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Research article

Designing the nationwide emission trading scheme in China

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Abstract: Emission trading scheme (ETS) is popular to abate anthropogenic emissions throughout the world. Previous researchers focused on evaluating ETS policy effect, but ETS design is usually neglected because ETS is already mostly sophisticated worldwide. This is not the case in China, as the Chinese nationwide ETS (CNETS) came into effect in July 2021. Implemented for a brief period, the CNETS lacks implementation details and thus may not achieve mitigation targets cost-effectively. In this paper, we attempt to narrow the research gap by comprehensively designing the CNETS. Our research framework is based on a dynamic recursive computable general equilibrium (CGE) model. The CGE model results show that the appropriate CNETS should include the coverage of the electricity generation and manufacturing sectors, higher carbon price (175 $CNY/t\ CO_2$), quota allocation based on the carbon intensity in the previous year, higher quota decline factor (2%) and time-decreasing free quota ratio. Although we have only designed the Chinese ETS in this paper, the research framework may become a paradigm of designing appropriate ETS.

Keyword: ETS; CGE; carbon quotas; carbon price; quota decline factor; free quota ratio

JEL Codes: Q56, Q58, R11

1. Introduction

Nowadays, carbon tax and emission trading scheme (ETS) are the two most popular climate policies for achieving mitigation targets (Li & Jia, 2016; Bi et al., 2019). Carbon tax usually requires strong administrative power by authorities, while ETS requires establishment of a carbon market (Liu & Lu, 2015). As the Chinese government plays a strong role in the economy, carbon tax could be preferable. Nevertheless, ETS may result in a more attractive economic outcome than carbon tax because carbon tax may have a punishing impact on productive activities and economic growth (Loisel, 2009). ETS advantages were already confirmed in literature. For example, the envisaged ETS in China would induce lower abatement cost to achieve mitigation targets (Dai et al., 2018). Similarly, Choi et al., (2017) empirically found that the South Korean ETS significantly abated the emissions and mildly decreased the GDP. Hence, ETS could help achieve mitigation targets cost-effectively.

Previous researchers tend to focus on evaluating ETS policy effect (Loisel, 2009; Choi et al., 2017; Nong et al., 2017), but less attention is paid to ETS design. This is because ETS worldwide, particularly in developed countries, is already sophisticated with detailed contents, and thus it is meaningless to theoretically design sophisticated ETS. For example, being the largest ETS in the world (Crossland et al., 2013), the EU ETS provides a solid paradigm in terms of lessons learned and potential pitfalls for implementing market-based measures in the shipping industry (Schinas & Bergmann, 2021). Nevertheless, during the evolution of the EU ETS from Phase I to IV (ICAP, 2022), policy risk existed as researchers could not exactly predict how the EU ETS would evolve; therefore, there were uncertainties over EU abatement target setting and policy support to achieve renewable energy development or energy efficiency improvement by 2020 (Blyth & Bunn, 2011). In its early years, the EU ETS had uncertain price expectations arising from severe price fluctuations (Deng & Zhang, 2019). California's Cap-and-Trade program (CA CAT) is another important ETS worldwide; however, it was not implemented smoothly during its development. For example, existing in the CA CAT, surplus allowances resulted in dropping prices and insufficient auctions, thereby causing emission allowance sales to be substantially lower than the expectations (Deng & Zhang, 2019). Consequently, the CA CAT failed to generate the expected amount of revenue that would have contributed to public expenditures (Bushnell, 2017). In many countries like China, ETS was implemented for a brief period with few experiences or has not been established yet. Hence, when designing ETS, these countries can learn from the experiences of the EU ETS and CA CAT, namely avoiding severe price fluctuations and too many free quotas.

In this paper, we are particularly interested in designing the Chinese ETS. This is because China has already become the biggest carbon emitter, but its ETS still lacks implementation details: Although Chinese ETS pilots could date back to 2013, the Chinese nationwide ETS (CNETS) was formally established in July 2021. As a newly introduced climate policy, the CNETS has great uncertainties in policy design, and its implementation may not help China cost-effectively achieve mitigation targets. Hence, we attempt to comprehensively design the CNETS with the appropriate sectoral coverage, carbon price, number of quotas and free quota ratio. This is because these aforementioned components in the CNETS are quite rough at present and remain to be designed in details. For instance, the CNETS covers power sectors only, and this sectoral coverage rate is even lower than that in Phase I of the EU ETS (Lin & Jia, 2020a). Regarded as marginal cost of emission abatement (Wu et al., 2016), carbon price influences ETS effects, but the current price in the CNETS is quite low. The number of quotas is linked to abatement effort with more quotas inducing less abatement. Most carbon quotas are allocated free in the CNETS, but free allocation could be inefficient (Betz et al., 2010). Hence, the inappropriate ETS components impede the CNETS from cost-effectively abating carbon emissions.

To our best knowledge, very few studies have simultaneously incorporated all the aforementioned components in designing the CNETS. In this paper, we attempt to narrow the research gap by capturing all the aforementioned ETS components in the research framework, and the step-by-step design eventually arrives at the final policy with each component optimal. Although the framework is based on the Chinese ETS, it may become a paradigm of ETS design; in other words, this paper contributes to the literature by establishing a research framework to appropriately design ETS.

This paper has six sections: In Section 1, we introduce the research aim and background. Section 2 displays the structure of the employed CGE model. In Section 3, we describe the main components of the designed ETS. Section 4 shows the CGE model results using graphs and tables. In Section 5, we discuss the major findings in comparison with the literature and limitations to be addressed in future research. In Section 6, we summarize the main ideas of this paper and present the policy implications.

2. CGE model structure

Computable general equilibrium (CGE) models originated from the pioneering work of Johansen (1960) based on the general equilibrium theory of Walras. The equilibrium conditions of the CGE model are market clearance, zero profit and income balance (Chen, 2021a). Market clearance means no free disposability; this is to say, the flows of commodities and factors must be absorbed by production and consumption within and beyond the economy (Wing, 2004). Zero profit implies constant returns to scale in production and perfectly competitive markets for the produced commodities (Wing, 2004). Income balance denotes that all the entities within and beyond the economy exhaust their incomes, but deficits are not allowed (Chen, 2021a).

Following our previous work (Chen, 2021b; Chen, 2022; Chen & Wang, 2023a; Chen & Wang, 2023b; Chen & Wang, 2023c), the CGE model in this paper includes four economic entities (the representative household, enterprise, foreigner and government). The social accounting matrix (SAM) of the CGE model is built based on China Input-Output Table, and it can be found in Chen (2021b). There are 42 sectors in the input-output table, but only 29 sectors are left through sectoral disaggregation and aggregation, shown in Table S1 in Supplementary Materials. The electricity sector is disaggregated into one transmission and distribution sector and eight generation sectors consisting of four nonrenewable and four renewable generation sectors (Chen & Wang, 2023a). The renewable generation sectors are assumed to exploit renewable energy only and thus have zero carbon emissions; therefore, these sectors are exempted by climate policy (Chen & Wang, 2023a). More details, particularly equations, on the electricity disaggregation could be found in our previous work (Chen, 2021b; Chen, 2022). The CGE model is divided into five blocks:

①Production block

In this block, the top production relation is formed by a Leontief combination of intermediate inputs and added values, while the lower production relations are modeled by constant elasticity of substitution (CES) functions (Chen & Wang, 2023b). The parametric values of the elasticities are from Guo et al. (2014) who have confirmed the parametric robustness; in addition, we have also confirmed the parametric robustness in our previous work (Chen, 2021; Chen, 2022). Hence, we do not need to perform sensitivity analysis to test whether the parametric values have undue influences on the model results in this paper.

②Income-expenditure block

In this block, the representative household, enterprise, and government are introduced to denote all the households, enterprises, and governments in China (Chen & Wang, 2023a). Household income is from labor, capital, and money transfer; the enterprise earns its income from capital; the government has its income from economic (consumption and production) taxes. The household consumes commodities and pays consumption tax to the government, whilst the enterprise's expenditure includes labor wage, production tax paid to the government and money transfer to the household. The government spends its income on governmental consumption and money transfer to the household.

③Trade block

In this block, the foreigner, representing all the countries except China, exports commodities consumed by the household, and it consumes commodities imported from the enterprise (Chen & Wang, 2023a). Trade balance is reached when the monetary value of the overall export equals that of the overall import (Chen & Wang, 2023c). The international trade is based on the Armington assumption that commodities produced internationally are imperfect substitutes (Chen & Wang, 2023a). Profit maximization drives the enterprise and foreigner to sell commodities either in the domestic or foreign market (Chen & Wang, 2023b).

④Dynamic block

In this paper, the research period is 2021–2030 because the Chinese nationwide emission trade scheme (CNETS) came into effect in 2021, and the deadline for achieving the Nationally Determined Contributions (NDC) target of peaking the emissions is 2030. Hence, the CGE model is dynamic, and we have added a dynamic block to show how the dynamic variables change in the business as usual (BAU) scenario. For example, the projected Chinese energy consumption follows the outlined growth routine in International Energy Outlook. The outputs of energy sectors follow the energy consumption growth, whilst the outputs of nonenergy sectors follow the Chinese GDP projection in the regional GDP long-term forecast by the Organization for Economic Co-operation and Development (OECD). Nevertheless, the designed ETS may change the projection routines of energy consumption and output growth, because it increases cost of nonrenewable energy input and thus affects economic growth. In contrast, some dynamic parameters are exogenously determined irrespective of ETS implementations. For example, the Chinese population is assumed to follow the medium variant scenario for the Chinese population in World Population Prospects.

⑤ETS block

In this block, the government implements the emission trading scheme (ETS) to curb anthropogenic emissions generated from exploitation of nonrenewable energy in commodity consumption and production. By selling carbon quotas to sectors, the government gets revenues from the ETS. Nevertheless, free quotas are also allocated to sectors based on the grandfathering rule. According to Chen & Wang (2023a), the relation between allocated carbon quotas and free quotas is shown in Equation (1). The subscripts *i* and *t* refer to ETS-covered sector and time (year), respectively. FCQ_{it} and CQ_{it} denote free quotas and carbon quotas. fqr is free quota rate, and its value is 0.9, based on the Chinese ETS pilots and Phase I of the EU ETS (Lin & Jia, 2018; Chen & Wang, 2023a).

$$FCQ_{it} = CQ_{it} \times fqr. \tag{1}$$

Previously, the ETS market was usually assumed to be clear when demand for quotas was equal to supply (Dai et al., 2018; Mu et al., 2018), shown in Figure 1a. P_0 and Q_0 are equilibrium price and quantity of quotas in market. In Figure 1, the real ETS market is simplified by perfect competition without considering penalties for emission noncompliance (Jia et al., 2022a). Nevertheless, ETS market clearance may not be easily achieved, as transaction cost could soar when the market approaches equilibrium (Chen & Wang, 2023a). In addition, emission compliance may not occur immediately after ETS implementation, and there could be an adaptation period for emission compliance (Chen & Wang, 2023a).

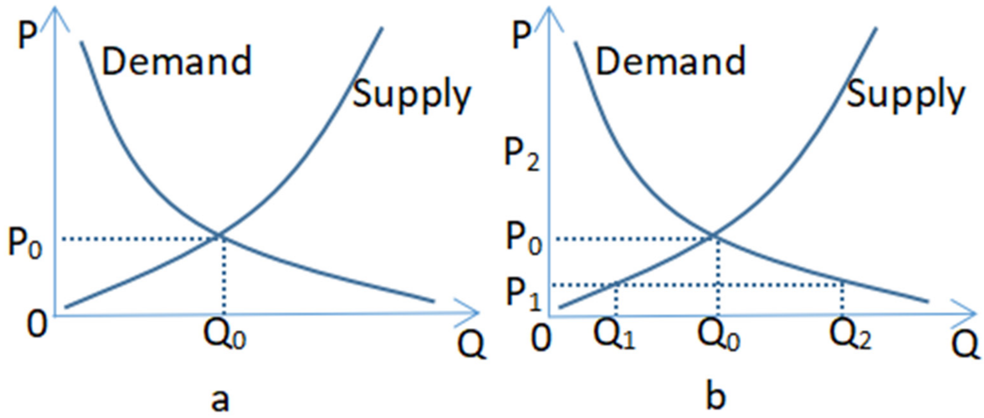

Figure 1. Balanced and unbalanced ETS market.

Hence, unbalanced ETS markets could be closer to reality than balanced markets. There are many reasons explaining unbalanced ETS markets, but in this paper, we have referred to the ETS punishment mechanism, namely penalty for non-compliance or excess emissions. ETS penalties exist in the EU ETS (ICAP, 2022), Korean ETS (Kim & Yu, 2018) and Chinese ETS pilots (Li & Jia, 2016). Under ETS penalty, quota supply is usually unequal to quota demand; in most cases, quota supply is lower than demand, shown in Figure 1b. Because the Chinese government plays a strong role in the economy, it can influence the ETS market by administrative powers. For example, if the government sets carbon price at P_1, then quota supply and demand are Q_1 and Q_2. The difference between quota demand and supply, namely $Q_2 - Q_1$, is defined as ETS-uncovered over-emissions. P_2 is penalty price, which is much higher than normal carbon price P_1. Equations to quantify unbalanced ETS market, with a numeric example provided, can be found in Supplementary Materials or Chen and Wang (2023a).

The CGE model is formed based upon some assumptions. Firstly, as we do not consider unemployment impact in this paper, full labor employment is assumed, and thus labor employment is equal to labor supply. Secondly, we assume that there is no training cost for labor and installation cost for capital; therefore, labor and capital can move freely among sectors during ETS-induced policy shock. Nevertheless, labor and capital are not allowed to flow internationally in this paper. Thirdly, as we do not consider how ETS affects induced technological progress, technology is assumed to be exogenous, and ETS is assumed to be technologically neutral. Lastly, CES elasticity relations are assumed to be unaffected by ETS. If a commodity is in shortage caused by ETS, its substitute is consumed more by rational entities, but the elasticity relation between the commodity and its substitute does not change. Although the above assumptions on the CGE model are not in line with reality, they are necessary to simplify the complicated real world, otherwise too many variables would soar model dimensionality, thereby disabling us to find a model path.

3. ETS design

To analyze policy effects of the designed ETS, we have simulated a business as usual (BAU) scenario. In this scenario, no ETS is implemented, and the economic development follows the projection routine specified in the dynamic block of the CGE model. In the scenarios with the ETS implementation, we have made several assumptions: First, ETS abatement cost of a participating sector is paid as the deduction of the sector’s output, and it becomes governmental revenue. Second, as we do not consider revenue recycling in this paper, ETS revenue is assumed to be kept by the government. Last, we assume that quota trading occurs evenly during the research time interval, namely a year. This assumption avoids soaring quota trading at the end of each time interval so that quota trading is not opportunistic; therefore, traded quotas become continuous rather than discrete.

In Sections 3.1–3.4, the ETS is designed with the default components gradually replaced by the optimal components. For example, Section 3.1 focuses on sectoral coverage with the other ETS components fixed at the default levels; the ETS in Section 3.2 is targeted at carbon price with the optimal sectoral coverage from Section 3.1 and other default ETS components.

3.1. Sectoral coverage

China officially introduced the nationwide ETS market (CNETS) in July 2021. Currently, the CNETS covers power generation only but will expand the coverage rate to incorporate more sectors in the future. Hence, it is meaningful to study how sectoral coverage influences ETS effects in China.

In this paper, the sectoral coverage is designed based on the evolution of the EU ETS and a previous study on the ETS coverage rate in China (Lin & Jia, 2020a). The scope of the EU ETS is from the International Carbon Action Partnership (ICAP, 2022): in Phase I, the covered industries consisted of the electricity, energy production and nonmetal production industry; in Phase II, the aviation industry was added; in Phase III and IV, most of the industries are covered, but there are a few exclusions, such as the agriculture and service sectors. The designed sectoral coverage in Lin and Jia (2020a) ranged from just the electricity sector to all the sectors. Hence, the designed coverage-related scenarios in this paper are shown in Table 1.

Table 1. The designed coverage-related scenarios.

Scenarios	Covered Sectors	Covered Emission Rate
EGE	Electricity Generation	25.59%
ECM	Electricity Generation, Chemical, Mineral	38.96%
EGP	Electricity Generation, Chemical, Mineral, Food, Textile, Timber, Machine, Metal, Construction, Transport	67.68%
EENP	Electricity Generation, Chemical, Mineral, Food, Textile, Timber, Machine, Metal, Construction, Transport, Energy Production, Water Production, Heat Production	96.28%
FULL	All the Sectors	100%

Table 1 depicts the evolution of the ETS from low to high emission coverage rate. According to Table 1, the electricity generation accounts for about a quarter of Chinese anthropogenic emissions. The emission coverage rate in the EENP scenario is close to that in the FULL scenario, and the coverage differences lie in the agriculture, service and electricity transmission and distribution sector. Noticeably, covered emission rate in Table 1 is calculated based on emissions of the primary, secondary and tertiary sectors, but household or residential emissions are excluded in the calculation. For example, the covered emission rate of the FULL scenario is 100%, which means that the ETS in the FULL scenario covers all the emissions from the primary, secondary and tertiary sectors.

In the designed scenarios of Table 1, the default carbon price is 60 $CNY/t\,CO_2$, which is close to the current ETS price in China (Huanbao, 2022). The default carbon quotas are allocated based on the emissions in 2020, which is the base year of this paper. According to Lin and Jia (2018), the default quota decline rate and free quota ratio is 0 and 0.9, respectively. As we step forward, the default ETS components are gradually replaced by the optimal components from the CGE model results.

3.2. Carbon price

Carbon price is regarded as marginal abatement cost. High carbon price may lead to insufficient funds for technological upgrading and even bankruptcies (Chen et al., 2020), whereas low price may undermine the capacity of ETS market to mitigate emissions (Lin & Jia, 2019).

In this paper, the designed price-related scenarios are based on the carbon price in the Chinese ETS pilots and EU ETS. The carbon price ranged from 20–100 $CNY/t\,CO_2$ in the seven Chinese ETS pilots (Li & Jia, 2017), and the current price in the CNETS is around 60 $CNY/t\,CO_2$ (Huanbao, 2022). In contrast, the EU ETS price was about 25 $EUR/t\,CO_2$ (equivalently 175 $CNY/t\,CO_2$) in 2019 (Hintermayer, 2020); then the price rose to 96 $EUR/t\,CO_2$ (equivalently 675 $CNY/t\,CO_2$) in February 2022 and dropped to 70 $EUR/t\,CO_2$ (equivalently 490 $CNY/t\,CO_2$) in March 2022 (ESMA, 2022). As the CNETS is not linked to the ETS elsewhere, we do not consider ETS linkage in this paper. Although some previous researchers studied benefits of ETS linkage, particularly focusing on linking the CNETS to the EU ETS (Liu & Wei, 2016), such linkage may not be viable in reality. This is because the CNETS and EU ETS have disparities in sectoral coverage, carbon price, governmental regulation and so on. Having been implemented since 2005, the EU ETS is sophisticated and has entered the fourth phase, whereas the CNETS was officially launched for two years with many internal issues to be solved foremost.

Table 2. The designed price-related scenarios (unit: $CNY/t\ CO_2$).

Scenario	Carbon Price
LCP	20
MCP	60
HCP	100
LEU	175
MEU	490
HEU	675

In Table 2, the carbon price in the LCP scenario is the lowest price in the Chinese ETS pilots; the price in the MCP scenario is the price of the CNETS; the price in the HCP scenario is the highest price in the Chinese ETS pilots. The prices in the LEU, MEU and HEU scenarios are the prices at the different periods of the EU ETS.

3.3. Carbon quotas

In ETS, quota owners charge for allowing individuals and organizations to emit CO_2 (Allan et al., 2014); therefore, quota allocation is linked to the number of surplus quotas to be traded in the market. Carbon quotas could decline over time, and quota decline may motivate society to abate more emissions or promote technical progress (Lin & Jia, 2018). Hence, quantities of carbon quotas are influenced by quota allocation scheme (QAS) and quota decline factor (QDF) in this paper.

In this paper, QAS can be based on the sectoral emissions in 2020 or 2005, namely QAS2020 and QAS2005, respectively. This is because 2020 is the base year of this paper; China has pledged to lower its emissions per unit of GDP by 60% to 65% in 2030 from the 2005 level (NDRC, 2015). According to the China Energy Statistical Yearbook (NBS, 2021), the Chinese emissions in 2005 were much lower than that in 2020; therefore, the QAS2020 induces much more carbon quotas than the QAS2005.

Equation (2) shows the allocation of carbon quotas in this paper. $CEQAS_i$ is the sectoral emissions in 2005 or 2020; t_0 refers to the base year 2020. ω is quota decline factor (QDF): zero ω induces time-invariant carbon quotas, whereas positive ω induces time-decreasing quotas.

$$CQ_{it} = CEQAS_i \times (1-\omega)^{t-t_0}. \tag{2}$$

According to Lin and Jia (2018), sectoral quotas can be also based on the sectoral emissions or intensity in the last year, shown in Equations (3) and (4), respectively. The subscript $t-1$ denotes the last year; CE_{it} stands for sectoral carbon emissions; $SGDP_{it}$ is sectoral output.

$$CQ_{it} = CE_{i,t-1} \times (1-\omega), \tag{3}$$

$$CQ_{it} = SGDP_{it} \times \frac{CE_{i,t-1}}{SGDP_{i,t-1}} \times (1-\omega). \tag{4}$$

The designed QAS-related scenarios are shown in Table 3, where QDF is assumed to be zero. Nevertheless, QDF could also be 0.5%, 1% and 2%, according to the Chinese ETS pilot experiences (Lin & Jia, 2018). Hence, the QDF-related scenarios are shown in Table 4.

Table 3. The designed QAS-related scenarios.

Scenarios	Allocated Carbon Quotas
CQ20	Sectoral Emissions in 2020
CQ05	Sectoral Emissions in 2005
CQSE	Sectoral Emissions in the Last Year
CQCI	Sectoral Intensity in the Last Year

Table 4. The designed QDF-related scenarios.

Scenario	Quota Decline Factor
OM00	0%
OM05	0.5%
OM10	1%
OM20	2%

3.4. Free quota ratio

Free quota ratio (FQR), namely proportion of free allowance (Neuhoff, 2006), may also influence ETS effects. In this paper, the designed FQR is from Li and Jia (2016) and Wu et al., (2022), but we have also referred to the FQR in EU ETS and Chinese ETS pilots. The designed FQR-related scenarios in this paper are shown in Table 5.

Table 5. The designed FQR-Related scenarios.

Scenario	2021	2030	Annual Change Rate
FQ90	90%	90%	0
FQ50	50%	50%	0
FQ30	30%	30%	0
FQ00	0%	0%	0
FQHL	90%	0%	−10.00%
FQML	50%	0%	−5.56%
FQHM	90%	50%	−4.44%

In Table 5, 90% is the highest designed FQR in Wu et al. (2022), and it complies with Phase II of the EU ETS when the government could auction up to 10% of the total number of allowances (Verde et al., 2019). 50% is the lowest designed FQR in Wu et al. (2022), and it complies with Phase III of the EU ETS when over 40% of emission allowances were auctioned off (Stenqvist & Ahman, 2016). The FQR of 30% is from the end of Phase III of the EU ETS when free allowances for sectors not at risk of carbon leakage would be 30% in 2020 (Verde et al., 2019). The zero FQR is from the EU ETS target that free allowance will be phased out in 2027 (Stenqvist & Ahman, 2016). FQHL, FQML and FQHM are designed with the gradually decreasing FQR over time, and thus these scenarios are analogous to the evolution of the high to low FQR in the EU ETS.

3.5. Evaluation criteria

In this paper, selecting the appropriate ETS component is determined by ETS cost, GDP loss, emission abatement and unit abatement cost. ETS cost refers to direct abatement cost including payment of auctioned quotas and penalty for over-emissions, whereas GDP loss denotes overall welfare loss incurred by ETS implementation. Emission abatement is the desired ETS outcome in this paper. Unit abatement cost (UAC_t) is straightforward to reveal which climate policy is cost-effective, and it is defined in Equation (5), according to Sartor et al. (2014). UCE_t and UFE_t refer to unit carbon emissions and free emissions under ETS, respectively. $SGDP_{it}$ denotes output of ETS-covered sector; P_t is carbon price.

$$UAC_t = P_t \times (UCE_t - UFE_t) = P_t \times \left(\frac{\sum_i CE_{it}}{\sum_i SGDP_{it}} - \frac{\sum_i FCQ_t}{\sum_i SGDP_{it}}\right). \tag{5}$$

In the Chinese Nationally Determined Contributions (NDC), China has pledged to peak its emissions before 2030; China pledged to lower its emissions per unit of GDP by 60%–65% in 2030 from the 2005 level (NDRC, 2015). In this paper, we have checked whether the final ETS will help China meet the NDC target in 2030.

4. Results

4.1. Sectoral coverage

Figure 2 shows the effect of sectoral coverage on ETS cost. According to Figure 2, higher sectoral coverage induces higher ETS cost. This is because higher coverage means more sectors participating in ETS, and thus overall abatement cost increases. Interestingly, the ETS costs in the EENP and FULL scenarios will increase in 2021–2024 but become stable thereafter, whilst the ETS costs in the other three scenarios will fluctuate over time.

In Supplementary Materials, Figure S1 shows how ETS sectoral coverage affects GDP loss over time. Higher sectoral coverage rate induces higher GDP loss, and thus sectoral-coverage effect on GDP loss is quite similar to that on ETS cost. Similarly, Figure S2 shows that sectoral coverage is positively related to emission abatement. Emission abatement will steadily decline in 2023–2030, implying that ETS emission abatement will diminish if sectoral coverage is the only designed ETS component.

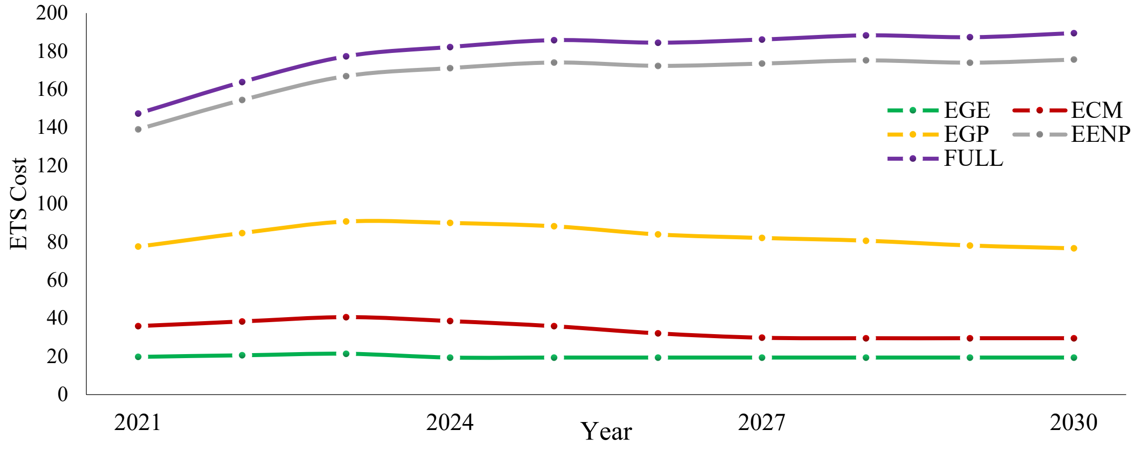

Figure 2. Sectoral coverage effect on ETS cost (unit: 10^9 CNY).

Figure S3 in Supplementary Materials denotes time-decreasing unit abatement cost (UAC), implying that ETS emission abatement will become less costly in future. Sectoral coverage significantly affects UAC, meaning that sectoral coverage is an indispensable ETS component. According to Figure S3, the highest UAC is in the EGE scenario, which resembles the CNETS covering electricity generation only. The ECM and EGP scenarios induce much lower UAC than the EGE scenario, implying that incorporating manufacture industries decreases UAC. The UAC in the EENP scenario is higher than that in the EGP scenario, implying that incorporating energy production sectors increases UAC. Although the FULL scenario induces the lowest UAC, the sectoral coverage is too broad, and thus it may not be easily applied in the CNETS. Hence, we believe that the sectoral coverage in the EGP scenario is more appropriate than the other scenarios, and thus it is adopted in this paper.

4.2. Carbon price

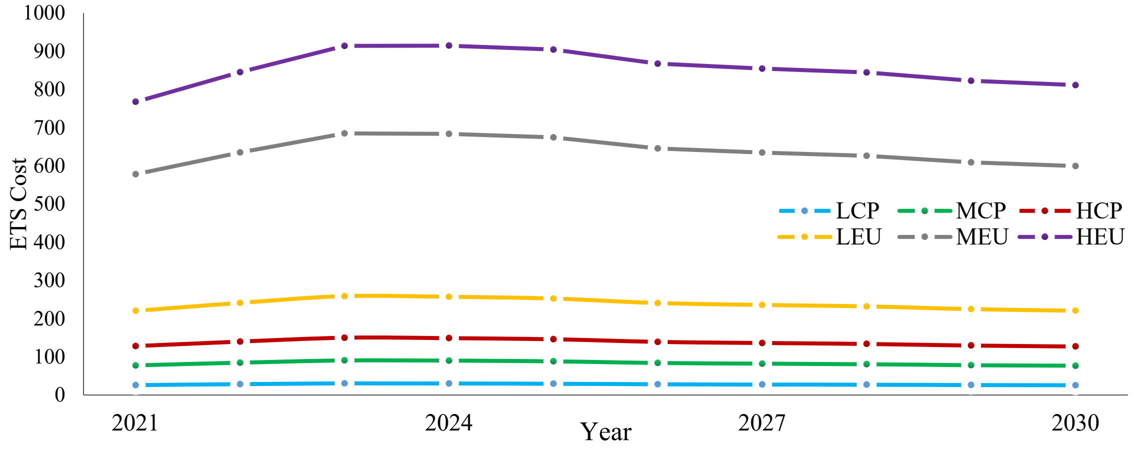

Figure 3. Carbon price effect on ETS cost (unit: 10^9 CNY).

According to Figure 3, higher carbon price induces higher ETS cost over time because auctioned quotas are costlier at higher price. As penalty price is assumed to be twice carbon price in this paper, higher carbon price also induces higher penalty price for over-emissions.

In Supplementary Materials, Figure S4 shows how carbon price affects GDP loss over time. Carbon price is positively related to GDP loss because it reflects the degree of intervention on market mechanism. Nevertheless, at higher price, more ETS revenues are collected both from auctioning quotas and fining over-emissions. Similarly, Figure S5 shows that carbon price is positively related to emission abatement because higher price induces higher mitigation cost, and thus rational entities have more incentives to abate emissions.

According to Figure S6, carbon price positively affects UAC, but the curves for UAC will be convergent in the long term, implying that higher carbon price may be preferable to lower price in the future. In this paper, we have chosen 175 $CNY/t\,CO_2$ as the appropriate price. Considering the current price in the CNETS is too low, we have not chosen a higher price, because there could be a long time for the evolution from low to high price, according to the EU ETS experience (ESMA, 2022). More importantly, exorbitant prices may induce some covered sectors to be overwhelmed (Lin & Jia, 2017), and thus ETS implementation may be severely hindered. Hence, medium carbon price is more practically meaningful.

4.3. Carbon quotas

How quota allocation scheme (QAS) affects ETS cost is shown in Figure 4. The ETS cost in the CQ05 scenario is much higher than that in the CQ20 scenario, implying that more quotas induce lower ETS cost. The ETS costs in the CQSE and CQCI scenarios are the lowest, implying that the QAS based on the last-year emissions or intensity induces the most quotas among the designed QAS. The flat curves in Figure 4 imply that this QAS effect is quite stable over time.

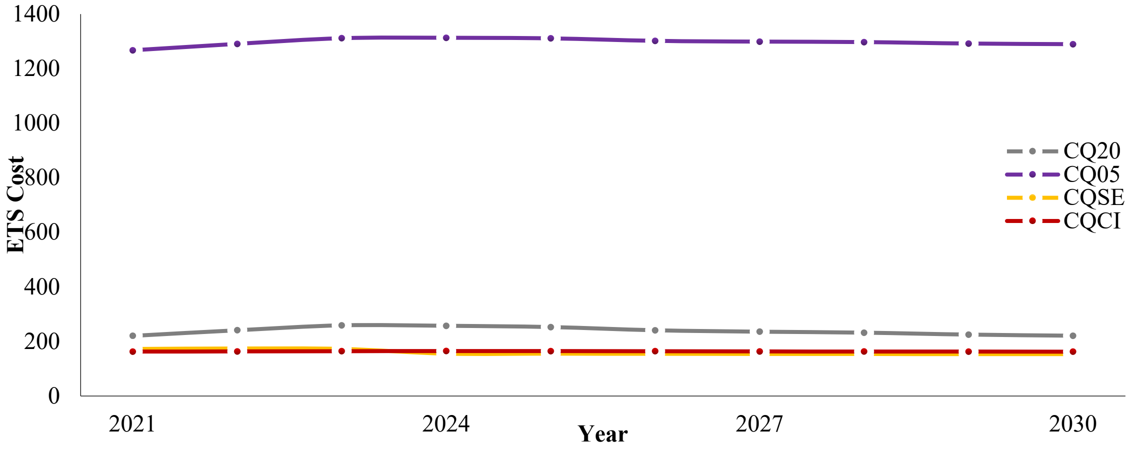

Figure 4. QAS effect on ETS cost (unit: 10^9 CNY).

In Supplementary Materials, Figure S7 shows that QAS with more quotas induces less GDP loss; therefore, QAS effect on GDP loss is similar to that on ETS cost. Figure S8 implies that the number of carbon quotas is negatively correlated with emission abatement because sectors have less incentives to abate emissions when more quotas are allocated. In Figure S9, the UAC in the CQ05 scenario is the highest, whilst the CQCI scenario has the lowest UAC. This result implies that UAC is negatively related to the number of quotas. Hence, we have adopted the QAS in the CQCI scenario.

According to Figure 5, quota decline factor (QDF) is negatively related to ETS cost. This result implies that although lower QDF means more quotas and thus looser emission cap, it induces higher ETS cost. In Figure 5, all the curves show similar trends over time: the curves will rise in 2021–2024 and decline in 2024–2030.

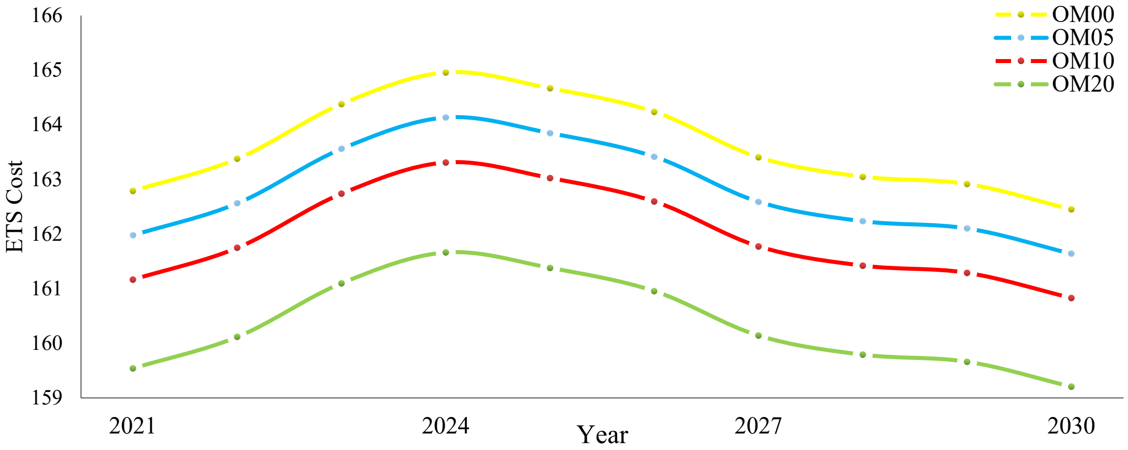

Figure 5. QDF effect on ETS cost (unit: 10^9 CNY).

In Supplementary Materials, Figure S10 shows higher QDF induces lower GDP loss. Similarly, Figure S11 displays that higher QDF induces less emission abatement; however, the scenario difference is minimal. In all the QDF-related scenarios, emission abatement steadily declines over time. According to Figure S12, QDF is positively related to UAC. Nevertheless, all the curves have downward trends, implying that the UAC will be lower in the future than that at present. Hence, the QDF in the OM20 scenario is deemed as the most appropriate QDF in this paper.

4.4. Free quota ratio

Figure 6 shows how free quota ratio (FQR) affects ETS cost. According to Figure 6, lower FQR induces higher ETS cost, because at lower FQR, more quotas are paid by sectors through auctions. This FQR effect remains stable in the FQ90, FQ50, FQ30 and FQ00 scenarios; in contrast, the ETS costs in the FQHL, FQML and FQHM scenarios will steadily increase over time, owing to the time-decreasing FQR. This is the case in the EU ETS where the declining free allowance rate increased mitigation cost (Christodoulou et al., 2021).

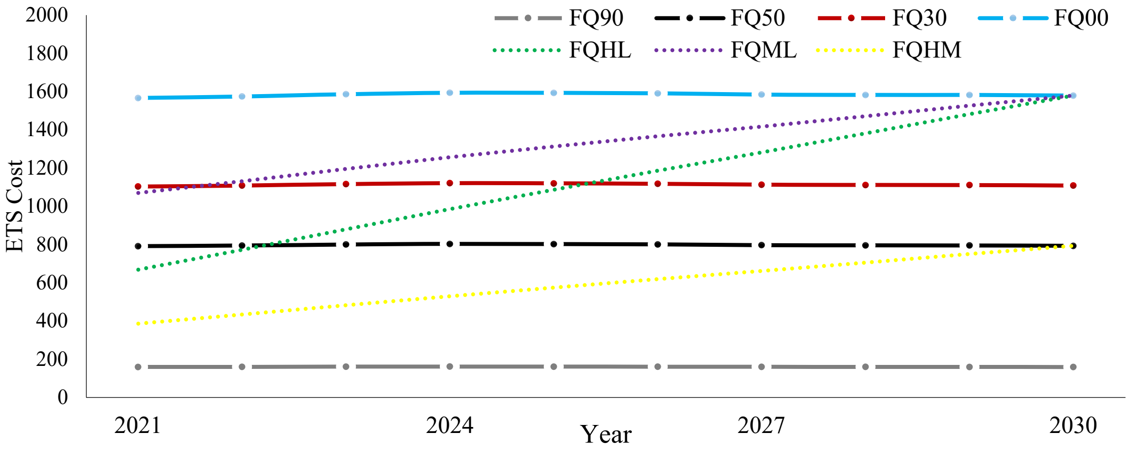

Figure 6. FQR effect on ETS cost (unit: 10^9 CNY).

In Supplementary Materials, Figure S13 implies that lower FQR induces more GDP loss. Similarly, Figure S14 shows that lower FQR induces more emission abatement, because at lower FQR, sectors have more incentives to abate emissions owing to costlier emission abatement. The curves for the FQHL and FQHM scenarios fluctuate over time, whereas emission abatement in the other scenarios gradually decreases with time-variant decrease rate. This finding implies that time-decreasing FQR is appealing, as it may counteract the time-decreasing ETS effect on emission abatement.

According to Figure S15 in Supplementary Materials, FQR is negatively related to UAC, and this effect is quite significant as the UAC in the FQ00 scenario is much larger than that in the FQ90 scenario. If FQR is fixed, UAC gradually declines over time; therefore, it is meaningful to adopt time-decreasing FQR to take advantages of the time-decreasing FQR effect on UAC. Currently, most quotas are allocated free in the CNETS; therefore, FQR should start at a prominent level in the designed ETS. In 2030, the UAC in the FQHL scenario may be too high, and it will be modest in the FQHM scenario. Hence, the time-decreasing FQR in the FQHM scenario is considered as the most appropriate FQR in this paper.

In summary, the appropriate ETS should be designed with the sectoral coverage in the EGP scenario, carbon price in the LEU scenario, quota allocation in the CQCI scenario, quota decline factor in the OM20 scenario and free quota ratio in the FQHM scenario.

4.5. ETS effects at sectoral level

To analyze ETS effects at the sectoral level, we have focused on the nonrenewable electricity generation (NEG) sector, consisting of supercritical coal generation, ultra-supercritical coal generation, sub-c coal generation and natural gas generation sectors in this paper. This is because the current CNETS covers the NEG sector only, and the emissions of the NEG sector are covered in all the designed scenarios in this paper.

In Supplementary Materials, Figures S16 and S17 show how sectoral coverage affects abatement cost and emission abatement of the NEG sector, respectively. Sectoral coverage has complicated effects on sectoral abatement cost, which will be the highest in the long term in the narrowest coverage.

Full sectoral coverage is also not recommended because sectoral abatement cost in the FULL scenario is higher than that in most scenarios. Sectoral emission abatement is positively related to ETS coverage, with wider coverage causing higher sectoral emission abatement. Similarly, Figures S18 and S19 imply that sectoral abatement cost and emission abatement are both positively related to carbon price.

In Supplementary Materials, Figures S20 and S21 show effects of the quota allocation scheme (QAS) on abatement cost and emission abatement of the NEG sector. ETS cost and emission abatement in the CQ05 scenario are much higher than that in the other scenarios because fewer quotas are allocated in the CQ05 scenario. Figures S22 and S23 display how quota decline factor (QDF) changes sectoral abatement cost and emission abatement. Rising QDF decreases sectoral abatement cost, but QDF minimally affects sectoral emission abatement. How the quota decline factor (QDF) affects sectoral abatement cost and emission abatement are shown in Figures S24 and S25, respectively. These two figures imply that sectoral abatement cost and emission abatement are negatively related to FQR.

4.6. NDC targets

It remains to be seen whether the appropriate ETS will help China meet the committed NDC targets in 2030. According to Figure S26 in Supplementary Materials, the Chinese carbon intensity will steadily decline over time under the ETS. The carbon intensity in 2005 was 0.31 $kg\ CO_2/CNY$, calculated based on China Energy Statistical Yearbook and China Input-Output Table. In 2030, the carbon intensity will be approximately 0.07 $kg\ CO_2/CNY$, which is less than 60% of the 2005 level. Hence, the ETS will help China meet the NDC target of lowering its intensity by 60%–65% from the 2005 level.

Figure S27 in Supplementary Materials shows ETS effect on the annual emission growth rate in China. The emission growth rate will become negative in 2026 and then slightly fluctuate in 2027–2030. Hence, the Chinese anthropogenic emissions may peak in 2026, and thus the ETS may help China meet the NDC target of peaking the emissions before 2030.

5. Discussion

As ETS could be the most efficient climate policy (Yoon & Jeong, 2016), we have studied economic and emission abatement effects of the designed ETS with the appropriate sectoral coverage, carbon price, quota allocation schemes, quota decline factor and free quota ratio.

Sectoral coverage is positively related to ETS cost and GDP loss. Similarly, Mu et al. (2018) argued that the economic cost of the nationwide ETS would be much larger than the ETS with the lower sectoral coverage. This finding disagrees with Lin and Jia (2020a) who argued that wider ETS coverage would lead to higher GDP performance. The result differences can be explained by the model assumptions: ETS components except coverage could vary freely in Lin and Jia (2020a), whilst we study effects of sectoral coverage by fixing other ETS components in this paper. Sectoral coverage is also positively related to emission abatement. Although the lowest unit abatement cost (UAC) is in the full sectoral coverage, we have not chosen the full sectoral coverage as the appropriate coverage. This is because participating sectors need to be carefully selected, owing to the difficulties in monitoring, reporting and verification for the full coverage in China (Lin & Jia, 2020b). Hence, we have chosen the sectoral coverage in the EGP scenario where the UAC is the second lowest.

Carbon price positively affects economic cost and emission abatement of ETS because price denotes marginal cost of emission abatement (Koch et al., 2014). Although the lowest price induces the lowest UAC, it undermines ETS capacity of emission mitigation (Lin & Jia, 2019). According to the EU ETS experience, higher prices may not increase compliance cost of achieving environmental targets (Abrell et al., 2019). Hence, 175 $CNY/t\ CO_2$ is chosen as the appropriate price, which is much higher than the current CNETS price.

In the quota allocation scheme (QAS), the number of quotas is negatively related to ETS cost. This finding complies with Yu et al. (2018) who concluded that a larger possession of initial quotas would lead to lower sectoral abatement cost. Fewer carbon quotas also increase GDP loss as stricter carbon cap would result in more GDP loss (Wang et al., 2015). Considering that UAC is negatively related to the number of quotas, we have chosen the QAS with the most quotas in this paper.

In addition to QAS, quota decline factor (QDF) also affects the number of quotas. The CGE model results show that QDF negatively affects ETS cost and emission abatement. This finding disagrees with Lin and Jia (2018) who argued that higher QDF would induce higher economic cost. The result differences lie in the price determination: the carbon price in Lin and Jia (2018) was endogenously determined by quota supply and demand whereas the price is fixed at the appropriate level in this paper. QDF positively affects UAC, but this QDF effect diminishes over time; therefore, the highest QDF (2%) is adopted to take advantage of the time-decreasing QDF effect on UAC.

Free quota ratio (FQR) significantly influences ETS effects. Zero FQR induces much higher economic cost and emission abatement, compared to positive FQR. This finding is in line with the previous research showing that FQR was negatively related to welfare (Li & Jia, 2016). Similarly, Wu and Li (2020) indicated that higher FQR would induce lower GDP loss and thus greater GDP. Although the highest FQR induces the lowest UAC, we have chosen time-decreasing FQR because free allocation distorts investment and hampers ETS efficiency (Bartels & Musgens, 2008).

In summary, the CGE model results in this paper fit in well with the literature except for some result differences caused by model assumptions. Nevertheless, this paper has several shortcomings to be addressed in future research. First, when designing ETS, we have overlooked essential ETS components, like revenue recycling (Li et al., 2019), penalty for over-emissions (Dong et al., 2016) and regional ETS disparity (Zhang et al., 2021). Only when all the important ETS components are considered will ETS be designed appropriately. Second, only direct ETS effects on economic cost and emission abatement are analyzed in this paper; however, ETS has indirect effects, like improving energy structure (Tang et al., 2016), promoting renewable energy exploitation (Yu et al., 2017) and enhancing technical progress (Zhou et al., 2020). Future research may collectively model both direct and indirect ETS effects in a policy evaluation framework. Lastly, in the CGE model, we have used the representative household to denote all the Chinese households, but this assumption disables us to study inequality impact of the ETS. The representative household of the CGE model can be divided into household groups to study how climate policy affects inequality, like urban-rural inequality (Jia et al., 2022b).

6. Conclusions and policy implications

In the ETS design, sectoral coverage is positively related to ETS economic cost and emission abatement. Although full sectoral coverage induces the lowest unit abatement cost (UAC), coverage of electricity generation and manufacturing sectors is more appropriate considering real constraints. Carbon price is positively related to ETS cost and emission abatement. Although the lowest price induces the lowest UAC, higher price is chosen to make use of the time-decreasing price effect on UAC and avoid low price undermining ETS abatement capacity.

Both quota allocation schemes (QAS) and quota decline factor (QDF) affect the number of quotas. If more quotas are allocated, ETS cost and emission abatement will be lower; by comparison, lower QDF induces higher ETS cost and emission abatement. As UAC is inversely related to the number of quotas, we have chosen the QAS with the most quotas. Conversely, QDF is positively related to UAC, but this QDF effect is slight and time-decreasing; therefore, the highest QDF (2%) is adopted in this paper.

Free quota ratio (FQR) influences ETS effects. Compared to positive FQR, zero FQR induces higher ETS cost and emission abatement. Although the highest FQR induces the lowest UAC, time-decreasing FQR has been chosen in this paper. This is because high FQR may be inefficient in the long term, and thus we have chosen the time-decreasing FQR resembling the FQR evolution in the EU ETS.

Overall, this paper implies that the CNETS should be designed with coverage of electricity generation and manufacturing sectors, higher carbon price, quota allocation based on the carbon intensity in the previous year, higher quota decline factor and time-decreasing free quota ratio. This designed ETS could help China meet the NDC targets of peaking the emissions before 2030 and lowering the intensity by 60%–65% in 2030 from the 2005 level.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

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