the impacts of originating local emissions trade among ETS participating sectors inside Shanghai and the ROC, and the ETreg scenario, which is corresponding to the CAPreg scenario and to verify the impacts of launching inter-regional emissions trade. Detailed description is provided in Table 1 and Table A2.

2.4. Data sources

Data for this study come from different sources due to their complexity. The key sources include the input-output tables of Shanghai and China [53,54], energy balance tables [55,56], carbon emission factors of different fossil fuels [57]. Energy prices of coal, oil and gas for the year of 2007 are used in this model [55,56].

3. Results

3.1. Carbon emissions and intensity

As depicted in Fig. 2, the total carbon emission of Shanghai in 2030 will reach 590.35 Mt under the BaU scenario, 207% above the 2007

Table 1
Key indicators for five designated scenarios of Shanghai and ROC.

Scenarios	Indicators: 2007–2030	Emissions constraints	Emissions trading
BaU	Investment growth rate per year: 15.02% in Shanghai and 14.19% in ROC Annual Population growth rate: 1.00% in Shanghai and 0.52% in ROC Annual energy efficiency improvement of Solid fuel: 2.3%, liquid fuel: 1.5%, gaseous fuel: 1%, electricity: 0.5%	No emission constraints	Not allowed
CAPsec	Same as BaU	See Table A2	Not allowed
CAPreg	Same as BaU	Achieving China's INDC target	Not allowed
ETsec	Same as BaU	Same as CAPreg scenario	Only allowed intra-regional emissions trading among ETS participating sectors inside Shanghai or ROC
ETreg	Same as BaU	Same as CAPreg scenario	Allowed inter-regional emissions trading

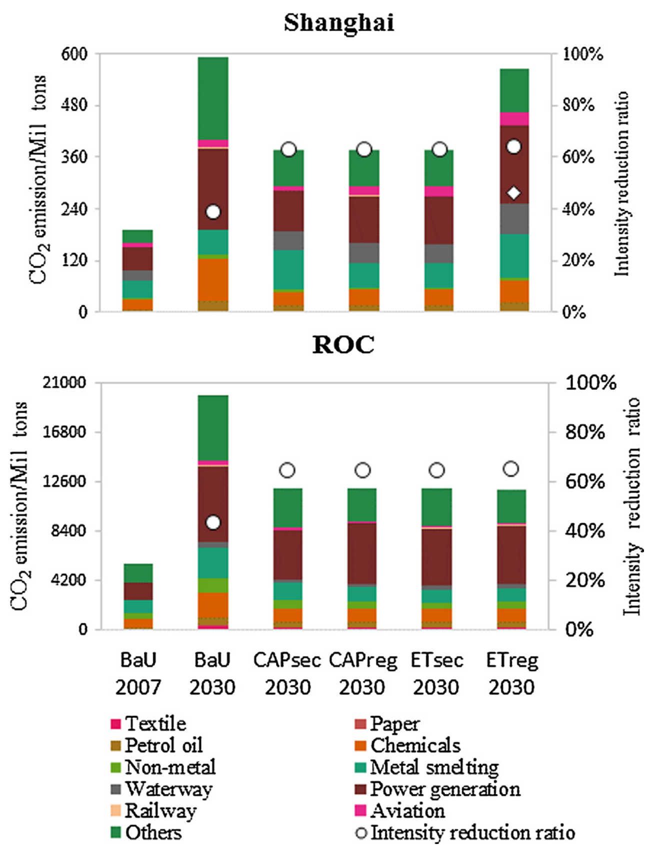

Fig. 2. Sectoral CO_2 emission and carbon intensity in Shanghai and ROC (○ represents reduction ratio of actual carbon emissions intensity, ◊ represents reduction ratio of apparent carbon emissions intensity under ETreg scenario).

level. When enacting a carbon emissions cap on different sectors in Shanghai (under the CAPsec scenario) or the whole region of Shanghai (under the CAPreg scenario), projected carbon emissions will be 62% lower than the BaU scenario in 2030. When comparing the emission trade scenarios (ETreg and ETsec), Shanghai's emissions will increase by 189.91 Mt by the year 2030 under a national emissions scheme (ETreg scenario), offset by a corresponding decrease in the ROC. Inter-regional carbon trade would enable Shanghai, which has higher emission mitigation costs to purchase carbon emission quotas from ROC, to reduce the overall costs of achieving China's NDC target. Further detailed investigation of trade volume of carbon market will be demonstrated in Section 3.2. In addition, once the national carbon trade market is established, total carbon emission of the ROC will be 11899.42 Mt in 2030, decreased by 189.91 Mt carbon emission relative to that under the ETsec scenario.

Furthermore, to verify whether achieving China's NDC target to lower carbon dioxide emissions per unit of GDP by 60% to 65% relative to the 2005 level by 2030 or not, we calculate intensity reduction ratio for Shanghai and ROC under the five study scenarios in 2030 compared with the 2007 level, which the results are exhibited in Fig. 2. Under the BaU scenario, the NDC target will not be achieved in Shanghai. When capping carbon emissions on different sectors or directly on the whole region of Shanghai (CAPsec and CAPreg scenarios), carbon emissions intensity will decrease by 62.8% and 63.1% compared to 2007, respectively. Specifically, launching national ETS (ETreg scenario) generates negative effects on performing NDC target of Shanghai, which can only achieve emission intensity reduction objective by 46.15% in 2030 in contrast to the 2007 level. The reason is that when national carbon trade market is established, Shanghai will become a buyer to purchase the cheaper emissions quotas from the ROC. Therefore, the apparent carbon emissions, rather than actual carbon emissions, are incorporated into the accounting system. However, the purchased amount of Shanghai will not be accounted as its emissions due to the corresponding costs when judging whether the NDC target is achieved or not. Simultaneously, carbon emission intensity of ROC under the ETreg scenario will decrease by 65.39%, indicating accomplishing NDC target and implementing national ETS could attain the greatest carbon emissions intensity abatement target.

Through further investigation into sectoral carbon emissions in Shanghai, sectoral emissions under the ETreg scenario are higher than those under the ETsec scenario. The reason is that when launching national carbon trade, Shanghai will purchase the lower-priced emissions quotas from ROC to decrease its emissions reduction expenses, leading to increasing sectoral carbon emissions. Furthermore, the total emissions of power generation (31.9%), metal smelting (17.7%), waterway (12.7%) and chemicals (9.4%) sectors account for over 71% of total carbon emissions in Shanghai under the ETreg scenario in 2030. Aviation and petrol oil sectors account for 5.2% and 3.5%, respectively, and the total emissions of other sectors only account for approximately 18%. Compared with the ETsec scenario, carbon emissions of power generation and metal smelting sectors will increase by 68.34 and 42.36 Mt under the ETreg scenario respectively, dominating the increments of carbon emissions between these two scenarios. In addition, the emissions shares of metal smelting and waterway sectors will increase at the maximum level among ETS participating sectors in Shanghai under the ETreg scenario, by 73.3% and 69.6% respectively. Simultaneously, the emissions shares of each ETS participating sector in Shanghai under the ETreg scenario increase by more than 20% relative to the ETsec scenario, except the textile sector (only increasing by 18.3%).

3.2. Impacts on the carbon market

As shown in Fig. 3, each ETS participating sector capped by the government needs to undertake distinct carbon abatement costs, which are endogenously generated by the CGE framework with regard to the total factor productivity, cumulative capital, effective labor and technology. Sectoral carbon abatement costs are equivalent to the marginal

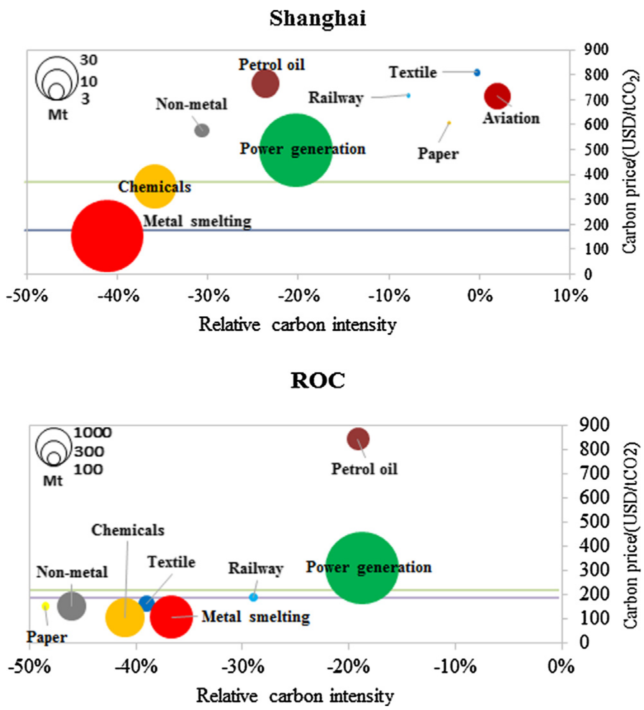

Fig. 3. Carbon intensity reduction ratio under BaU scenario (x-axis), carbon prices (y-axis) and sectoral carbon emissions in 2030 (Bubble size represents sectoral carbon emissions under CAPsec scenario, the green lines are carbon trade prices under ETsec scenario, and the blue lines are carbon trade prices under ETreg scenario).

costs of constraints to accomplish the carbon emissions reduction quotas assumed by participating sectors under the CAPsec scenario. Therefore, the distribution of carbon abatement costs among these sectors is unequal. In Shanghai, textile and petrol oil sectors will undertake the highest carbon abatement costs of 809 and 765 USD/tCO_2 in 2030, respectively. Conversely, metal smelting and chemicals sectors will bear the lowest carbon abatement costs, with figures of 155 and 353 USD/tCO_2, respectively, which denotes that these two sectors could achieve carbon emissions reduction targets relatively easily. Generally, the average carbon abatement cost of Shanghai is higher than that of ROC, and carbon abatement costs of the entire ETS participating sectors (except petrol oil sector) surpass those of ROC, which manifests that it will be more difficult for Shanghai to complete its carbon emissions reduction targets than the ROC without carbon emissions trading. The difference in carbon abatement costs of textile sector between Shanghai and the ROC is more prominent than others, reaching 645 USD/tCO_2. Furthermore, metal smelting and chemicals sectors still face the lowest carbon abatement cost of 108 USD/tCO_2 in the ROC. Conversely, petrol oil sector undertakes an extremely high carbon abatement cost of 843 USD/tCO_2.

As pointed out by Wu et al. [52], sectoral abatement costs are determined by not only the endogenous factors but also the exogenous elements. The endogenous factors of sectoral carbon emissions reduction are largely attributed to industrial internal properties, such as capital stock, labor cost, energy cost and technology. The exogenous elements are based on supply and demand of carbon emissions quotas. If demanded carbon emissions quotas exceed available quotas, the overall carbon price will rise until a new equilibrium is reached. However, if supplied carbon emissions quotas exceed demanded quotas, sectoral carbon prices will be zero due to the circumstance that they no longer need to undertake any carbon emissions reduction obligations. Since each ETS participating sector is presumed to reduce its carbon emission by the identical reduction ratio relative to the BaU scenario, the exogenous elements are fixed and sectoral carbon abatement costs are determined mainly by those endogenous factors. In Shanghai, the possible carbon intensity reduction ratios without any policy interventions under the BaU scenario are relatively higher for the metal smelting and chemicals sectors. The respective sectors can achieve emissions reduction obligations at lower costs and could realize large emission reductions by substituting intensive energy sources, improving energy utilization efficiencies, and applying energy-efficient technologies. Conversely, the possible carbon intensity reduction ratios under the BaU scenario for the textile and paper sectors are extremely low, indicating it will be more difficult for these sectors to meet the reduction obligations. Particularly, the carbon intensity of aviation sector will increase in 2030 in contrast to the 2007 level without any policy interventions, owing to the fact that this sector heavily relies on traditional energy (especially fossil fuels based energy) and it is hard to find alternative energy sources to substitute primary energy. Therefore, the marginal cost of carbon emission reduction for the aviation sector is relatively higher. This will lead this sector to undertake the heaviest carbon emission reduction burden among all the ETS participating sectors in Shanghai. Furthermore, the possible carbon intensity reduction ratios for most sectors in the ROC under the BaU scenario are higher than those of corresponding sectors in Shanghai, illustrating that carbon emissions reduction targets in the ROC can be easily achieved. Especially, paper and non-metal sectors in the ROC will receive the lowest carbon intensity reduction ratios and therefore can easily reduce their sectoral emissions.

Carbon emissions from power generation, chemicals and metal smelting sectors accounted for the majority of Shanghai's total carbon emissions. Thus, carbon abatement costs from these three sectors would be the majority of the total carbon abatement cost.

When initiating local emissions trade among the ETS participating sectors within Shanghai (under the ETsec scenario), the carbon price is close to the carbon abatement cost of chemicals sector (see Fig. 3). Most sectors will, therefore, be buyers, excluding the metal smelting sector which has a very low carbon abatement cost. Once national emissions trade market is established (under the ETreg scenario), the carbon price is predicted to be about half the price of that under the ETsec scenario because participating sectors in the Shanghai region have higher abatement costs than those in the ROC. A national carbon trade will mitigate the price disparity between Shanghai and the ROC.

Under the ETsec scenario, when local emissions trade is initiated in Shanghai, carbon prices will vary among all the ETS participating sectors, depending on distinct carbon abatement costs. Sectoral positions (seller or buyer) in the carbon trade market will be determined by the variance between intrinsic abatement costs relative to prevailing carbon trade prices. This price variance will be maintained until the carbon prices are identical among all the ETS participating sectors to attain the equilibrium price in the CGE model, which is 344 USD/tCO_2 in Shanghai shown in Fig. 3, higher than the equilibrium price in the ROC with 194 USD/tCO_2. Shown in Fig. 4, total trade volume in Shanghai will be 15.9 and 34.0 Mt in 2020 and 2030 respectively, with a double increase by 2030 than the level of 2020 under the ETsec scenario. Apparently, metal smelting, power generation and aviation sectors will be the most active sectors in the carbon market, no matter they are in Shanghai or in the ROC. In Shanghai, the majority of the ETS participating sectors would be buyers based on relatively higher marginal carbon abatement costs. Power generation and aviation sectors are the two biggest buyers, which will purchase 11.8 and 11.7 Mt CO_2 respectively in 2030, 75% of the total purchase volume. Inversely, the metal smelting sector with the lowest abatements costs will be the largest seller, with a figure of 33.8 Mt CO_2 by 2030, accounting for 99% of total sale volume. Simultaneously, in the ROC, the biggest buyer and seller are power generation sector (695.1 Mt) and metal smelting sector (324.9 Mt), respectively.

Under the ETsec scenario, total carbon trade volume of Shanghai will be 34.0 Mt in 2030, accounted for 9.1% of total carbon emissions, and monetary trade value will represent 1.4% of its GDP (Fig. 5).

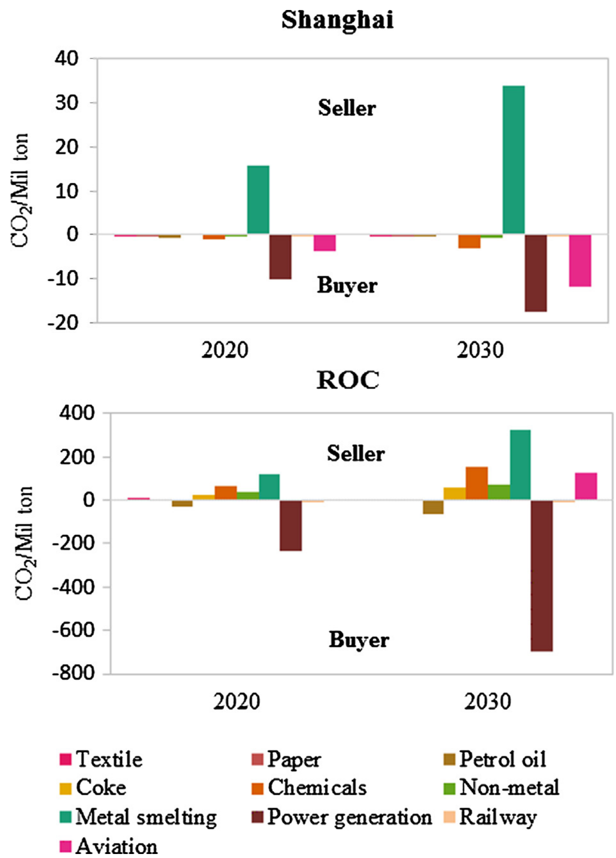

Fig. 4. Trading volume of carbon market in Shanghai and ROC in 2020 and 2030.

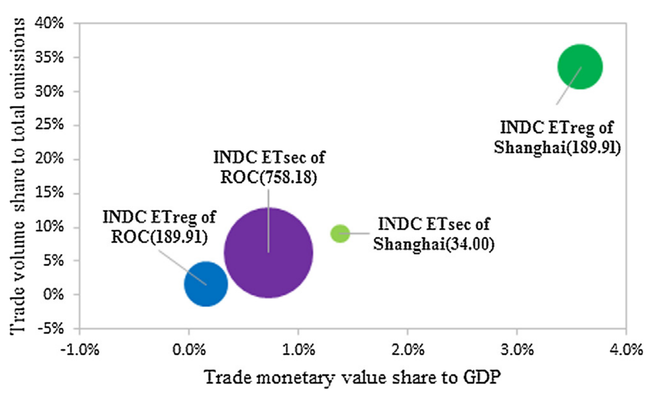

Fig. 5. Carbon trade monetary value share to GDP versus carbon trade volume share to total emissions in 2030 (Bubble size represents total carbon trade volume).

Although there is an enormous disparity of scope and magnitude of carbon trade markets between Shanghai and the ROC when local emissions trade among sectors prevails, both trade volume and trade monetary value of the ROC are lower than those of Shanghai. Once the inter-regional emissions trade system is launched, carbon trade volume of Shanghai will increase to 189.9 Mt in 2030, far more than the volume of Shanghai under the ETsec scenario, accompanying by trading volume share to total emissions and trade monetary value share to GDP increasing to 33.6% and 3.6%, respectively. Additionally, on the basis of the enormous disparity mentioned above, trade volume share to total emissions (1.6%) and trade monetary value share to GDP (0.2%) of ROC are significantly lower than those of Shanghai.

3.3. Macroeconomic impacts

Implementing carbon constraint policies or launching a carbon trade market will decrease the GDP in Shanghai and the ROC compared with the baseline scenario. In general, the predicted GDP loss for Shanghai will be higher than that for the ROC in 2030 under all the scenarios, demonstrating that scientific and technological levels and economic prosperity of Shanghai substantially surpass those of the ROC. As the wealthiest and most advanced mega-city in China, marginal carbon emissions abatement cost of Shanghai is relatively higher. Moreover, the GDP losses for Shanghai will be lower under the carbon emissions trade scenarios (including both the ETsec and the ETreg scenarios) than those under the carbon constraint scenarios (including both the CAPsec and the CAPreg scenarios), which indicates that carbon emissions trade can offset the higher carbon abatement costs and better allocate scarce resources to corresponding sectors. Therefore, the social costs caused by carbon emissions are properly and explicitly investigated, thus internalizing the external effect of carbon emissions. Moreover, when initiating an inter-regional emissions trade market, the GDP loss of Shanghai under the ETreg scenario will be −2.8% in 2030, lower than that of Shanghai under the ETsec scenario (−5.2%), indicating that Shanghai can purchase surplus carbon emissions quotas from the ROC to cut its emissions reduction expenses and to undertake fewer carbon emissions reduction obligations relative to the previous scenario with local emissions trade. Such a purchase can partially offset the GDP loss for achieving its NDC targets (Fig. 6). Therefore, Shanghai can produce the more composite commodities, expand its production scales, increase its investment share and further improve the local residential welfare.

Furthermore, the GDP loss of the ROC under the ETreg scenario will be higher than that of ROC under the CAPreg scenario (Fig. 6), indicating that the ROC is a seller in the national carbon trade market. This may increase the future mitigation burdens for the ROC to achieve their NDCs and be transferred to undertake part of emissions reduction obligations in Shanghai. However, for China as a whole, establishing a national carbon emissions trade market described under the ETreg scenario is the best option to minimize the overall GDP losses when compared to other scenarios.

3.4. Sectoral outputs

When implementing carbon constraint policies or launching a carbon trade market, the total output will decrease in both Shanghai and the ROC relative to the BaU scenario, with the distinct loss rates. As demonstrated in Fig. 7, when setting carbon emissions caps on each ETS participant sector in Shanghai (the CAPsec scenario), the total output will decrease by 524.0 MilUSD relative to the BaU scenario, with a 17.4% decrease in 2030. Moreover, all the sectoral outputs will decrease relative to the baseline scenario except the food production sector. The metal smelting sector (−184.2 MilUSD) and chemicals sector (−121.2 MilUSD) will have the heaviest output losses, followed

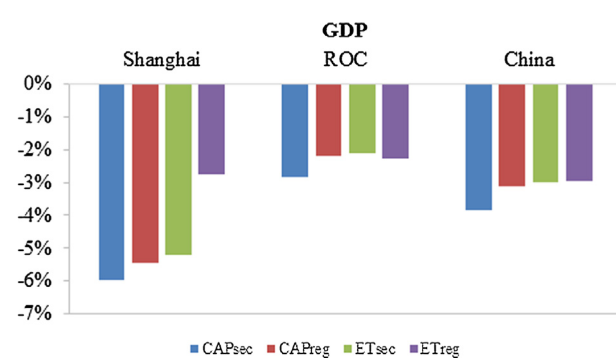

Fig. 6. Macroeconomic impacts on GDP relative to the BaU scenario in 2030.

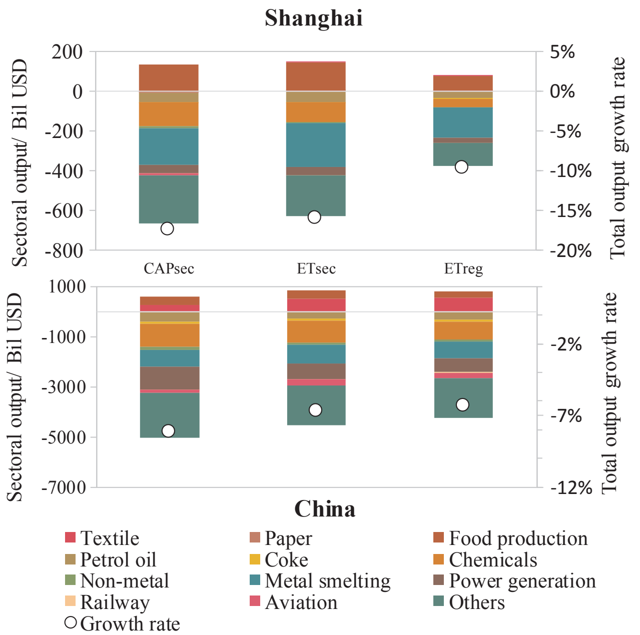

Fig. 7. Changes of sectoral output under CAPsec, ETsec and ETreg scenarios relative to the BaU scenario in 2030.

by the petrol oil sector (−51.0 MilUSD) and the power generation sector (−44.8 MilUSD) in Shanghai by 2030. On the contrary, implementing carbon constraint policies could generate a positive effect on several sectoral outputs, such as the food production sector, whose sectoral output will increase by 138.1 MilUSD, mainly because the carbon abatement costs of carbon-intensive industrial products increase significantly relative to foodstuff. Therefore, residential consumption may prefer the relatively cheaper foodstuff, rather than more expensive industrial products. Simultaneously, demand substitution elasticity of foodstuff is extremely low. Thus, when implementing external policies to interfere with GDP and total sectoral output, it has little impact on the food production sector. Generally, these will eventually increase both the production and output of food production sector.

Furthermore, when local emissions trade among different sectors in Shanghai prevails (under the ETsec scenario), the total output loss will be −478.4 MilUSD (−15.9%) compared with the BaU scenario in 2030, which offsets 45.7 MilUSD output loss relative to the CAPsec scenario. Also, sectoral output increment of food production sector under the ETsec scenario will exceed that under the CAPsec scenario, leading to the comparative advantage. Simultaneously, sectoral output losses of other ETS participating sectors under the ETsec scenario will be lower than those corresponding sectors under the CAPsec scenario with the exception of metal smelting and coke sectors (two sellers in the local emissions trade market), indicating that these two sectors will take more stringent emissions reduction obligations. However, in general, sectoral outputs under the ETsec scenario are higher than those under the CAPsec scenario in Shanghai.

In addition, shown in Fig. 7, once establishing an inter-regional emissions trade market (under the ETreg scenario), the total output of Shanghai relative to the BaU scenario will decrease by 289.7 MilUSD (−9.6%) in 2030, increasing by 188.7 MilUSD compared with that of Shanghai under the ETsec scenario, which offsets the total output loss in Shanghai induced by achieving NDC targets. Also, the majority of sectoral outputs from all the ETS participating sectors under the ETreg scenario will surpass those under the ETsec scenario. Particularly, sectoral output increments for metal smelting sector (72.0 MilUSD) and chemicals sector (54.7 MilUSD) between these two scenarios will be extremely high, followed by the machinery sector (19.7 MilUSD), the power generation sector (16.9 MilUSD) and the petrol oil sector (16.1 MilUSD). Sectoral outputs of non-metal, aviation, paper, manufactured gas, railway and coke sectors will increase slightly. The total increment from these sectors will be 8.8 MilUSD. Nevertheless, accompanying the expansions of carbon trade volume under the ETreg scenario, sectoral outputs of food production and textile sectors will decrease by 70.3 and 1.3 MilUSD respectively, due to the fact that carbon abatement cost of the ROC is significantly lower than that of Shanghai in the national carbon trade market. Therefore, Shanghai will become the buyer that purchases low-priced emissions quotas from the ROC to reduce its total expenses of carbon emissions reduction. As a result, sectoral outputs under the ETreg scenario are higher than those under the ETsec scenario in Shanghai.

Under the ETreg scenario, the total output loss of the ROC will be −3.4 BilUSD (−6.3%) relative to the BaU scenario in 2030, increasing by 213.7 MilUSD compared with the ETsec scenario, which is fundamentally identical to sectoral output increment in Shanghai between these two scenarios. As shown in Fig. 7, under the ETreg scenario, the total output loss value share of ROC will be greatly lower than that of Shanghai. Launching a national carbon trade system could not only restrict carbon emissions but also moderate negative effects on economic indicators including the total output and the sectoral outputs by compensating output losses through carbon emissions quotas trade. Similarly, the majority of sectoral outputs of all the ETS participating sectors under the ETreg scenario in the ROC will surpass those under the ETsec scenario, in which sectoral output gains in the chemicals sector (118.6 MilUSD) will be the highest, followed by the power generation sector (81.5 MilUSD) and the metal smelting sector (75.3 MilUSD). Conversely, the food production sector will experience the highest output loss with -122.3 MilUSD. In conclusion, launching an inter-regional carbon emissions market is the optimal scenario to compensate sectoral output loss for achieving China's NDC target.

4. Discussions

4.1. Comparison with other studies

Using this CGE model, carbon prices under the ETsec scenario are higher than simulated results found by Wang et al. [18] (37 USD/tCO_2) in 2020 and Wu et al. [52] (69 USD/tCO_2) in 2020 and 2030. In Wu and his colleagues' model, GDP and residential losses in Shanghai will reach 1.7% in 2020 and 4.7% in 2030 [52]. However, the designed models in these two studies are static and single-region CGE models, ignoring exogenous economic variables against the established growth rates. Our CGE model introduces the macroeconomic indicators with time-delay to the multi-sector, multi-region, recursive dynamic CGE model to restrict the predicted values of the economic variables that fluctuate with time and increasing micro-level behavior mechanisms. Therefore, loss rates of GDP investigated in this study are much higher than those, at 2.8% and 10.8% respectively in 2020 and 2030. The different results reflect that the CGE model captures the impacts of launching a national carbon trade market exposing the vulnerability of Shanghai given its large economy relative to the ROC. Furthermore, carbon emissions intensity reduction rates found in our study are lower than those presented by Li et al. [14]. In addition, Gavard et al. [30] estimate US carbon price and EU carbon price in 2030 of 80 USD/tCO_2 and 49.3 USD/tCO_2 respectively, which are much lower than the simulation results of national carbon emissions prices from our study. Zuckerman et al. [33] estimated US carbon prices to range from 125 to 157 USD/tCO_2 based on different Cap and Trade regulation scenarios which are slightly lower than the results in our study. Therefore, we can conclude that the carbon trading market of the developed countries, such as EU and US, has basically reached the equilibrium point, while China's carbon market is still in its early development stage, so the carbon price of China is much higher than that of EU or US.

4.2. Policy implications

Based on our results, we propose the following policy suggestions to optimize China's national ETS to help achieve NDC targets with the minimal social and economic disruption. With the introduction of a national ETS, the aviation sector will bear the highest carbon emission reduction costs among all participating sectors in Shanghai, due to the fact that this sector heavily relies on traditional fossil fuels, especially kerosene, which is difficult to replace with clean energy in the short term. While the aviation sector has just established energy efficiency standards, it has done so without any effective implementation measures [58]. Stakeholders in this sector should look to other countries which have been able to reduce carbon emissions by expanding the use of biofuels. Moreover, the Chinese government should guide and assist the aviation sector to minimize its overall carbon emission.

Shanghai, as the wealthiest and most advanced mega-city in China and China's largest CO_2 emitter at the city level [59], should undertake higher emissions abatement responsibility than that enacted by China's central government to help achieve China's NDCs targets. Consequently, Shanghai should seek to host the national ETS and play a leadership role to ensure a successful national ETS. In this regard, Shanghai was chosen as the national carbon trade market at the end of 2017. Also, the Shanghai government developed its own low carbon plans, including releasing research and development funds to support low carbon technologies, capacity building efforts to advance low carbon development, carbon capture and storage pilots, and renewable and clean energy initiatives. For instance, in order to guide local residents to move toward low carbon consumption, necessary promotion activities have been conducted, such as low carbon pamphlets and workshops, TV, Internet and newspaper promotions. Moreover, low carbon facilities have been constructed, such as a more convenient public transit system, more charging stations for new energy vehicles, shared bicycles, etc, although more efforts should be further made.

The national government should establish comprehensive and clear regulations to govern a national ETS. Shanghai has established its own carbon trade market, but only a few sectors with higher carbon emissions intensity levels participate. It will be crucial to expanding the local carbon trade market so that more local sectors are included. The Shanghai government is going to support more high-tech industry and phase out those energy intensive industries. Therefore, the economic resources can be efficiently and effectively adjusted and reallocated to improve the total factor productivity. Moreover, effective enforcement on relevant regulations is also important so that the whole carbon emissions market can be operated within a legal framework.

Many developed countries have already established carbon trading markets and collected many experiences. As a developing country, the Chinese government should collaborate with these countries, especially into the areas of determining appropriate carbon emissions prices, how to govern carbon trade markets, how to train the relevant stakeholders and how to set up the best mechanism, including transaction criteria.

4.3. Limitations and future work

This CGE model assumes a perfect market, sufficient information availability and rational behaviors by all the ETS participating sectors. These assumptions require a balance between maximum producer profits and maximum consumer utility, which do not exist in the reality. In addition, the ROC is assumed to have the same administrative level as in Shanghai. However, the ROC includes both developed and developing Chinese regions, with clear regional disparity from social and economic perspectives. Both technological and administrative abilities are still weak there, indicating potential difficulties for them to implement low carbon development. Also, they may establish their regional carbon emissions trade market by using different trade mechanism. Therefore, this paper only investigates the overall impacts of inter-regional emissions trade between Shanghai and the ROC, ignoring inter-regional emissions trade among these provincial administrations in the ROC. Under such a circumstance, future studies should aim to investigate the impacts of more detailed inter-regional emissions trade mechanism among other provincial administrations.

5. Conclusions

This study aims to investigate the macroeconomic and environmental impacts of launching national ETS policies on Shanghai and the Rest of China through applying a multi-sector, multi-region, recursive dynamic CGE model. Simulation results demonstrate that textile and petrol oil sectors will bear the highest carbon abatement costs in Shanghai, while carbon abatement cost of metal smelting sector will be relatively lower. When initiating carbon emissions trade under the scenario with local carbon emissions trading among ETS participating sectors, metal smelting sector would be the largest seller while power generation sector would be the largest buyer. Furthermore, the equilibrium carbon trade price under the scenario with inter-regional carbon emissions trading will be half of that of Shanghai under the scenario with local carbon emissions trading among ETS participating sectors, since Shanghai is the buyer in the national carbon emissions trade market. Also, the monetary shares of carbon emissions trade to GDP and that of trade volume to the total emissions of Shanghai under the scenario with inter-regional carbon emissions trading are substantially higher than those of Shanghai under the scenario with local carbon emissions trading among ETS participating sectors. In order to achieve China's Nationally Determined Contributions target, launching a national carbon trade system (under the ETreg scenario) could partially offset the GDP loss and sectoral output reduction both in Shanghai and the ROC, which could achieve national optimization between economic development and environmental protection. Policy recommendations are also raised in order to further facilitate Shanghai's low carbon development efforts. Although these policies are based upon the local realities, they can provide useful insights to other regions so that decision-makers in other regions can initiate more appropriate policies by considering their own situations.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apenergy.2018.08.117.

References

[1] Rockström J, Steffen W, Noone K, Persson A, Rd C, Lambin E, et al. A safe operating space for humanity. Nature 2009;461:472–5.
[2] Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. Nature 2003;421:37–42.
[3] Vliet M, Franssen W, Yearsley J, Ludwig F, Haddeland I, Lettenmaier D, et al. Global river discharge and water temperature under climate change. Global Environ Change 2013;23:450–64.
[4] Cook J, Nuccitelli D, Green S, Richardson M, Winkler B, Painting R, et al. Quantifying the consensus on anthropogenic global warming in the scientific literature. Environ Res Lett 2013;8:24024–7.
[5] IPCC 2014, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 pp.
[6] Meehl G, Tebaldi C, Adamssmith D. US daily temperature records past, present, and future. 201606117; 2016.
[7] Meehl G, Washington W, Arblaster J, Hu A, Teng H, Tebaldi C, et al. Climate system

response to external forcings and climate change projections in CCSM4. J Clim 2012;25:3661–83.
[8] He J. China's INDC and non-fossil energy development. Adv Clim Change Res 2015;6:210–5.
[9] Commission, NDAR. Enhanced actions on climate change: China's intended nationally determined contributions; 2015.
[10] Munnings C, Morgenstern R, Wang Z, Liu X. Assessing the design of three carbon trading pilot programs in China. Energy Policy 2016;96:688–99.
[11] Bryant G. Creating a level playing field? The concentration and centralisation of emissions in the European Union Emissions Trading System. Energy Policy 2016;99:308–18.
[12] Zhao X, Jiang G, Nie D, Chen H. How to improve the market efficiency of carbon trading: A perspective of China. Renew Sustain Energy Rev 2016;59:1229–45.
[13] Liu L, Chen C, Zhao Y, Zhao E. China's carbon-emissions trading: Overview, challenges and future. Renew Sustain Energy Rev 2015;49:254–66.
[14] Li W, Lu C. The research on setting a unified interval of carbon price benchmark in the national carbon trading market of China. Appl Energy 2015;155:728–39.
[15] Zhang D, Karplus V, Cassisa C, Zhang X. Emissions trading in China: Progress and prospects. Energy Policy 2014;75:9–16.
[16] Chang K, Chang H. Cutting CO_2 intensity targets of interprovincial emissions trading in China. Appl Energy 2016;163:211–21.
[17] Lund P. Impacts of EU carbon emission trade directive on energy-intensive industries — Indicative micro-economic analyses. Ecol Econ 2007;63:799–806.
[18] Wang P, Dai H, Ren S, Zhao D, Masui T. Achieving Copenhagen target through carbon emission trading: Economic impacts assessment in Guangdong Province of China. Energy 2015;79:212–27.
[19] Zhang D, Rausch S, Karplus V, Zhang X. Quantifying regional economic impacts of CO_2 intensity targets in China. Energy Econ 2013;40:687–701.
[20] Lo A. Carbon trading in a socialist market economy: Can China make a difference? Ecol Econ 2013;87:72–4.
[21] Chevallier J. Carbon futures and macroeconomic risk factors: A view from the EU ETS. Energy Econ 2009;31:614–25.
[22] Chevallier J. Carbon price drivers: An updated literature review. Ssrn Electronic J 2011;4:1–7.
[23] Oberndorfer U. EU emission allowances and the stock market: Evidence from the electricity industry. Ecol Econ 2009;68:1116–26.
[24] European-Commission, 2009. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Towards a comprehensive climate change agreement in. 032 Page of Copenhagen Sec Sec European Council 4, p. 206–7.
[25] Salant S. What ails the European Union's emissions trading system? Journal of Environmental Economics and Management 2016;80:6–19.
[26] Mattoo A, Subramanian A, Dominique V, He J. Reconciling climate change and trade policy. Soc SciElectron Publ 2009;26(224):296–319.
[27] Calel R, Dechezleprêtre A. Environmental policy and directed technological change: Evidence from the European carbon market. Rev Econ Statist 2016;42:551–74.
[28] Medina V, Pardo Á, Pascual R. The timeline of trading frictions in the European carbon market. Energy Econ 2014;42:378–94.
[29] Jia J, Xu J, Fan Y. The impact of verified emissions announcements on the European Union emissions trading scheme: A bilaterally modified dummy variable modelling analysis. Appl Energy 2016;173:567–77.
[30] Gavard C, Winchester N, Paltsev S. Limited trading of emissions permits as a climate cooperation mechanism? US–China and EU–China examples. Energy Econ 2016;58:95–104.
[31] Shen B, Dai F, Price L, Lu H. California's cap-and-trade programme and insights for China's pilot schemes. Energy Environ 2014;25:551–76.
[32] Gavard C, Winchester N, Henry J, Sergey P. What to expect from sectoral trading: A US-China example. Soc Sci Electron Publ 2011;02:9–26.
[33] Zuckerman J, Laughlin K, Abramskiehn D, Wang X. Cap and trade in practice: barriers and opportunities for industrial emissions reductions in California. CPI Working Paper; June 2014.
[34] Xiong L, Shen B, Qi S, Price L. Assessment of allowance mechanismin China's carbon trading pilots. Energy Procedia 2015;75:2510–5.
[35] Zhang X, Qi T, Ou X, Zhang X. The role of multi-region integrated emissions trading scheme: A computable general equilibrium analysis. Appl Energy 2017;185(Part 2):1860–8.
[36] Böhringer C, Löschel A. Climate policy beyond Kyoto: Quo Vadis? Kyklos 2005;58:467–93.
[37] Fujimori S, Masui T, Matsuoka Y. Gains from emission trading under multiple stabilization targets and technological constraints. Energy Econ 2015;48:306–15.
[38] Fujimori S, Masui T, Matsuoka Y. Development of a global computable general equilibrium model coupled with detailed energy end-use technology. Appl Energy 2014;128:296–306.
[39] Wang K, Wang C, Chen J. Analysis of the economic impact of different Chinese climate policy options based on a CGE model incorporating endogenous technological change. Energy Policy 2009;37:2930–40.
[40] Zhang Z. Macroeconomic effects of CO_2 emission limits: A computable general equilibrium analysis for China. J Policy Model 1998;20:213–50.
[41] Dai H. Integrated assessment of China's provincial low carbon economy development towards 2030: Jiangxi province as an example. Tokyo: Tokyo Institute of Technology; 2012.
[42] Rutherford T. Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax. Comput Econ 1999;14(1–2):1–46.
[43] Dai H, Masui T, Matsuoka Y, Fujimori S. The impacts of China's household consumption expenditure patterns on energy demand and carbon emissions towards 2050. Energy Policy 2012;50:736–50.
[44] Dai H, Masui T, Matsuoka Y, Fujimori S. Assessment of China's climate commitment and non-fossil energy plan towards 2020 using hybrid AIM/CGE model. Energy Policy 2011;39:2875–87.
[45] Dai H, Xie X, Xie Y, Liu J, Masui T. Green growth: The economic impacts of large-scale renewable energy development in China. Appl Energy 2016;162:435–49.
[46] Cheng B, Dai H, Wang P, Xie Y, Chen L, Zhao D, et al. Impacts of low-carbon power policy on carbon mitigation in Guangdong Province, China. Energy Policy 2016;88:515–27.
[47] Cheng B, Dai H, Wang P, Zhao D, Masui T. Impacts of carbon trading scheme on air pollutant emissions in Guangdong Province of China. Energy Sustain Dev 2015;27:174–85.
[48] Dong H, Dai H, Dong L, Fujita T, Geng Y, Klimont Z, et al. Pursuing air pollutant co-benefits of CO_2 mitigation in China: A provincial leveled analysis. Appl Energy 2015;144:165–74.
[49] Tian X, Geng Y, Dai H, Fujita T, Wu R, Liu Z, et al. The effects of household consumption pattern on regional development: A case study of Shanghai. Energy 2016;103:49–60.
[50] Tian X, Dai H, Geng Y. Effect of household consumption changes on regional low-carbon development in 2020: A case study of Shanghai. China Populat Resour Environ 2016;26:55–63.
[51] Xie Y, Dai H, Dong H, Hanaoka T, Masui T. Economic impacts from PM2.5 pollution-related health effects in China: A provincial-level analysis. Environ Sci Technol 2016;50.
[52] Wu R, Dai H, Geng Y, Xie Y, Masui T, Tian X. Achieving China's INDC through carbon cap-and-trade: Insights from Shanghai. Appl Energy 2016;184:1114–22.
[53] National Bureau of Statistics of China (NBS). Input-output tables of China 2012. China Statistics Press, Beijing [in Chinese].
[54] National Bureau of Statistics of China (NBS), Input-output tables of China 2007. China Statistics Press, Beijing [in Chinese].
[55] National Bureau of Statistics of China (NBS), China energy statistical year book 2012. China Statistics Press [in Chinese].
[56] National Bureau of Statistics of China (NBS). China Energy Statistical Yearbook 2008: Beijing: China Statistics Press.
[57] Agency, I.E., 2006. IPCC guidelines for National Greenhouse Gas Inventories. Energy 2.
[58] Hao H, Liu Z, Zhao F. An overview of energy efficiency standards in China's transport sector. Renew Sustain Energy Rev 2017;67:246–56.
[59] UNDP, 2015 China sustainable cities report: measuring ecological and human development.