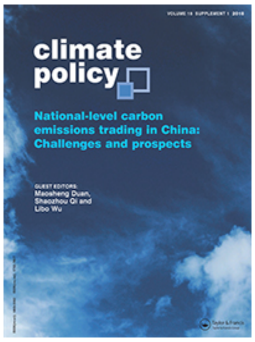

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Evaluating various choices of sector coverage in China's national emissions trading system (ETS)

Haoqi Qian[a], Ying Zhou[a] and Libo Wu[a,b]

[a]School of Economics, Fudan University, Shanghai, People's Republic of China; [b]School of Data Science, Fudan University, Shanghai, People's Republic of China

ABSTRACT

Sector coverage matters greatly in designing China's national emissions trading system (ETS), with issues to be considered including impacts on emission reduction, economic and social welfare change, and carbon leakage to uncovered sectors. In this article, we evaluate various policy choices by setting up six scenarios in a China computable general equilibrium model. To investigate the optimal choice determining which sectors should be covered, criteria such as emission scale, trade intensity, emission intensity and complex indicators of optimal carbon revenue are compared. In addition, double counting of electricity production- and consumption-related carbon emissions is also included as a specific scenario, as it might be utilized to deal with the problem of price regulation of the electricity sector in China. The simulation result shows that the emissions intensity scenario can achieve the best emissions reduction effect, and the optimal carbon revenue scenario can achieve the best economic and welfare effect. All scenarios show that partial coverage will not lead to significant inter-sectoral carbon leakage in the current construction of the national ETS. Although the double counting of emissions from the electricity sector can lead to the lowest inter-sectoral carbon leakage rate, its emissions reduction effect, economic effect and welfare effect are all inferior to the other scenarios.

Key policy insights

- Sector coverage matters significantly in the design of an emissions trading system.
- Effects on emission reduction, welfare change and carbon leakage are key issues to consider in determining the sector coverage.
- Coverage of sectors with high emissions and emission intensities will lead to the highest emission reduction effects and will also moderate economic and welfare losses
- Double counting of electricity-related emissions will lead to efficiency loss but lower carbon leakage

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1. Introduction

Sector coverage is one of the most important concerns in constructing a carbon market. In principle, an emissions trading scheme has higher cost effectiveness if it covers a wider range of emissions. However, this is not always applicable in practice owing to data issues and high administrative costs (Jotzo, 2013). As a result, whether a certain sector should be included in a carbon emissions trading scheme is crucial because the sector coverage determines, to a great extent, the overall emissions reduction effects and the social welfare outcome (Jiang, Xie, Ye, Shen, & Chen, 2016). As China accelerates its pace towards a nationwide emissions trading scheme (ETS), sector coverage has become one of the most urgent issues to be explored for ensuring the schemes' success.[1]

CONTACT Libo Wu wulibo@fudan.edu.cn School of Economics, Fudan University, Guoquan Road 600#, Shanghai, People's Republic of China; School of Data Science, Fudan University, Handan Road 220#, Shanghai, People's Republic of China

Since 2013, China has launched eight pilot ETSs.[2] These pilot ETSs have tried different ways to choose sectors for participation in the emissions trading markets. As summarized by Zhang, Karplus, Cassisa, and Zhang (2014), different criteria, such as absolute emissions, emissions intensity and share of emissions in total, have been adopted by the current pilot ETSs in choosing sector coverage. Wu, Qian, and Li (2014) note that the rapid changing economic structure in Shanghai has brought about uncertainty in choosing regulated sectors. Qi, Wang, and Zhang (2014) indicate that the selection of regulated sectors in Hubei is mainly dependent on the sectors' contribution to total emissions, as well as its economic development stage. Jiang, Ye, and Ma (2014) explain why commercial, building and transportation sectors are selected in the Shenzhen market. Table 1 shows the latest sector coverage information of these pilot ETSs.

Currently, choices of sector coverage are mainly driven by concerns over the impact on emissions. None of the existing pilot ETSs has taken carbon leakage concerns into consideration. The inter-sectoral carbon leakage effect could, however, be significant, especially when sectors are only partially covered in the ETS. Baylis, Fullerton, and Karney (2013, 2014) and Jarke and Perino (2017) show that inter-sectoral carbon leakage will occur due to both a 'trade effect' and an 'abatement resource effect'. Moreover, many other factors not listed in Table 1 may also influence the government's decision on the sector coverage. A first concern in terms of sector coverage lies in the economic and welfare impacts of the different sector coverage policies. Second, it is important to know the net contributions to total emission reduction of the different sector coverage policies. Third, since all of the pilot ETSs in China double-count the emissions from the electricity generation processes for both power producers and end-users, an evaluation of these policy settings would also be beneficial in order to know clearly its merits (Zeng, Weishaar, & Vedder, 2018).

For the first question, a social optimum is achieved when the marginal abatement costs (MACs) are equalized among sectors, when various sectors have quite different MACs (van de Bergh & Delarue, 2015;; Xiao, Wei, & Wang, 2014 Zhou, Fan, & Zhou, 2015; Timilsina, Sikharulidze, Karapoghosyan, & Shatvoryan, 2017). Economic and welfare impacts are minimized when sectors with the lowest MACs are included in the ETS. Sectors that have the lowest MACs are also considered to be sectors with the biggest abatement potential. Yu, Agbemabiese, and Zhang (2016) evaluate abatement potentials for the different Chinese sectors. Heinrichs, Jochem, and Fichtner (2014) show that the transport sector has the greatest abatement potential and should be covered by the ETS.

As for the net total emission reduction contribution of the ETS, it greatly depends on the extent of emission spillover into other sectors or regions (Juergens, Barreiro-Hurlé, & Vasa, 2013). Different sector coverages mean different inter-sectoral or inter-regional carbon leakage rates that weaken the effects of ETS (Allevi, Oggioni, Riccardi, & Rocco, 2016; Cullenward, 2014). Martin, Muûls, de Preux, and Wagner (2014) have constructed an index consisting of a combination of carbon intensity and trade intensity to evaluate the carbon leakage risk and found that carbon intensity is strongly correlated with leakage risk. As a result, it is important to evaluate emission leakage risks for different sector coverage designs.

Third, double counting issues related to ETS, caused by including both direct and indirect emissions from the electricity sector in ETS, raise concerns. Zeng et al. (2018) find that double counting of electricity emissions will cause inter-regional carbon leakage through inter-regional electricity flows. Xiong, Shen, Qi, Price, and Ye (2017) note that double counting will lead to a higher overall cap of ETS. Jotzo and Löschel (2014) note that if direct emissions are covered in ETS, the large electricity users will face higher electricity prices and abatement costs than other users. In this way, double counting will be an effective approach to generate a mitigation incentive for the electricity sector and for sectors with high electricity consumption (Chevallier, 2010; Wang, Teng, Wang, Zhou, & Cai, 2018). Munnings, Morgenstern, Wang, and Liu (2014) note that, as the electricity price and dispatch are both highly regulated by the National Development and Reform Commission (NDRC), double counting is an effective mechanism that can pass carbon prices on to consumers of electricity in the current pilot ETSs.

In existing literature, computable general equilibrium (CGE) is a widely used tool to assess economic and social impacts of emission trading schemes. Most studies focus on investigating impacts of different mechanism design issues such as cap setting, allowance allocation and market linkage (Fan, Wu, Xia, & Liu, 2016; Hübler, Voigt, & Löschel, 2014; Li & Jia, 2016; Loisel, 2010). A comprehensive review of these studies can be found in Jiang et al. (2016). Recently, researchers have begun to evaluate impacts of different designs of sector coverage

Table 1. Updated sector coverage information of eight pilot ETSs.

(a)

Pilot ETS	Emissions effect concern	Carbon leakage concern	Criteria	Threshold (tons CO_2)	Threshold (toe)
Beijing	Main	None	Total emissions	10,000 (existing) 5000 (new)	
Chongqing	Main	None	Total emissions	20,000	
Guangdong	Main	None	Total emissions	20,000	
			Energy consumption		10,000
Hubei	Main	None	Energy consumption		10,000 (key sectors) 60,000 (other sectors)
Shanghai	Main	None	Total emissions	10,000 (key sectors) 100,000 (water transportation sector)	
			Energy consumption		5000 (key sectors) 50,000 (water transportation sector)
Shenzhen	Main	None	Total emissions	3000	
			Construction area	10,000 square metres	
Tianjin	Main	None	Total emissions	20,000	
Fujian	Main	None	Energy consumption		10,000 (key sectors) 5000 (planned sectors)

Data source: collected by authors.[15]

(b)

Pilot ETS	Number of entities	Common covered sectors	Differential covered sectors
Beijing	947	Electricity and heat production, petrochemical, iron and steel	All other industrial sectors, public transportation and service sectors.
Chongqing	230		Industrial sectors[a].
Guangdong	218		Cement and aviation.
Hubei	236		Chemical, cement, nonferrous metal, Manufacture of universal equipment, construction, pulp and paper, food production
Shanghai	312		All other industrial sectors, transportation sector and commercial buildings.
Shenzhen	824		All other industrial sectors and commercial buildings.
Tianjin	109		Chemical, metal production, oil and gas production, manufacture of special equipment and commercial buildings.
Fujian	277		Chemical, cement, metal production, nonferrous metal, pulp and paper and aviation. Construction and transportation (Planned).

Data source: collected by authors.
[a]There is no public firm list to determine the covered sectors.

using CGE models (Choi, Liu, & Lee, 2017; Liu, Tan, Yu, & Qi, 2017; Wang, Zhu, & Fan, 2018). This article is related to two recent studies that use the CGE model to evaluate different designs of sector coverage for China's ETS (Lin & Jia, 2017; Mu, Evans, Wang, & Cai, 2017). Mu et al. (2017) place an emphasis on eight sectors in the current policy design proposed by the Chinese government and additionally on emission-intensive sectors, whereas Lin and Jia (2017) design different sector coverage scenarios based on existing international experiences.

As a comparison, this article contributes to the existing literature on China's ETS by not only putting emphasis on the double counting issue, but also by evaluating a wider range of designs of sector coverage, based on different criteria.[3] Moreover, the results of this article also provide solid evidence for the future design of China's national ETS, from a sector coverage perspective.

The remainder of this article is organized as follows. In Section 2, we build a static China computable equilibrium model to evaluate sector coverage policies and we describe the process of setting different policy scenarios. In Section 3, simulation results are given, and we discuss the results from three perspectives: the emission reduction effect, the inter-sectoral carbon leakage effect and the economic and welfare effect. Section 4 gives concluding remarks and policy suggestions.

2. CGE model

2.1. Model setting

The CGE model[4] used in this article is a one-period static model (see Böhringer, Fischer, & Rosendahl, 2014 or Böhringer, Rosendahl, & Storrøsten, 2017 for recent applications of the multi-region, multi-sector version of this CGE model; see Qian, Wu, & Tang, 2017 for a recent application of the recursive dynamic version of this CGE model).

The model consists of 42 normal sectors, one capital formation sector, one government sector and one representative household sector. Normal sectors use nested elasticity of substitution (CES) technologies to provide goods and services. The capital formation sector represents one macro closure that savings equals investment. The government has a balanced budget that uses taxation and the auction revenue of emission permits to provide public goods and to transfer payments to households. A representative household maximizes its utility subject to its total income, which consists of factor income, transfer payments and an exogenous trade surplus.

In this CGE model, the gross domestic product (GDP) and other economic and welfare indicators are endogenously determined and are calculated from equilibrium results.[5] As a static model with only one period, we assume there is no exogenous nationwide economic shock or technical progress. Thus, the design of the emissions trading scheme is the only factor that causes equilibrium results to deviate from the original results.

2.1.1. Production technology

Production technologies in the CGE model are modelled as a nested multi-input CES function to specify substitution possibilities in production between capital, labour, energy and intermediate inputs. Value-added composite of capital and labour is first nested with energy and is then nested with intermediate inputs at the top level. In each layer, the CES function of factor inputs or composite bundle inputs can be expressed as follows:

$$Z_j = \left(\sum_{i=1}^{n} \alpha_{ji} X_{ji}^{-\rho_j} \right)^{-1/\rho_j}, \tag{1}$$

where Z_j is output in layer j, and X_{ji} is ith input in layer j. α_{ji} is the cost share of input X_{ji} in layer j, and $\sigma_j = 1/(\rho_j + 1)$ is the elasticity of substitution among inputs in layer j.

Emissions are treated as inputs with negative externalities in proportion to energy inputs.[6] While primary energies are treated as intermediate inputs in the energy conversion sector, it is assumed there are no emissions in energy conversion procedures. Therefore, emissions of different types of energy from final energy consumption are endogenously determined by the CGE model. Figure 1 illustrates complete structures of the production technologies for the energy conversion sectors and the normal sectors.

In Figure 1, K represents capital input, L represents labour input. Abbreviations such as *s*, *vae*, *vm*, *va*, *ese* and *se* are the elasticities of substitution in different levels.

2.1.2. Emissions permit market

The national emissions trading scheme is modelled as an emission permit market in the CGE model. An emission is treated as a factor input in our model and it has the same meaning as an emission permit. In the emission permit market, the total amounts of emission permits demanded are determined by production technologies and the total amount of emission permits supplied is determined by the government. Therefore, the supply of emission permits is exogenous and the market equilibrium price will change as the endogenous demands for emission permits change. Here, we define the amount of emission permits supplied by the government as the emissions cap, which can be expressed as follows:

$$S = D \times \alpha, \tag{2}$$

where S stands for the supply of emissions permits. D represents the initial demand for emission permits of the covered sectors, which is equal to the total emissions from final energy consumption and is calculated using real

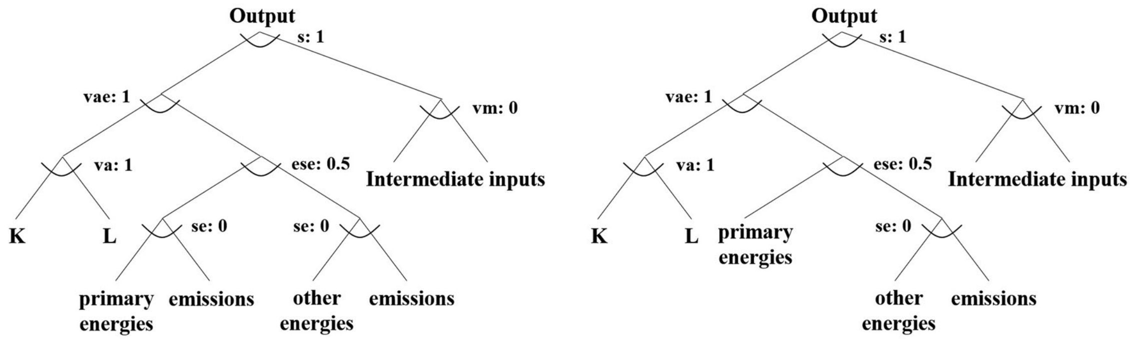

Figure 1. Production technologies. Left: Production technology for a normal sector. Right: Production technology for the energy conversion sector.

data. α represents the supply coefficient chosen by the government. If the government wants to set a strict cap on total emissions by establishing a carbon market, then it will choose $\alpha < 1$ to reduce the total supply of emission permits. In this case, the market equilibrium price of the emission permits will be greater than zero due to the excess demand for emission permits.[7]

Emission permits are assumed to be auctioned to firms and the auction revenue of emission permits is expressed as follows:

$$REV = S \times EMP, \tag{3}$$

where *REV* stands for the auction revenue of emission permits, and *EMP* stands for the market price of emission permits. In equilibrium, *EMP* equals the firms' MACs; thus, the firms' MACs are equalized in the emissions trading scheme.[8] Auction revenue is collected by the government and will be redistributed to the economy through government purchases.

2.2. Data source

In our CGE model, the Input–Output (IO) table data come from the Input-Output Table of China (IOTC), published by the National Bureau of Statistics in the year 2012. The intermediate input values are directly drawn from IOTC and are measured in monetary value. Labour inputs are the compensation of employees from the IOTC. The capital inputs are summations of the depreciation of fixed assets and the operating surplus, from the IOTC. The government tax revenue is a summation of all sectors' net taxes on products, as listed in the IOTC. Household consumption is the summation of the consumption of rural and urban residents, as given in the IOTC. Household saving is equal to the summation of gross fixed capital formation and changes in inventories, from the IOTC. Emissions are calculated by multiplying the final energy consumption and the emission factors. The final energy consumption data come from the China Energy Balance Sheet 2012 and the emission factors come from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. We further divide emissions by energy inputs measured in monetary terms in the IOTC to get the emission coefficients that can be used in the CGE model to calculate the emission results in different scenarios.

2.3. Scenario setting

In this article, we set up five scenarios to compare with the business-as-usual (BAU) scenario. These five scenarios are the business-as-usual with double counting (BAUDC) scenario, the emissions-scale (ES) scenario, the trade-intensity (TI) scenario, the emissions-intensity (EI) scenario and the policy-equivalence (PE) scenario. To make the simulation results comparable among these scenarios, the market size of the ETS in each scenario should be as close to each other as possible. As the BAU scenario is the reference scenario in this article, the number of covered sectors in the other scenarios are chosen to make the market size of the ETS as close as possible to that of the BAU scenario.[9]

2.3.1. Business-as-usual scenario

According to the official No. 57 [2016] File released by the General Office of the NDRC on 11 January 2016, eight sectors[10] will be included in the first stage, to build the national carbon emissions trading scheme. These eight sectors include the petrochemical, chemical, building materials, steel and iron, non-ferrous, papermaking, power and aviation sectors. These eight sectors are mapped to seven two-digit sectors, according to the Industrial Classification for National Economic Activities 2011. Mapping rules and new sectors are listed in Table A1. The total amount of emissions of the new seven sectors is 5.55 billion tons of CO_2 and accounts for 62.9% of national emissions. Therefore, the initial demand for emission permits in Equation (2), D, is 5.55 billion tons of CO_2 in the BAU scenario.

2.3.2. Business-as-usual scenario with the double counting scenario

In this scenario, except for indirect emissions from the covered sectors, the direct emissions from electricity generation sector are additionally added to the ETS and thus increase the overall market size of the emission permit market compared to the BAU scenario. This can be expressed as:

$$D_{\mathrm{BAUDC}} = D_{\mathrm{BAU}} + D_{\mathrm{eletricity}}, \tag{4}$$

where D_{BAUDC} and D_{BAU} are demands for emission permits in the BAU scenario and the BAUDC scenario, respectively. $D_{\mathrm{electricity}}$ represents the demand for emission permits of the electricity sector that is equal to the total direct emissions in the electricity generation process.

2.3.3. Emission-scale scenario

In the ES scenario, sectors are chosen according to their relative scale of total emissions. Sectors with higher emission levels are more easily monitored and have more potential for reducing their emissions level. As a result, it is quite natural to choose those sectors that are large polluters.

2.3.4. Trade-intensity scenario

Trade intensity is one of the factors that will affect the probability that one sector will leak its emissions into other regions. Sectors with higher trade intensities are prone to be exposed to higher risks of carbon leakage. According to Article 10a of the amended ETS directive 2003/87/EC (European Parliament and the Council of the EU, 2009), the trade intensity of one sector is defined as follows:

$$\mathrm{TRINT}_i = \frac{\mathrm{import}_i + \mathrm{export}_i}{\mathrm{output}_i + \mathrm{import}_i}, \tag{5}$$

where TRINT_i is the trade intensity index of sector i. import_i is the value of the imported goods of sector i. export_i is the value of the exported goods of sector i. output_i is the output value of sector i.

If we take trade intensity as the only factor in the choice of sector coverage, then more than half of the sectors are chosen to be covered in the national emission trading scheme, according to the rankings of TRINT from the highest to the lowest.

2.3.5. Emission-intensity scenario

Emissions intensity is not only another factor that will affect the probability that one sector will leak its emissions into other regions but is also an important indicator that shows whether a sector is emissions intensive or not. From the sector perspective, we define emissions intensity as follows[11]:

$$\mathrm{EMINT}_i = \frac{\mathrm{emission}_i}{\mathrm{output}_i}, \tag{6}$$

where EMINT_i is the emissions intensity index of sector i. $\mathrm{emission}_i$ is the emissions level of sector i, measured in kg/CO_2.

If we take emissions intensity as the only factor in the choice of the sector coverage, five sectors are chosen for coverage in the national emissions trading scheme, according to the rankings of EMINT from the highest to the lowest.

2.3.6. Policy-equivalent scenario

This scenario uses the optimal carbon revenue return index (OCRRI) proposed by Qian and Wu (2017) to rank all industrial sectors and then the sector coverage is chosen based on the ranking results. The OCRRI is a policy equivalent index that makes the quantity instrument equal to the intensity instrument and is defined as follows:

$$OCRRI = \frac{E[NB_I] - E[NB_Q]}{E[NB_{QCR}] - E[NB_Q]} \quad 0 \le OCRRI \le 1. \tag{7}$$

The numerator in formula (7) is the difference of expected benefits between the emissions intensity target policy, $E[NB_I]$, and the emissions trading policy, $E[NB_Q]$. The denominator in formula (7) is the difference of expected benefits between the emissions trading policy with carbon revenue, $E[NB_{QCR}]$, and the emissions trading policy.[12] Therefore, OCRRI measures the relative advantage of the emissions intensity policy over the emissions trading policy. If one sector's OCRRI is relatively low, then it means a low free allocation ratio of emission permits can make the emissions trading policy at least as good as the carbon intensity policy. As a result, sectors with low OCRRIs have a higher priority for inclusion in an emissions trading scheme.

2.3.7. Summary of six scenarios

Sector coverages of all six scenarios and detailed information are shown in Table 2 and the detailed sector name for each sector code is shown in Table A2. Full ranking results can be seen in Table A3.

In our CGE model, we make some simplified assumptions in setting the national emissions permit cap. The total supply of emission permits in each scenario is set to the same ratio to total demand of emission permits in the base year, and this ratio is determined by parameter α in Equation (2). In addition, we also choose several α values to test the robustness of the simulation results.

3. Simulation results and discussion

In this article, we run a total of six scenarios to compare their emission effects, economic effects and welfare effects. Each scenario runs four times in which different emissions cap parameters, α, are equal to 0.95, 0.90, 0.85 and 0.80. The differences in the simulation results of all scenarios are compared to the BAU scenario to examine the relative advantages of these scenarios.

3.1. Emission reduction effect

The simulation results show that total emissions drop in all scenarios when the emissions caps are set to the levels of the sectors covered in the national emissions trading scheme (shown in lines for primary axis).

Table 2. Overview of scenario settings.

Ranking criterion	BAU Official document	BAUDC Official document	ES Total emission	TI *TRINT*	EI *EMINT*	PE *OCRRI*
Sector codes included in emissions trading scheme	10,11,12,14, 25,28,30	10,11,12,14, 25,28,30	12,13,14,25	02,03,04,05, 07,08,09,10, 11,12,14,15, 16,17,18,19, 20,21,22,23, 29,30,35,41	12,13,14,25, 26	02,05,06,11, 13,14,15,19, 22,24,25,26, 28,33,35,36, 42
Double counting of emissions	No	Yes	No	No	No	No
Number of sectors	7	7	4	24	5	17
Market size of ETS (billion ton)	5.55	9.00	5.61	5.48	5.8	5.34
Emissions coverage (percentage)	62.9	62.9	63.6	62.2	65.8	60.6

Figure 2 shows that changes in total emissions are only slightly different for all scenarios (shown in lines for the primary axis). Among these scenarios, the EI scenario performs best in terms of the change in total emissions that results in the lowest total emissions level, while the double counting of emissions in the BAUDC scenario doesn't significantly help to reduce total emissions. This can be seen from comparisons of the scenarios to the BAU scenario (shown in the bars on the secondary axis), which show that the BAUDC scenario performs worst and reduces the least amount of total emissions.

We separate total emissions into two parts: one part represents the emissions of all sectors, and the other represents the emissions from the household sector.[13] Figure 3 shows that the results are similar to changes in total emissions. In the BAUDC scenario, the total industrial sectors emit more than in the BAU scenario, which leads to a weak emissions reduction effect, while the EI scenario performs best, with reductions in most emissions from all industrial sectors (shown in bars on the secondary axis). However, emissions from the household sector are reduced more in the BAUDC scenario than in other scenarios. This is mainly the result of changes in the energy price faced by firms in the household sector. As shown in Figure 4, the electricity price for the household sector increases by 4.8% in the BAUDC scenario, and the electricity consumption of the household sector will then decrease, which ultimately leads to lower emissions. In contrast, the electricity price decreases by 3.1% in the TI scenario, so emissions from the household sector increase. Similarly, gas prices increase in both the EI scenario and the PE scenario, which also leads to lower emissions in these two scenarios.

We should note that although coal prices decrease in all scenarios, the net emission reduction effects for the household sector are still mainly determined by electricity prices and gas prices. From the IO table, we can calculate that the share of costs of coal, oil, petroleum products, electricity and gas for the household sector are 0.08%, 0.00%, 1.17%, 1.44% and 0.69%, respectively. Thus, electricity consumption contributes most to the net emissions reduction effects. The electricity price is the highest in the BAUDC scenario, resulting in the largest net emissions reduction effect, while the electricity price is the lowest in the TI scenario, resulting in an increase in total emissions in the household sector. In the EI and the PE scenarios, gas prices are higher than those in other scenarios, resulting in a large emissions reduction in the household sector.

From Figure 5, we can see that emission intensities decline in all scenarios (shown in the lines for the primary axis). However, the decline in emissions intensity in the BAUDC scenario is relatively lower than that in other scenarios, and the EI scenario still performs best among all scenarios (shown in bars on the secondary axis). Meanwhile, we can see that the PE scenario performs much better in reducing emissions intensity than in reducing total emissions.

The underperformance of the BAUDC scenario in emissions reduction effects is mainly caused by its distorted price signal. As shown in Figure 6, the equilibrium emissions permit price of the BAUDC scenario is significantly

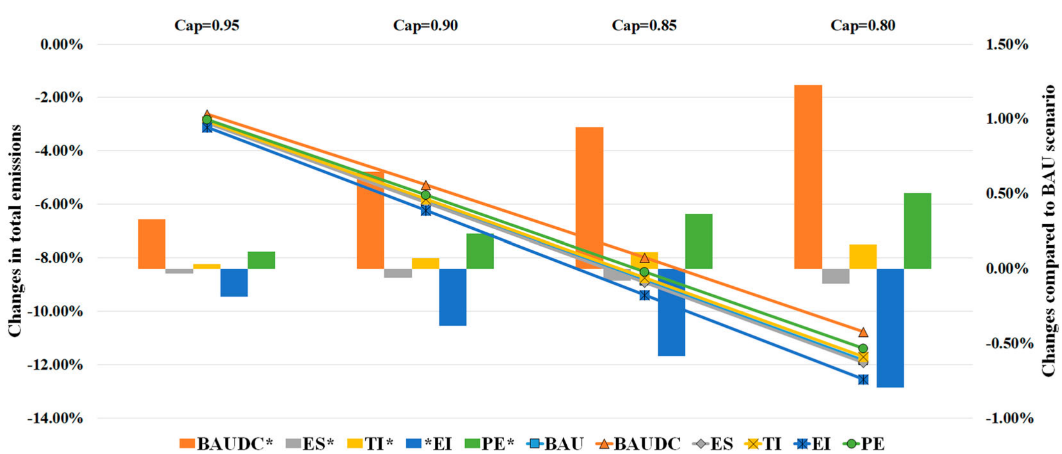

Figure 2. Changes in total emissions (scenarios with a star are shown in bars on the secondary axis).

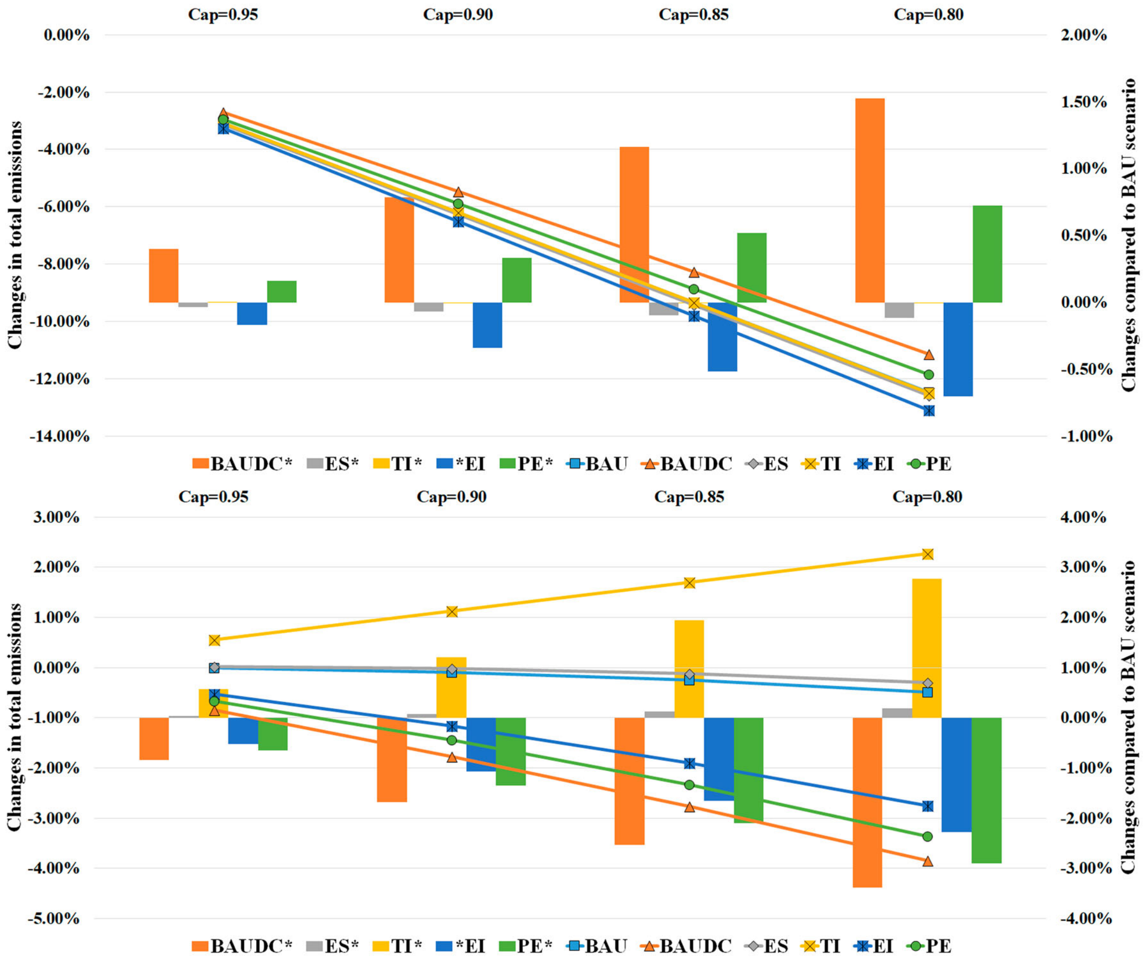

Figure 3. Changes in total emissions (scenarios with a star are shown in bars on the secondary axis). Top: Changes in total emissions from all industrial sectors. Bottom: Changes in total emissions from the household sector.

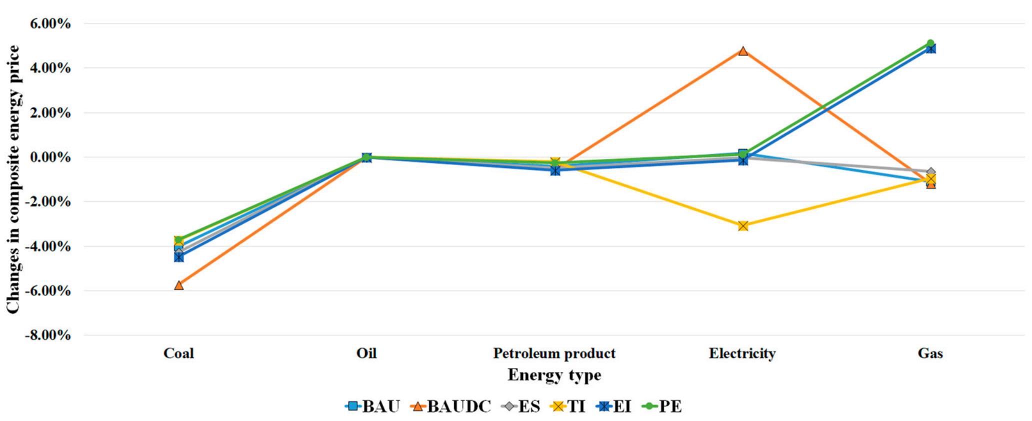

Figure 4. Changes in the energy price of household sector.

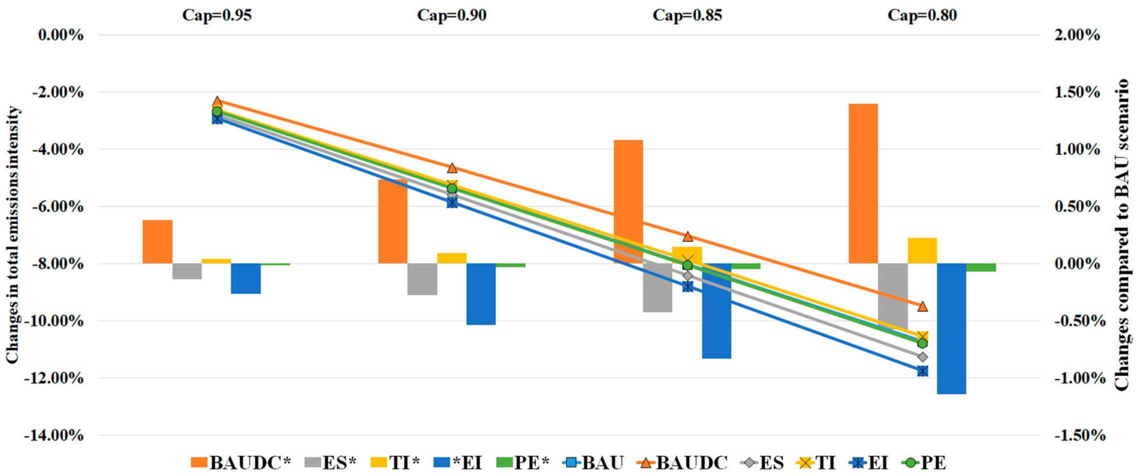

Figure 5. Changes in emissions intensity (scenarios with a star are shown in bars on the secondary axis).

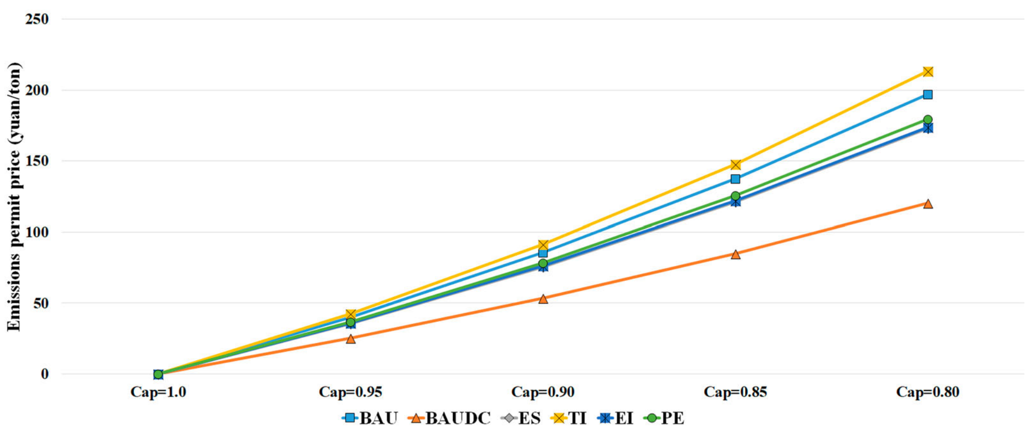

Figure 6. Equilibrium price of emissions permit.

lower than the prices of other scenarios. For a cap setting that equals 0.8, the permit price of the BAUDC scenario is 120.3 yuan/ton, while the prices of the other scenarios range between 173 yuan/ton to 213 yuan/ton. Because emissions from the electricity sector are double counted in the BAUDC scenario, the emissions trading market size increases greatly, resulting in a lower emissions permit price, and this distorted price signal gives the economy less incentive to reduce emissions.

3.2. Inter-sectoral leakage effect

As all emission permits are assumed to be auctioned to covered sectors, an increase in the overall costs of these sectors will occur. As a result, the sectors with high carbon leakage indices will leak part of their emissions to other sectors, and the total emissions of the uncovered sectors is expected to increase. We can thus write the inter-sectoral leakage effect here as follows:

$$\text{inter - sectoral leakage effect} = \frac{\text{emission}_{uc}^{1} - \text{emission}_{uc}^{0}}{\text{emission}_{uc}^{0}}, \tag{8}$$

where emission_{uc}^{0} is total emissions of the uncovered sectors when there is no national ETS, emission_{uc}^{1} is total emissions of the uncovered sectors when a national ETS exists. The inter-sectoral leakage effects defined in Equation (8) are shown in Figure 7.

Figure 7 shows that the BAUDC scenario has the lowest inter-sectoral leakage effect, which equals −1.01% when the emissions cap is set as 0.8. This means that total emissions from the uncovered sectors will decrease by 1.01% compared to total emissions when there is no national emissions trading scheme. For other scenarios, the inter-sectoral leakage effects of the BAU scenario, ES scenario, TI scenario, EI scenario and PE scenario are 0.08%, 0.12%, 0.08%, −0.09% and 0.08%, respectively, and are all quite close to zero. This means that there are hardly any significant inter-sectoral carbon leakage effects under any of the sector coverage scenarios.

In order to investigate why inter-sectoral carbon leakage effects do not take place, we further study the changes of costs of input goods and input factors as the inter-sectoral carbon leakage rate is mainly dependent on them. We can see from Figure 8 that changes in the output prices of all sectors, except the electricity sector, are quite similar. Therefore, there is no obvious demand shift of these goods, and there are few changes in emissions. Moreover, Figure 8 shows that input factor prices behave similarly among all scenarios, also resulting in few changes in emissions. As a result, the net inter-sectoral leakage effect is mainly determined by changes in electricity prices. Changes in the emissions of each uncovered sector are shown in Figure A1 to Figure A3.

Figure 9 shows changes in the electricity price, faced by all sectors. Owing to the double counting of emissions from the electricity sector in the BAUDC scenario, we can see that the electricity price increases in the BAUDC scenario due to additional emissions abatement costs. As a result, almost all sectors face higher electricity prices and thus reduce their consumption of electricity. This ultimately decreases these sectors' emissions. As a comparison, there are no economy wide increases in electricity prices in other scenarios.

3.3. Economic and welfare effect

Building a national emissions trading scheme could make whole nations suffer certain losses, due to increased abatement costs imposed on covered sectors.

Figure 10 shows that the GDP in all scenarios suffers losses (shown in lines on the primary axis). However, there is one obvious difference in that the GDP in the BAUDC scenario is lower than that in the BAU scenario, while the ES, EI and PE scenarios still perform better than the BAU scenario (shown in the bars on the secondary axis). We further decompose GDP into three components – labour compensation, capital compensation and government revenue – to see contributions of different components to these results. Figure 10 shows different changes of the GDP components in the scenarios compared to the BAU scenario. The results show that labour compensation is the main contributor in the BAUDC scenario, while all three components in the ES, EI and PE scenarios are higher than those in the BAU scenario.

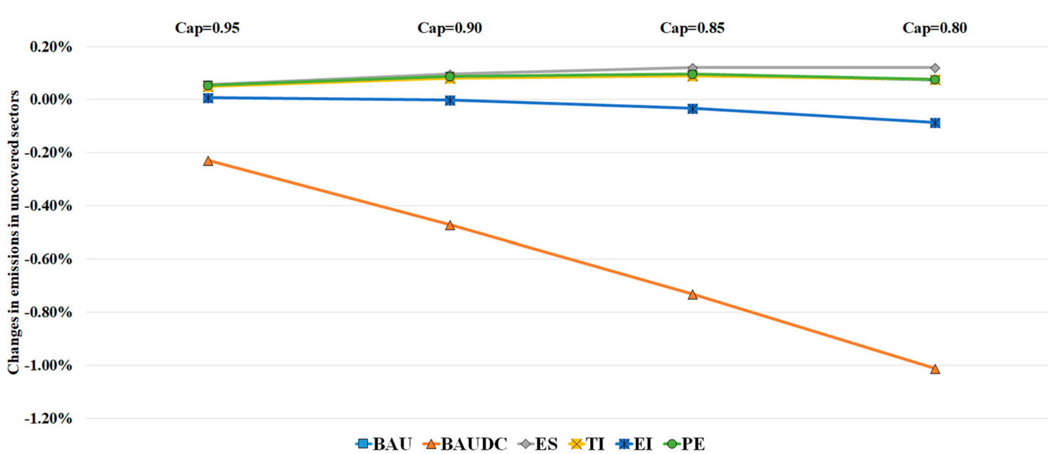

Figure 7. Changes in total emissions from uncovered sectors.

Figure 8. Changes in prices. Top: Changes in the output price of all sectors. Bottom: Changes in the factor price of all sectors.

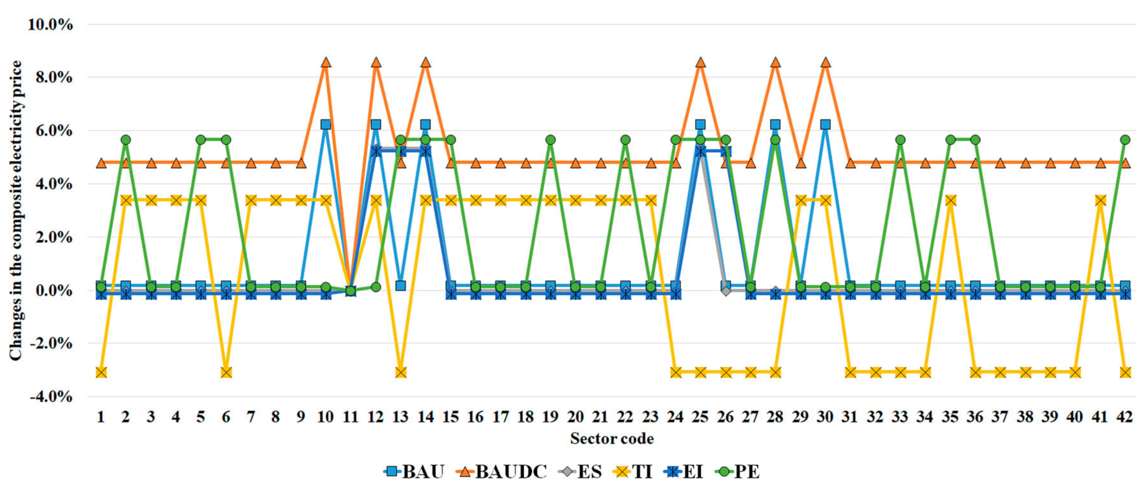

Figure 9. Changes in the electricity input price of all sectors.

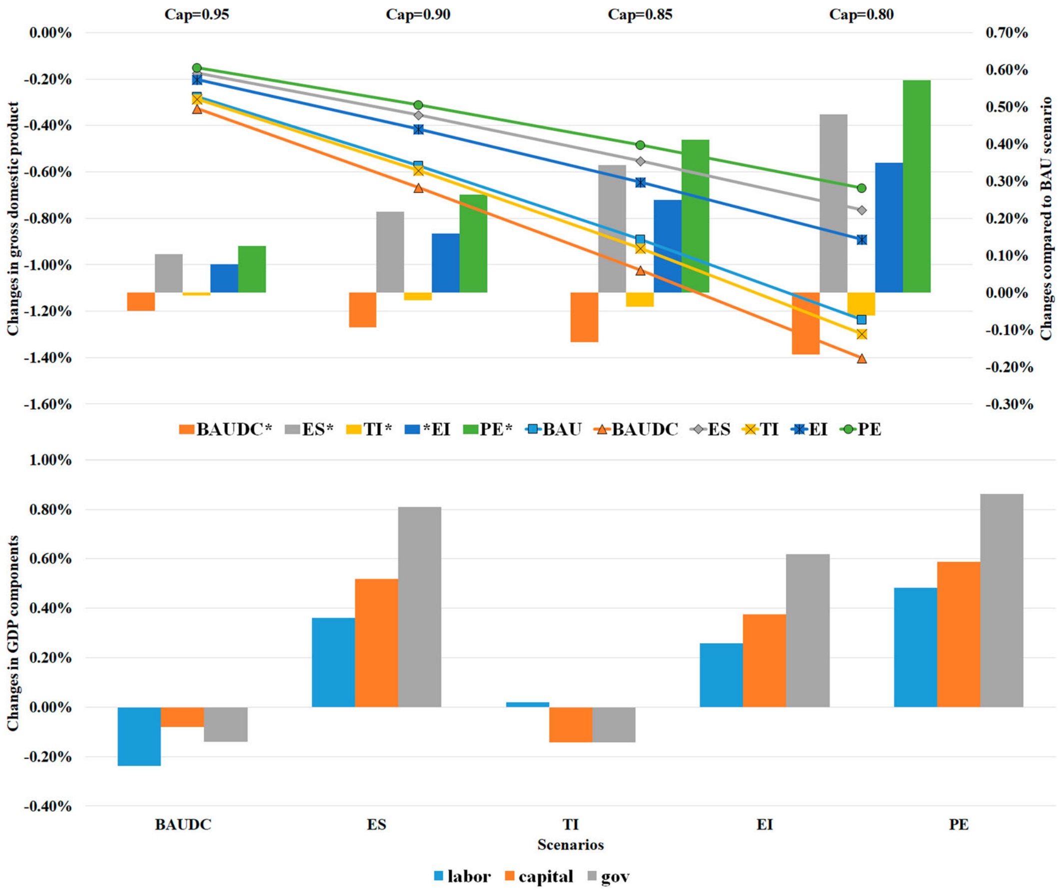

Figure 10. Changes in GDP (scenarios with a star are shown in bars for secondary axis). Bottom: Changes in GDP components.

Welfare is measured by the total utility of representative households, which is composed of the consumption of goods. Similar to economic effects, the national emissions trading scheme will also cause a negative welfare effect, due to the increase in prices of commodities, caused by increased production costs. Figure 11 shows that although welfare suffers losses in all scenarios (shown in the lines on the primary axis), the ES, EI and PE scenarios still perform better than the BAU scenario, due to higher factor compensation (including labour and capital). The TI scenario performs worst, and the household sector consumes the least among all scenarios. Moreover, welfare in the BAUDC scenario is just slightly lower than that in the BAU scenario, indicating that the double counting issue will not affect the welfare effect.

3.4. Summary of the scenario rankings

Figure 12 illustrates the rankings of all scenarios in six dimensions. A scenario will locate far from the centre point if it performs best in a certain dimension. We can see that the PE scenario performs best in three dimensions, which are welfare loss, GDP loss and output loss, while the EI scenario performs best in two dimensions, which are the emissions reduction rate and the emissions intensity reduction rate. The BAUDC scenario performs best in one dimension, namely, the inter-sectoral leakage rate, but worst in three dimensions: the emissions reduction rate, the emissions intensity reduction rate and GDP loss. The ES scenario performs second best in all dimensions except inter-sectoral leakage rate. The BAU scenario performs at an average level among all scenarios, while the TI scenario performs worse than the BAU scenario, in all dimensions.

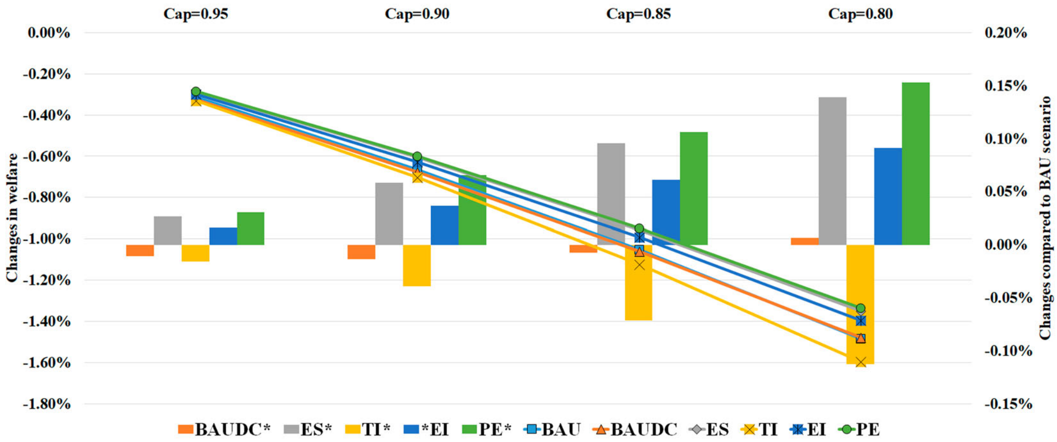

Figure 11. Changes in welfare (scenarios with a star are shown in bars on the secondary axis).

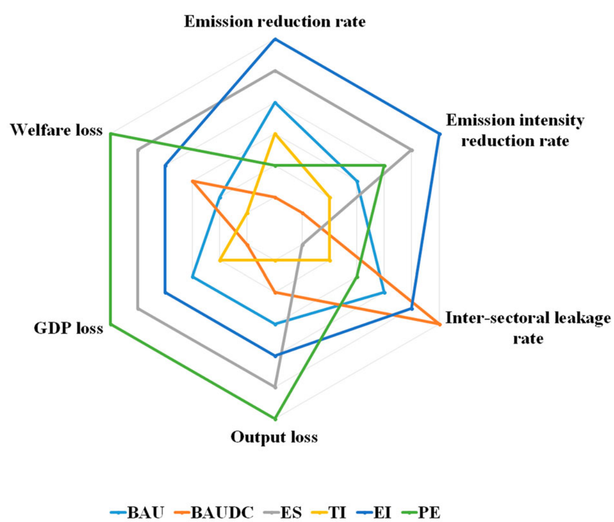

Figure 12. Rankings of scenarios.

In summary, none of the six scenarios can achieve the largest emission reduction while simultaneously experiencing the least economic and welfare loss. As a result, policy makers should be careful when designing the ETS, due to the trade-offs between economic loss and emissions reduction. Since the most important goal of establishing the ETS is to control emissions and to contribute to mitigating global climate change, establishing an ETS focussed on emission reduction effects should be given more priority. As a result, choosing sector coverage based on emissions intensity (EI scenario) and emissions scale (ES scenario) can reduce emissions effectively with relatively small economic and welfare losses.

4. Conclusion

China has accelerated its pace towards a national ETS to fulfil its overall emissions reduction target. In this article, we use a China national CGE model to evaluate various policy choices from the perspective of sector coverage by paying special attention to sectoral heterogeneity and the double counting of emissions from power generation.

First, simulation results show all scenarios have a positive emissions reduction effect, a negative economic effect and a negative welfare effect, but the degrees of these effects are quite different among all scenarios. The EI scenario performs best in reducing total emissions and emissions intensity, and the PE scenario performs best in minimizing the economic and welfare losses. Among all six scenarios, the ES scenario is the most balanced. As the main goal of ETS is to contribute to mitigating global climate change, policy makers should consider covering those sectors that have high total emissions and emissions intensities in the future.

Second, simulation results also show that inter-sectoral leakage is not a significant issue for the current construction of a national ETS. Net inter-sectoral leakage effects are mainly determined by changes in electricity prices. As a result, the double counting of emissions from the electricity sector in the BAUDC scenario leads to the highest electricity price and the lowest emissions from uncovered sectors. While the simulation results are based on a full pass-through of the incremental costs of electricity production to downstream sectors and end-users, such a situation could be realized with the dramatic reform of the Chinese electricity market.

Third, double counting distorts the price signal of emission permits and thus results in the lowest emissions reduction effect and economic effect. Emissions prices are significantly lower than those in other scenarios. A low emission permit price that deviates from the normal level gives less incentives for entities to upgrade their low-carbon technologies or to switch to clean energies (Lin, Wang, Wu, & Qi, 2017). From this perspective, more polices, including a research subsidy policy and other low-carbon technology promoting policies, should also be considered to complement the ETS.

Finally, there remain some limitations in current simulations using the CGE model, as some practical situations are not yet accurately modelled. The complexity of the Chinese electricity market calls for an in-depth investigation on the extent of deregulation and its impacts on the operation of the carbon market. This may help us to understand more deeply the impacts of the double counting issue. To concentrate on the main concern, the issue of sector coverage, this article uses a CGE model without considering the actions taken by other countries. Further work could be the use of a global CGE model introducing each country's Nationally Determined Contribution under the 2015 Paris Agreement, which could then be used to examine global emissions and economic impacts.

Notes

1. In December 2017, the National Development and Reform Commission released the No. 2191[2017] document to announce the official start of China's national ETS construction program. In the first phase of China's national ETS, only the electricity generation sector is covered. Other energy intensive and resource sectors are planned to be included in the future.
2. The Fujian pilot ETS is a voluntary ETS launched in 2016, while the other seven pilot ETSs were officially launched in 2013.
3. Simulation results of CGE models are sensitive to parameters and model structures, so that it is always difficult to compare results among different models due to different assumptions. Nevertheless, results in this paper are valid when compared to several similar studies with key indicators such as output losses, GDP losses and welfare losses (Fan et al., 2016; Tang, Shi, & Bao, 2016; Mu et al., 2017).
4. The CGE model is a GTAP-E type model solved by the General Algebraic Modeling System (GAMS) and basic model settings can found in Rutherford and Paltsev (2000).
5. GDP is equal to a whole nation's value added and is calculated as the summation of factor income and tax income.
6. For energy type *e*, the amount of emissions composited with this type of energy is energy *e*'s quantity multiplied by its emission coefficient. The emission coefficient for energy *e* is calculated using real data in year 2012 by dividing emissions by the final energy consumption. The composite procedure can be described by a Leontief production function and is realized by setting the elasticity of substitution between energy and emission to zero.
7. We assume there are no direct ETS costs, including transaction costs, MRV costs and market operating costs.
8. As emissions is treated as an input in the firm's production function, we can apply an envelope theorem to the firm's cost minimization problem to get a shadow price of emissions, which is the firm's MAC. While the emission permit market is cleared in equilibrium, each firm's MAC is equal to the market price of the emission permit.
9. Since the market size of the ETS is not continuous with the increase in the number of covered sectors, the market sizes of the ETS in other scenarios cannot be exactly the same as that in the BAU scenario. Therefore, the number of covered sectors is determined when the market size of the ETS is the closest to that of the BAU scenario.
10. These eight sectors contain a total of 16 sub sectors with four-digit sector codes.
11. Rather than use China's national emissions intensity goal in which emissions are divided by the GDP, we use the sector's output level instead of value added to focus linkages of a sector's emission level and the output level. The European Commission also adopts this indicator to calculate a sector's risk of carbon leakage.

12. Qian and Wu (2017) extend the policy comparison model proposed by Newell and Pizer (2008) and calculate OCRRIs for all industrial sectors by using the CGE model. Because their CGE model uses the same model settings and real data based on the IOTC in year 2012, we are able to set up the PE scenario by directly using their simulation results.
13. There are no emissions from the government sector because energy consumption is zero in the IOTC.
14. Results for four emission cap parameter are robust and we choose one situation, i.e. emission cap parameter equals 0.90, to represent other situations.
15. Data were collected from the following: No. 2146[2016] document released by the Beijing Development and Reform Commission, No 791[2016] document released by Hubei Development and Reform Commission, No. 9[2016] document released by Shanghai Development and Reform Commission, No. 430[2016] document released by Guangdong Development and Reform Commission, No. 538[2014] released by Chongqing Development and Reform Commission, "Notice on the launch of emission trading scheme in year 2016" released by Shenzhen Development and Reform Commission and No. 31[2016] document released by General Office of Tianjin Provincial Government.

Disclosure statement

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Appendix

Table A1. Sector mapping rules in BAU scenario.

Sector	Sector code (four digits)	Sub-category (main products)	Corresponding sectors in Input–output table
Petrochemical	2511	Crude oil processing	Oil, coking product and nuclear fuel products
	2614	Ethylene	
Chemical	2619	Calcium carbide	Chemical products
	2621	Synthetic ammonia, methanol	
Building materials	3011	Cement clinker	Construction
	3041	Flat glass	
Steel and iron	3120	Crude steel	Metal smelting and rolling products
Non-ferrous	3216	Electrolytic aluminium	
	3211	Copper smelting	
Papermaking	2211	Pulp manufacturing	Papermaking, printing and stationery and sporting goods
	2212	Non-wood and bamboo pulp manufacturing	
	2221	Machine made paper and cardboard	
Power	4411	Pure power generation, cogeneration	Electricity, heat production and supply
	4420	Power grid	
Aviation	5611	Aviation passenger transport	Transport, warehousing and postal service
	5612	Aviation cargo transport	
	5631	Airport	

Table A2. Sector code and sector name.

Sector code	Sector name
01	Agriculture, Forestry, Animal Husbandry and Fishery
02	Mining and Agglomeration of Coal
03	Extraction of Petroleum and Natural Gas
04	Mining of Metal Ores
05	Mining of Non-metal Ores and other mining industries
06	Manufacture of Food Products and Tobacco Products
07	Manufacture of Textile
08	Manufacture of Wearing Apparel, Footwear, Headwear, Leather, Feather and Products
09	Wooden Products and Furniture Manufacturing
10	Manufacture of Pulp, Paper and Paperboard, Printing, Manufacture of Cultural, Educational and Sporting Products
11	Processing of Crude Oil, Coking and Nuclear Fuel
12	Chemical Industry
13	Manufacture of Non-metal Products
14	Manufacture and Casting of Metals
15	Manufacture of Metal Products
16	Manufacture of Universal and Special Equipment
17	Manufacture of Transportation Equipment
18	Manufacture of Electric Machines and Equipment
19	Manufacture of Telecommunication Equipment, Computers and Other Electric Equipment
20	Manufacture of Instruments and Appliances, Culture-related and Office Machinery
21	Manufacture of Arts and Crafts and Other Manufacturing
22	Recycling of Waste and Scrap
23	Production and Supply of Electricity and Heat
24	Manufacture and Supply of Gas
25	Manufacture and Supply of Water
26	Construction Industry
27	Transport and Warehousing Industries
28	Post Industry
29	Information Transmission, Computer Services and Software Industries
30	Information Transmission, Computer Services and Software Industries
31	Accommodation and Catering
32	Financial Industry
33	Real Estate Industry
34	Leasing and Commercial Service Industry
35	Research and Experimental Development Industry
36	Technical Service Industry
37	Water Resources, Environment and Public Accommodation Management Industry
38	Residential Services and Other Services

(Continued)

Table A2. Continued.

Sector code	Sector name
39	Education
40	Sanitation, Social Security and Social Welfare
41	Culture, Sports and Entertainment
42	Public Management and Social Organization

Table A3. Rankings of sectors for all scenarios.

	ES		TI		EI		CL		PE	
rank	sector code	index	sector code	index	sector code	index	sector code	index	sector code	index
1	14	1692	20	0.61	26	28.06	22	1.34	24	1
2	12	1629	21	0.56	13	9.93	04	1.23	13	2
3	13	1169	03	0.55	25	8.95	12	1.17	11	3
4	25	1124	04	0.41	14	8.52	14	0.96	15	4
5	30	586	08	0.39	12	7.02	13	0.71	25	5
6	28	229	23	0.36	22	6.45	03	0.56	14	6
7	26	190	19	0.27	04	3.03	10	0.48	05	7
8	15	169	16	0.26	15	2.64	15	0.41	22	8
9	04	147	10	0.23	05	2.64	30	0.35	28	9
10	10	147	41	0.22	24	2.56	16	0.27	02	10
11	11	144	09	0.21	30	2.56	20	0.26	42	11
12	01	138	17	0.21	27	2.55	09	0.25	36	12
13	06	123	22	0.21	10	2.10	17	0.23	19	13
14	35	111	35	0.19	11	1.94	07	0.22	33	14
15	16	95	18	0.17	07	1.36	21	0.22	35	15
16	07	94	12	0.17	09	1.19	08	0.21	06	16
17	03	77	29	0.16	17	1.08	05	0.20	26	17
18	05	74	07	0.16	16	1.06	19	0.19	12	18
19	17	72	15	0.15	37	1.05	11	0.18	10	19
20	02	71	30	0.14	03	1.02	35	0.18	17	20
21	18	65	14	0.11	35	0.99	23	0.09	16	21
22	29	65	11	0.09	19	0.71	18	0.09	18	22
23	42	64	02	0.08	02	0.64	37	0.05	07	23
24	19	59	05	0.08	28	0.62	02	0.05	27	24
25	36	52	13	0.07	06	0.59	41	0.05	09	25
26	09	51	31	0.07	36	0.57	06	0.04	40	26
27	20	47	06	0.07	08	0.54	29	0.02	31	27
28	33	36	32	0.07	18	0.51	25	0.02	21	28
29	08	34	01	0.06	20	0.43	31	0.02	08	29
30	38	34	37	0.05	21	0.40	01	0.02	37	30
31	22	34	38	0.02	42	0.32	32	0.01	38	31
32	39	29	33	0.01	40	0.28	36	0.01	30	32
33	37	27	36	0.01	01	0.26	28	0.00	32	33
34	34	26	39	0.01	31	0.26	38	0.00	39	34
35	40	25	28	0.01	23	0.24	40	0.00	41	35
36	31	25	40	0.01	41	0.22	33	0.00	29	36
37	32	24	42	0.00	38	0.22	39	0.00	04	37
38	27	20	25	0.00	32	0.20	42	0.00	20	38
39	23	8	26	0.00	39	0.18	26	0.00	34	39
40	41	8	34	0.00	29	0.13	24	0.00	03	40
41	24	5	27	0.00	33	0.10	27	0.00	23	41
42	21	5	24	0.00	34	0.08	34	0.00	01	42

Figures A1 to A3 show changes in emissions of uncovered sectors for each scenario when emission cap parameter is 0.90.[14] In Figures A1 to A3, changes in emissions of all covered sectors are set to zero, so we can clearly see net emission changes of all uncovered sectors. Sectors are ranked according to their emission level from highest to lowest which are divided into three groups. We can see that most sectors (mainly uncovered sectors) in BAUDC scenario have lower emissions than in other scenarios. These results are consistent with previous discussion and explain why BAUDC scenario performs best from perspective of inter-sectoral leakage effect.

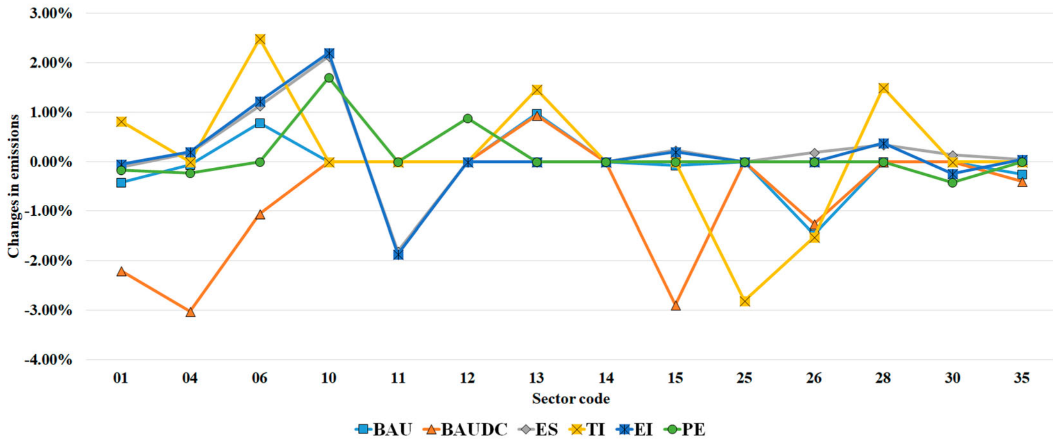

Figure A1. Changes in emissions of sectors in first group.

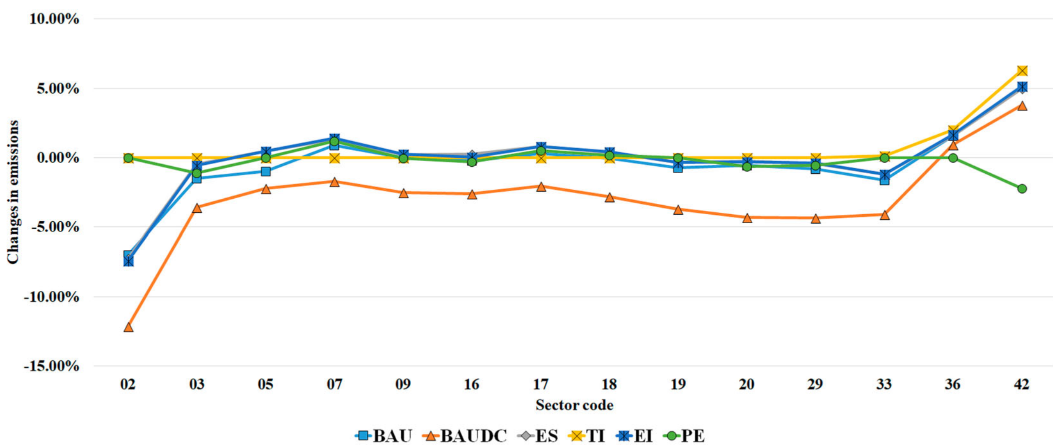

Figure A2. Changes in emissions of sectors in second group.

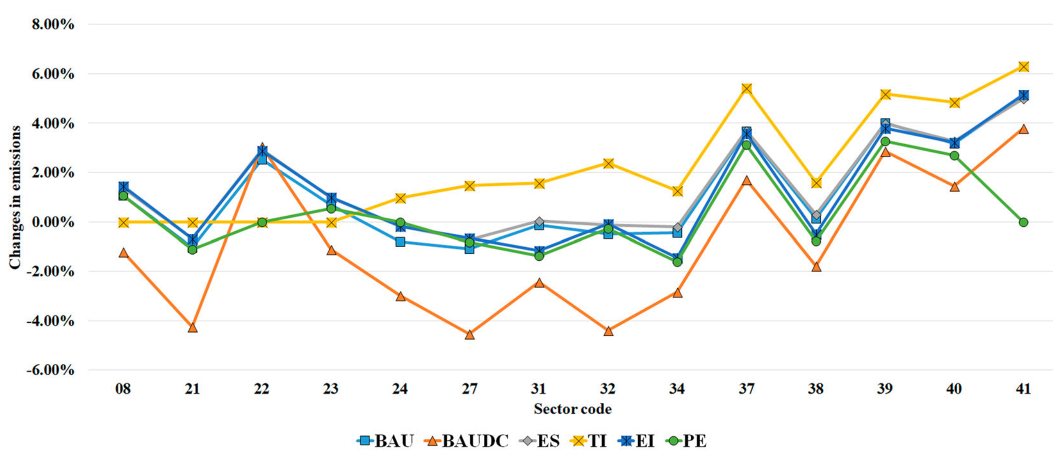

Figure A3. Changes in emissions of sectors in third group.