Carbon allowance auction design of China's emissions trading scheme: A multi-agent-based approach

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ABSTRACT

In this paper, a multi-agent-based ETS simulation model is proposed for carbon allowance auction design in China. In the proposed model, two main agents, i.e., the government (the ETS implementer) and the firms in different sectors (the ETS targets), are considered. Under the ETS policy, all agents make various decisions individually according to their own goals, and interact with each other through three main markets: the commodity market, the primary carbon auction market and the secondary carbon trading market. Different popular auction designs are introduced into the ETS formulation to offer helpful insights into China's ETS design. (1) Generally, the ETS would lead to positive effects on China's carbon mitigation and energy structure improvement, but a negative impact on economy. (2) As for auction forms, the uniform-price design is relatively moderate, while the discriminative-price design is quite aggressive in both economic damage and emissions reduction. (3) As for carbon price, the uniform-price auction might generate a slightly higher market clearing price than the discriminative-price auction, and the prices under two auction rules fluctuate about RMB 40 per metric ton. (4) As for carbon cap, the total allowances in the carbon auction market should be carefully set to well balance economic growth and mitigation effect.

1. Introduction

To effectively control carbon emissions, a cost-effective mitigation measure, emissions trading scheme (ETS), has aroused a world-wide attention. Different from other mitigation tools, ETS is a flexible approach using the market-driven mechanism rather than compulsory regulations (Egenhofer, 2007; Bredin and Muckley, 2011). In an ETS mechanism, each participant (usually represented by a firm) is allocated a certain quota of emissions permits in the primary ETS market, and trades with other participants in the secondary ETS market for additional permits to support its production or for benefit if redundant permits are left (Tang et al., 2016; Zhang et al., 2015). Since the first ETS market was built in the EU in the year 2005, the ETS has been popularly introduced as the most promising mitigation tool, such as in the Regional Greenhouse Gas Initiative (RGGI) of the U.S. in 2009, the New Zealand ETS in 2010, and the Domestic Emissions Reduction Scheme of Australia in 2012. As the largest carbon emitter, China announced seven ETS pilots in Beijing, Tianjin, Shanghai, Guangdong, Hubei, Chongqing and Shenzhen in 2011, and planned to build a nationwide ETS mechanism in 2017. Given that China's

current ETS policy varies largely across different pilots (see Table 1), an interesting question is raised concerning an appropriate ETS policy design for China. Under such a background, this study especially focuses on China's nationwide ETS, as well as the corresponding economic impact and mitigation effect, which reveals helpful policy implications for China's ETS design.

As a market-driven mitigation approach, the primary ETS market for initial allowance allocation may be the most important part in the ETS design (Zhang et al., 2014; Zhang and Hao, 2016). Table 1 lists the related information about the initial allowance allocation in the EU ETS and China's seven ETS pilots. According to the existing ETS policies and the related studies, the carbon allowance allocation methods can generally fall into history-based methods (e.g., grandfathering approach and benchmarking approach), auction-based methods (e.g., single-round auction and multi-round auction) and combinations coupling any two or more of above approaches. In current application, the history-based methods have widely been utilized for allocating free carbon permits, e.g., in the EU ETS and China's ETS pilot programs. However, for this market-driven tool of ETS, the auction-based methods possess their unique merits and have aroused

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Table 1
Related information about the initial carbon allowance allocation in the EU ETS and China's ETS pilots. (Source: Zhang et al. (2015), Tang et al. (2016), Xiong et al. (2017) and the Climate Action of European Commission (http://ec.europa.eu/clima/))

ETS market		Ratio of the corresponding permits to total carbon cap (%)			Allocation method for free permits		
		For free	For auction	At fixed prices	GF	BM	SD
China	Beijing	≥95%	< 5%	< 5%	√	√	
	Shanghai	100%	0%	0%	√	√	
	Tianjin	100%	0%	0%	√	√	
	Shenzhen	≤95%	≥3%	≥2%		√	
	Chongqing	100%	0%	0%			√
	Guangdong	≤97%	≥3%	0%	√	√	
	Hubei	≥90%	≤3%	< 7%	√	√	
EU ETS	Phase1	≥95%	≤5%	0%	√	√	
	Phase2	≥90%	≤10%	0%	√	√	
	Phase3	≤50%	≥50%	0%		√	

Notes: GF, BM and SD are the abbreviations for grandfathering, benchmarking and self-declaration methods, respectively; and the symbol "√" denotes the corresponding method is used.

an increasingly large interest. First, the auction markets for carbon allowances can effectively avoid the intrinsic shortcomings of the centralized allocation methods (particularly the history-based methods), i.e., political misallocation and regulatory distortion (Dewees, 2008; Dormady, 2014). Second, the auction-based methods can generate a higher surplus for consumers and a lower price level of products, compared with the grandfathering method (Goeree et al., 2010). Third, through market-based instruments, the auction-based methods cannot only reduce tax distortions but also provide greater incentive for technology innovation (Cramton and Kerr, 2002). To sum up, the history-based methods have led to inefficiencies in carbon market development, therefore, the auction-based methods are increasingly becoming the preferred allocation mechanism of policy-makers. For example, in the EU ETS and the four China's ETS pilots of Beijing, Shenzhen, Guangdong and Hubei, a certain proportion of carbon allowances are allocated via the auction-based methods. The RGGI allocates nearly 100% of carbon permits via the auction-based method (Dormady, 2014). Given such circumstances, the auction-based methods might be employed for allocating an increasingly larger proportion of emissions permits or even a 100% proportion in the later stages. Therefore, this paper specially focuses on the auction-based allocation methods and explores appropriate carbon allowance auction designs for China's ETS policy.

The auction forms can be generally divided into two main categories: static (or namely sealed and single-round) form and dynamic (or clock and multi-round) form. For carbon allowances, even though the question which auction form is better still remains a hot debate, an abundance of studies supported the former, due to its unique merits—simplicity of implementation, effectiveness in price discovery, and low transaction cost. For example, Cramton (1998) argued that due to the simplicity of implementation and bid evaluation, the sealed-bid auction can be considered as an effective auction form. Cong and Wei (2010) demonstrated that the static auction form with the virtue of simplicity outperforms the dynamic auction for carbon permits auction. Mandell (2005) argued that the multiple-round auction may be more conductive to collusion, while the single-round auction outperforms the multiple-round auction in terms of efficiency. Similarly, Burtraw et al. (2009) suggested that the clock auction is more likely to facilitate collusion than the sealed auction. Besides, due to a larger number of transactions, the multiple-round auction undoubtedly generates a much higher transaction cost than the single-round auction (Mandell, 2005; Klemperer, 2002). Goeree et al. (2013) suggested that the single-round form, e.g., the discriminatory price auction, can bring larger revenue for auctioneer than the clock auction. Similarly, Burtraw

et al. (2001) confirmed the superiority of the single-round auction over the clock auction, in terms of high revenue. Therefore, the simple but effective auction form, the single-round auction, is especially considered here for China's ETS design.

As for analysis techniques, the most popular numerical tools for investigating the ETS policy are simulation models, optimization programming models and experimental analysis methods. For simulation models, Edwards and Hutton (2001) examined the effects of various economic instruments for carbon emissions reduction, by employing the computable general equilibrium (CGE) model. Cong and Wei (2010) proposed a multi-agent-based simulation model to explore which carbon auction rule (the uniform-price or discriminative-price rule) is better. Similarly, Tang et al. (2015) developed a multi-agent-based simulation model for carbon emissions trading scheme, and evaluated its impacts on China's economy and environment. Tang et al. (2016) explored China's ETS based on a dynamic CGE model. As for optimization methods, Haita (2014) proposed an optimization model based on game theory to analyze the endogenous market power of an ETS auction market. As for experimental analysis, Cong and Wei (2012) compared uniform-price auction, discriminative-price auction and English clock auction in terms of carbon price, auction efficiency, demand withholding and fluctuations of power supplies. Similarly, Dormady (2014) studied the carbon emissions market via an experimental analysis approach. Among these above techniques, the typical bottom-up analysis technique, i.e., the multi-agent-based approach, possesses its unique merits for investigating the market-driven mitigation tool of ETS (Tang et al., 2015). In particular, the multi-agent-based model can effectively capture the activities and interactions between various specific agents in the economic system, in which a group of heterogeneous agents make independent decisions based on their respective goals and adjust their actions according to the changes of the external environment. Therefore, this study especially employs the multi-agent-based model to simulate the market-driven mitigation tool of ETS policy.

However, the existing numerical studies were mainly limited to one or some ETS-related sectors, which cannot capture the general impact of ETS on a nationwide scale. For example, Demailly and Quirion (2008) investigated the impacts of ETS only on iron and steel industry, Dormady (2014) for energy sector, Pentelow and Scott (2011) for tourism industry, Anger (2010) for aviation industry, Szabó et al. (2006) and Deja et al. (2010) for cement industry, and Cong and Wei (2010) for power sector. Nevertheless, given that China tends to establish a nationwide ETS in 2017, an overall evaluation for the impact of ETS on China's whole economy and environment becomes an urgent task (Tang et al., 2015). Therefore, this study tries to formulate a nationwide ETS simulation model covering different sectors in China's economic system, to explore an appropriate carbon allowance auction design for China's ETS policy.

Generally speaking, this study tries to build a nationwide ETS simulation model via the multi-agent-based approach, in which the auction-based allowance allocation is especially analyzed for China's ETS investigation. The major innovations of this paper can be summarized into the following three aspects. First, given that the ETS policy is a market-driven mitigation instrument, the most typical bottom-up analysis technique, i.e., the multi-agent-based model, is implemented to effectively capture the activities and interactions among various heterogeneous agents under the ETS, rather than the CGE approach (a typical top-down model) which conducts analyses at a whole sectoral level and fails to simulate the microscopic behaviors in the ETS market (such as carbon bidding, bidding strategy adjustment and speculation). Second, different from most existing numerical models focusing on certain ETS-related sectors, the proposed model covers all the sectors in China's economic system to provide a general analysis from the macroscopic perspective. Third, different designs in the carbon auction market, in terms of different auction forms and carbon caps, are investigated, which can offer helpful insights into

China's ETS design.

The main aim of this paper is to establish an ETS simulation model via the multi-agent-based approach and explore an appropriate carbon allowance auction design for China's ETS. The remainder of the paper is organized as follows. The proposed multi-agent-based ETS simulation model is formulated in Section 2. The simulation results are thoroughly analyzed, and some interesting policy suggestions can be obtained for China's ETS design, as discussed in Section 3. Section 4 concludes the paper and outlines the possible directions of future research.

2. Methodology formulation

In this section, a multi-agent-based ETS simulation model is formulated to investigate the ETS policy with different carbon allowance auction designs. Actually, this novel model is extended on the work by Tang et al. (2015), by incorporating the auction market for initially carbon allowance allocation. In the proposed model, two main types of agents, the government and firms in different sectors, are especially considered. Under the ETS policy, all agents would make various decisions individually according to their own goals, and interact with each other through three main markets, i.e., the commodity market, the primary ETS market (i.e., carbon auction market) and the secondary ETS market (i.e., carbon trading market). Each

agent behaves and adjusts its decisions according to political changes and market changes. Fig. 1 illustrates the general framework of the novel ETS simulation model.

As shown in Fig. 1, two main agents are especially considered in the proposed ETS simulation model, i.e., the government and firms. The government, as the implementer and supervisor of the ETS policy, behaves as the supplier of carbon allowances and the auctioneer in the primary carbon auction market, and behaves as the supervisor in the secondary carbon trading market to regulate the carbon price to guarantee market stability and avoid speculation. It is worth noticing that this study mainly focuses on the auction-based methods, and all the carbon permits are allocated via auction whereas free allowance is not considered in the proposed simulation model for simplicity. The firms behave as the main economic agents to produce, trade and consume commodities in the traditional commodity market, and also behave as the ETS targets to be bidders for carbon allowances in the primary ETS market and to be the traders to buy required permits or sell excess permits in the secondary ETS market.

2.1. Government agents

As the ETS implementer and supervisor, the behaviors of the government are (1) to provide the total carbon allowances $TotPermit_t$ in the primary carbon auction market at time t, (2) to regulate the
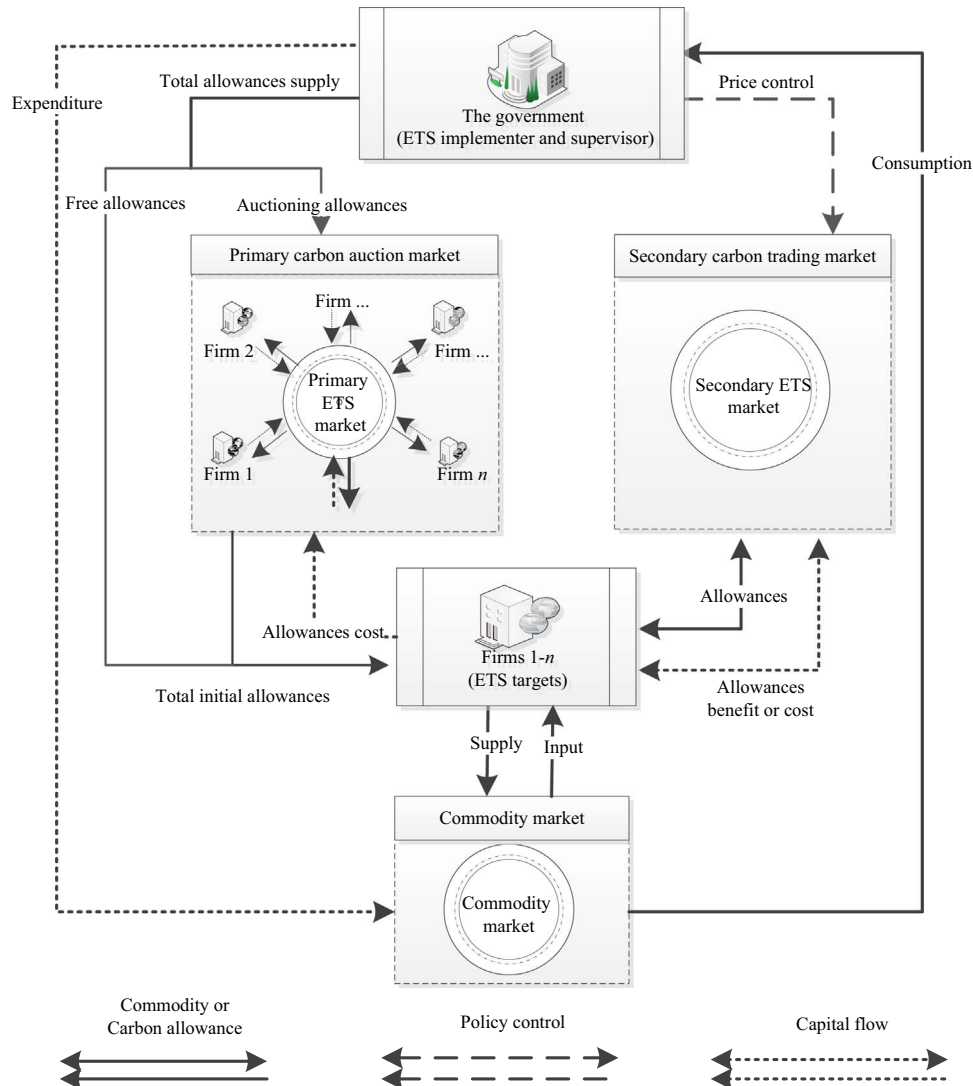

Fig. 1. General framework of the proposed ETS simulation model.

trading price $pc2_t$ in the secondary emissions trading market, (3) to observe the carbon dioxide emissions $C\_emission_{i,j,t}$ of different firms $j=1,2,…$ in different sectors $i=1,2,…$, (4) to impose penalties on illegitimate emissions, (5) to calculate the total carbon dioxide emissions $TCemission_t = \sum_i \sum_j Cemission_{i,j,t}$, and (6) to conduct its own ordinary economic activities (e.g., collecting taxes, consuming commodities and saving) (Tang et al., 2015). To reduce the total carbon emissions, the government controls the total carbon allowance supply (i.e., carbon cap) in the carbon market in terms of an annual mitigation rate η.

$$TotPermit_t = (1-\eta)TotPermit_{t-1}, \tag{1}$$

2.2. Firm agents

As the main economic agents and ETS targets, the behaviors of firms mainly involve making various decisions of outputs, bids for carbon allowances (in the primary ETS market), transactions of carbon allowances (in the secondary ETS market), production, commodity sales (in the traditional commodity market) and bidding strategy adjustments for the next period, as the flow diagram illustrated in Fig. 2. In the novel model, all firms are assumed to be rational agents in making these decisions. In particular, each firm first determines the output level according to business performance. Second, each firm makes the carbon bidding strategy, in terms of bid price and bid volume, according to the output decision and risk preference. To gain maximal profits, each firm makes the production decision with the cost minimization principle, sells excess carbon allowances for benefit or buys required allowances for avoiding penalty, and makes the marketing plan based on the sale maximum principle. Finally, each firm adjusts the carbon bidding strategy based on the historical experience and adaptive learning capability.

2.2.1. Output decision

At time t, firm j in sector i determines its output level $X_{i,j,t}$ according to its current business performance, in terms of the profit changes in the last stage, by following the learning principle (Liu et al., 2012).

$$X_{i,j,t} = \begin{cases} X_{i,j,t-1} + \Delta x_t, & \pi_{i,j,t-1} - \pi_{i,j,t-2} > \delta \\ X_{i,j,t-1}, & |\pi_{i,j,t-1} - \pi_{i,j,t-2}| \leq \delta \\ X_{i,j,t-1} - \Delta x_t, & \pi_{i,j,t-1} - \pi_{i,j,t-2} < -\delta \end{cases}, \tag{2}$$

where $\pi_{i,j,t}$ and $X_{i,j,t}$ represent the profit and the output of firm j in sector i at time t, and the nonnegative parameters Δx_t and δ denote the output adjustment and a given threshold, respectively. According to Eq. (2), firms decide to increase their output levels when the profits grew remarkably higher in the last period, to decrease the outputs when the profits declined drastically, or to remain the same levels when the changes in profit were limited within the given range $[-\delta, \delta]$.

2.2.2. Carbon bidding decision

In the primary ETS market, firms make different bidding strategies according to their different risk preferences and production plans, in which the private-value model is employed (Cong and Wei, 2010). Provided that each firm has a reservation price $pv_{i,j,t}$, i.e., the upper boundary of bid price determined based on the expected cost, which is known only by the firm itself. In particular, the reservation price $pv_{i,j,t}$ can be considered as the marginal profit of emitting a unit of carbon emissions in the previous period (Cong and Wei, 2010), as defined in Eq. (11). Accordingly, each firm will generate a bid price $pb_{i,j,t}$ no more than the reservation price, i.e., $pb_{i,j,t} \leq pv_{i,j,t}$ (as the determination process described in Section 2.2.6), and a bid volume $qb_{i,j,t}$ (i.e., the required carbon allowances for supporting its production).

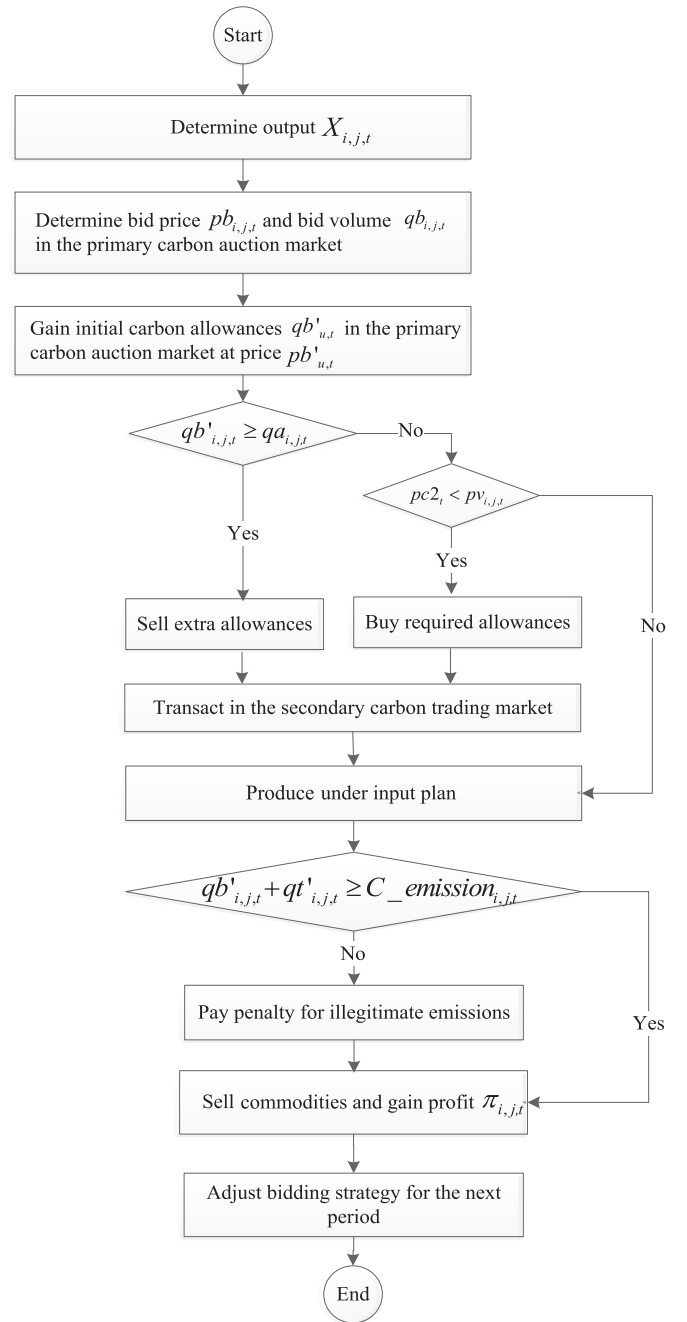In the carbon auction market, all firms are ranked in the order (i.e.,

Fig. 2. Flow chart of firm actions.

$u=1, 2,…, n$) from the highest bid price to the lowest bid price regardless of sectors. Accordingly, the equilibrium price $ep_t = pb_{u=m,t}$, $(m \leq n)$ can be obtained when the accumulated quantity reaches the total allowance supply, i.e., $\sum_{u=1}^{m} qb_{u,t} \leq TotPermit_t$ and $\sum_{u=1}^{m+1} qb_{u,t} > TotPermit_t$. For firm u, if its bid price $pb_{u,t}$ exceeds the equilibrium price, i.e., $pb_{u,t} \geq ep_t$ (or $u \leq m$), it wins in the carbon auction market and gains the carbon allowances; or it fails the bid and gets no carbon allowance otherwise.

In this paper, the most two popular auction forms, i.e., the uniform-price auction and the discriminative-price auction, are especially introduced into the ETS formulation. As for the uniform-price form, all winning firms (i.e., $u \leq m$) pay for the carbon allowances at the same level of the equilibrium price, i.e., $pb'_{u,t} = ep_t$, where $pb'_{u,t}$ denotes the price that the firm u pays for the carbon allowances in the carbon auction market at time t. The market clearing price pc_t is equal to the equilibrium price, i.e., $pc_t = ep_t = pb_{u=m,t}$. The actual carbon price $pb'_{u,t}$

and the gained volume $qb'_{u,t}$ of firm u in the primary carbon auction market are calculated according to Eq. (3) and Eq. (4), respectively (Liu et al., 2012).

$$pb'_{u,t} = \begin{cases} pc_t = pb_{m,t}, & u \leq m \\ +\infty, & u > m \end{cases}, \tag{3}$$

$$qb'_{u,t} = \begin{cases} qb_{u,t}, & pb_{u,t} > pb_{m,t} \\ qb_{u,t}\left(TotPermit_t & pb_{w,t} = ... = pb_{u,t} = ... = pb_{m,t}, w \leq u \\ \quad - \sum_{j=1}^{w-1} qb_{j,t}\right)/\sum_{j=w}^{m} qb_{j,t}, & \leq m \\ 0, & pb_{u,t} < pb_{m,t} \end{cases} \tag{4}$$

As for the discriminative-price form, different winning firms pay for the carbon allowances at different prices $pb'_{u,t}$ according to their different bid prices $pb_{u,t}$:

$$pb'_{u,t} = \begin{cases} pb_{u,t}, & u \leq m \\ +\infty, & u > m \end{cases}. \tag{5}$$

Firms gain carbon allowances $qb'_{u,t}$ similarly by following Eq. (4), while the market clearing price pc_t is otherwise calculated by Eq. (6).

$$pc_t = \sum_{u=1}^{m} pb_{u,t}qb_{u,t}/\sum_{u=1}^{m} qb_{u,t} \tag{6}$$

2.2.3. Carbon trading decision

From the primary carbon auction market, the firm u can gain its initial carbon allowances $qb'_{u,t}$. Then, the firm will further trade the carbon allowances with other firms through the secondary carbon trading market. In particular, if the allowances gained in the primary carbon market $qb'_{i,j,t} = qb'_{u,t}$ (where u denotes the order of firm j in sector i in the primary carbon auction market according to its bid price) exceeds the required emissions $qa_{i,j,t}$ during production, the firm will sell the extra allowances in the second carbon trading market for benefit, i.e., $qt_{i,j,t} = qa_{i,j,t} - qb'_{i,j,t} < 0$, where $qt_{i,j,t}$ denotes the net carbon permits which the firm j of sector i want to buy in the second carbon trading market at time t.

For the firms without enough allowances, i.e., $qt_{i,j,t} = qa_{i,j,t} - qb'_{i,j,t} \geq 0$, they will buy additional permits under the condition that the trading price $pc2_t$ in the secondary carbon trading market is no more than their respective reservation prices $pv_{i,j,t}$ (the highest levels they can afford), i.e., $pv_{i,j,t} > pc2_t$; or they will quit without the carbon trading activity otherwise.

2.2.4. Production decision

Based on the cost minimization principle, the constant elasticity of substitution (CES) production function is employed for firms to make production decisions. A five-layer nested structure (Bao et al., 2013; Tang et al., 2015, 2016) is built to describe the substitutions among various inputs. In the first layer, the fossil energy input $F_{i,j,t}$ of firm j in sector i at time t is comprised of six fossil energy resources $Fn_{n, i,j,t}$, where $n=1,2,...,6$ respectively denotes coal (M_C), crude oil (M_O), natural gas (M_G), processing oil (OIL), coke (COK) and gas (GAS). In the second layer, the energy input $E_{i,j,t}$ is comprised of the electricity input $ELE_{i,j,t}$ and the fossil energy input $F_{i,j,t}$. In the third layer, the energy composite input $E_{i,j,t}$ and capital investment $K_{i,j,t}$ compose the capital-energy input $KE_{i,j,t}$ with an energy factor-productivity coefficient $\theta_{i,j,t}$:

$$\begin{cases} \min \ (PE_{i,j,t}E_{i,j,t} + R_t K_{i,j,t}) \\ s.t. \quad KE_{i,j,t} = (\theta_{i,j,t}\alpha_{e,i}E_{i,j,t}{}^{\rho_{e,i}} + (1 - \alpha_{e,i})K_{i,j,t}{}^{\rho_{e,i}})^{1/\rho_{e,i}}, \end{cases} \tag{7}$$

where $PE_{i,j,t}$ denotes the composed price of energy input at time t, and R_t is the interest rate of capital investment. $\alpha_{e,i}$ represents the share of

energy input when composing the capital-energy input in sector i, and $\rho_{e,i} = (\sigma_{e,i} - 1)/\sigma_{e,i}$ (where $\sigma_{e,i}$ is the elasticity of substitution between energy input and capital investment). Then, the capital-energy input $KE_{i,j,t}$, combined with the labour input $L_{i,j,t}$, constitutes the capital-energy-labour input $KEL_{i,j,t}$ in the fourth layer. Meanwhile, the combined intermediate input $INT_{i,j,t}$ is comprised of various intermediate non-energy commodities using a Leontief function, as described in Eq. (8).

$$INT_{i,j,t} = \min\left(\frac{Int_{1,i,j,t}}{\alpha_{1,i}}, \frac{Int_{2,i,j,t}}{\alpha_{2,i}}, ..., \frac{Int_{7,i,j,t}}{\alpha_{7,i}}\right), \tag{8}$$

where $Int_{s, i,j,t}(s=1,2,...,7)$ denotes the intermediate input of non-energy commodity s used by the firm j in sector i at time t, and $\alpha_{s,i}$ is the input-output coefficient. The final output $X_{i,j,t}$ produced by firm j in sector i at time t is comprised of the total intermediate input $INT_{i,j,t}$ and the capital-energy-labour input $KEL_{i,j,t}$ via a CES function, at the top level of the nested production structure.

In the production process, the carbon dioxide emissions are generated when using the inputs of the primary energy (i.e., the six fossil energy resources).

$$Cemission_{i,j,t} = \sum_{n=1}^{6} a_n b_n c_n Fn_{n,i,j,t} \times \frac{44}{12}, \tag{9}$$

where $C\_emission_{i,j,t}$ denotes the carbon dioxide emissions generated by firm j in sector i at time t, and $Fn_{n, i,j,t}(n=1, 2,..., 6)$ denotes the input of fossil energy n. a_n, b_n and c_n are conversion factor, emissions factor and oxidization factor of fossil energy n, respectively.

2.2.5. Profit calculation

The firm j of sector i sells outputs in the traditional commodity market, gains profit $\pi_{i,j,t}$, and evaluates the reservation carbon price $pv_{i,j,t+1}$ for the next period (Cong and Wei, 2010):

$$\pi_{i,j,t} = Sales_{i,j,t} - Ecost_{i,j,t} - Interput_{i,j,t} - Tax_{i,j,t} - Labcost_{i,j,t} - Capcost_{i,j,t} \\ - Ccost_{i,j,t} \quad - Penalty_{i,j,t}, \tag{10}$$

$$pv_{i,j,t+1} = (Sales_{i,j,t} - Ecost_{i,j,t} - Interput_{i,j,t} - Tax_{i,j,t} - Labcost_{i,j,t} \\ - Capcost_{i,j,t})/Cemission_{i,j,t}, \tag{11}$$

where $\pi_{i,j,t}$ represents the profit of firm j in sector i at time t, $Sales_{i,j,t} = P_{i,t}Q_{i,j,t}$ is the sales income (where $P_{i,t}$ and $Q_{i,j,t}$ respectively denote the price of commodity i and the sales amount by firm j in sector i at time t), $Ecost_{i,j,t} = \sum_{n=1}^{6} PF_{n,t}Fn_{n,i,j,t} + P_{ele,t}ELE_{i,j,t}$ is the expenditure for the energy input (where $PF_{n,t}$ and $Fn_{n, i,j,t}$ denote the price and the input of fossil energy n, and $P_{ele,t}$ and $ELE_{i,j,t}$ represent the price and input of electricity, respectively), $Interinput_{i,j,t} = \sum_{s=1}^{7} PInt_{s,t}Int_{s,i,j,t}$ is the expenditure for the intermediate inputs (where $PInt_{s,t}$ and $Int_{s, i, j,t}$ respectively denote the price and the input of non-energy commodity s), $Tax_{i,j,t}$ is the production tax to the government, and $Labcost_{i,j,t}$ and $Capcost_{i,j,t}$ are respectively the costs of the labour and capital inputs.

Besides, $C\_cost_{i,j,t}$ and $Penalty_{i,j,t}$ denote the expenditure for carbon allowances and the penalty for illegitimate carbon emissions of firm j in sector i at time t, respectively. In particular, the total carbon allowances cover the permits gained in both the primary and secondary carbon markets:

$$Ccost_{i,j,t} = pb'_{i,j,t} \cdot qb'_{i,j,t} + pc2_t \cdot qt'_{i,j,t}, \tag{12}$$

where $pb'_{i,j,t} = pb'_{u,t}$ (where u denotes the order of the firm j in sector i in the primary carbon auction market according to its bid price), and $qt'_{i,j,t}$ represents its actual net trading volume in the second carbon trading market (see Eqs. (22) and (23)).

As for the penalty $Penalty_{i,j,t}$, if the actual carbon emissions generated during the production process exceed the total carbon permits $Permit_{i,j,t} = qb'_{i,j,t} + qt'_{i,j,t}$ from the two carbon markets, i.e., $Cemission_{i,j,t} > Permit_{i,j,t}$, the firm should be punished to pay the penalty

for such non-compliance carbon emissions:

$$NonCompliance_{i,j,t} = Cemission_{i,j,t} - Permit_{i,j,t},\qquad(13)$$

$$Penalty_{i,j,t}$$

$$= \begin{cases} 0, & NonCompliance_{i,j,t} < 0 \\ \xi pc_t \cdot NonCompliance_{i,j,t}, & 0 \le NonCompliance_{i,j,t} < PenaltyCa \\ & p_{i,t}/pr_t \\ PenaltyCap_{i,t}, & NonCompliance_{i,j,t} \ge PenaltyCap_{i,t}/ \\ & pr_t \end{cases},$$

(14)

where ξ is the penalty multiplier, which is practically set above 1 to ensure the penalty price (or rate) $pr_t = \xi pc_t$ is higher than the carbon market clearing price pc_t, and $PenaltyCap_{i,t}$ is the upper boundary of the penalties for the firms in sector i. According to the Chinese law, the penalty for a firm is often subject to a cap $PenaltyCap_{i,t}$, thus that the marginal cost of exceeding the cap becomes zero. However, the penalty caps are set to a sufficiently large value in this study, for simplicity.

2.2.6. Bidding strategy adjustment

As rational agents with adaptive learning capabilities, all firms adjust the bidding strategies according to the historical behaviors. Given that the losers in the primary carbon auction market gaining no carbon allowance would bear a much higher probability to be punished and suffer greater losses, they will adjust their bidding strategy with the main aim at winning the bids for the next period. In particular, for the firm j in sector i, if the bid price $pb_{i,j,t}$ is too low (i.e.,$pb_{i,j,t} < ep_t$) to win the auction, it adjusts $pb_{i,j,t}$ for the next period according to the following principle (Erev and Roth, 1998; Nicolaisen et al., 2001; Cong and Wei, 2010):

Strategy 1(for risk preference firms): $pb_{i,j,t+1} = pc_t + \frac{3}{4}(pv_{i,j,t} - pc_t)$,

Strategy 2 (for risk neutral firms): $pb_{i,j,t+1} = pc_t + \frac{1}{2}(pv_{i,j,t} - pc_t)$,

Strategy 3 (for risk averse firms): $pb_{i,j,t+1} = pc_t + \frac{1}{4}(pv_{i,j,t} - pc_t)$.

At time t=0, the firm j of sector i determines its bid price $pb_{i,j,t=0}$ randomly on the range of (0, $pv_{i,j,t}$], and the initial probability of choosing each strategy is set to be the same, i.e.,$prob_{x,i,j,t=0} = 1/3$, where $prob_{x,i,j,t}$ denotes the probability that firm j of sector i adopts the strategy $x \in \{1,2,3\}$ at time t. This probability $prob_{x,i,j,t}$ will be adjusted based on the propensity $prop_{x,i,j,t}$ toward strategy x.

$$prop_{x,i,j,t+1} = (1 - g)prop_{x,i,j,t} + \varphi_{x,i,j,t},\qquad(15)$$

$$\varphi_{x,i,j,t} = \begin{cases} (1 - e)\pi_{i,j,t}, & x = x_{i,j,t} \\ \frac{e}{2}\pi_{i,j,t}, & x \ne x_{i,j,t} \end{cases},\qquad(16)$$

where e denotes the experiment parameter and g represents the recency parameter, which are experimentally set to be 0.2 and 0.1, respectively (Erev and Roth, 1998; Cong and Wei, 2010). $x_{i,j,t} \in \{1, 2, 3\}$ is the strategy selection of firm j in sector i at time t. Accordingly, the probability of choosing strategy x for the next period is calculated by Eq. (17):

$$prob_{x,i,j,t+1} = prop_{x,i,j,t+1}/\sum_{k=1}^{3} prop_{k,i,j,t+1}.\qquad(17)$$

Accordingly, a firm selects the bidding strategy for the next period, by following Eq. (18):

$$x_{i,j,t+1} = \begin{cases} 1, & 0 \le r < prob_{1,i,j,t+1} \\ 2, & prob_{1,i,j,t+1} \le r < prob_{1,i,j,t+1} + prob_{2,i,j,t+1}, \\ 3, & prob_{1,i,j,t+1} + prob_{2,i,j,t+1} \le r \le 1 \end{cases}$$

(18)

where r is a random term on the range of [0,1].

2.3. Markets

In the proposed model, three main markets are involved, i.e., the traditional commodity market, the primary carbon auction market and the secondary carbon trading market, through which various agents interact with each other.

In the commodity market, the total supply of commodity i derives from the outputs of all firms in sector i, and the total demand mainly includes the production inputs used by different firms in different sectors, the investment inputs by different firms and the consumptions by other economic agents (e.g., the government and households). The price $P_{i,t}$ of commodity i is determined based on the cost-plus pricing principle (Matsui, 2012; Zhang et al., 2013):

$$P_{i,t} = (Ecost_{i,j,t} + Interput_{i,j,t} + Tax_{i,j,t} + Labcost_{i,j,t} + Capcost_{i,j,t} + Ccost_{i,j,t})(1 + profitrate_{i,t})/X_{i,j,t},\qquad(19)$$

where $profitrate_{i,t}$ is the mean profit rate of sector i at time t. As an effective market-driven mitigation tool, the ETS policy will stimulate the ETS targets (i.e., the firms) to reduce their carbon emissions, i.e., abatement behavior, through both substitution and income effects in the commodity market. On the one hand, the carbon costs for permits $C\_cost_{i,j,t}$ and the penalty for non-compliance emissions $NonCompliance_{i,j,t}$ will directly enhance the total production cost and hence the production price. Under this situation, the emission-intensive commodities will suffer from a sharp reduction in sales, given that firms prefer to the other inputs at lower prices when making the production decision (see Section 2.2.4). Through such a substitution effect, the ETS policy will effectively abate the total carbon emissions through production structure improvement, in which emissions-intensive output will be largely suppressed. On the other hand, as an adaptive learning agent, an emission-intensive firm, with a relatively low profit due to high carbon cost or/and penalty, will definitely cut down both the output level (see Eq. (2)) and the reservation carbon price (see Eq. (11)), which leads to an emissions shrinkage (see Eq. (9)) and a relatively small probability to win the auction (see Eq. (4)), respectively. Therefore, this income effect of ETS policy will largely promote firms' carbon abatement behavior, which largely reduces the total emissions.

In the primary carbon auction market, the firms gain the initial carbon allowances. The total carbon allowances $TotPermit_t$ are provided by the government (see Eq. (1)). The firms, as the bidders, bid for carbon allowances based on their production plans, as presented in Section 2.2.2. To determine the carbon price $pb'_{i,j,t}$, two popular auction pricing rules (i.e., the uniform-price form and discriminative-price form) are especially introduced, as also mentioned in Section 2.2.2. Besides, the firms, as rational agents with adaptive learning capabilities, make adjustments on their bidding strategies for the next period based on their historical bidding experiences and heterogeneous risk preferences, as discussed in Section 2.2.6.

Due to expectation distortion and contest tender risk, some firms cannot obtain sufficient permits from the primary carbon auction market to meet their actual emissions; therefore, they tend to buy the required permits or sell the extra amounts $qt_{i,j,t}$ in the secondary carbon trading market, as mentioned in Section 2.2.3. The market-maker method (LeBaron, 2006) is employed as the price formation mechanism in the secondary carbon trading market. Rather than a market clearing price in an ideal equilibrium in which total demand equals total supply, the carbon price in the secondary ETS market is determined by the difference between total permit supply $Permitsupply_t$ and total permit demand $Permitdemand_t$. When $Permitsupply_t \ge Permitdemand_t$, the secondary carbon trading market is a buyer's market, in which the carbon price will decrease and the actual trading volume $qt'_{i,j,t}$ of the firm j in sector i is calculated according to Eq. (22); or otherwise, the market becomes a seller's market, in which the carbon price will increase and $qt'_{i,j,t}$ is based on

Eq. (23).

$$Permitsupply_{t'} = \sum_{qt_{i,j,t}<0} -qt_{i,j,t}, \ t = 1, 2, \ldots, \quad (20)$$

$$Permitdemand_t = \sum_{qt_{i,j,t}\geq 0} qt_{i,j,t}, \ t = 1, 2, \ldots, \quad (21)$$

$$qt'_{i,j,t} \Big|_{Permit.supply_t \geq Permit.demand_t} = \begin{cases} 0, & qt_{i,j,t} = 0 \\ Permitdemand_t \cdot qt_{i,j,t}/Permit.supply_t, & qt_{i,j,t} < 0, \\ qt_{i,j,t}, & qt_{i,j,t} > 0 \end{cases} \quad (22)$$

$$qt'_{i,j,t} \Big|_{Permit.supply_t < Permit.demand_t} = \begin{cases} 0, & qt_{i,j,t} = 0 \\ Permit.supply_t \cdot qt_{i,j,t}/Permit.dmand_t, & qt_{i,j,t} > 0. \\ qt_{i,j,t}, & qt_{i,j,t} < 0 \end{cases} \quad (23)$$

As for the carbon price, to maintain market stability and avoid speculations, some China's existing ETS markets, e.g., in Beijing, Shenzhen and Hubei, would reserve a small amount of allowances to stabilize the carbon trading prices (Xiong et al., 2017). Therefore, the carbon trading price $pc2_t$ in the secondary ETS market is controlled around the market clearing price of the primary ETS market pc_t within a certain range $\alpha \sim U(0\%, 30\%)$.

$$pc2_t = \begin{cases} (1+\alpha)pc_t, & Permit.supply_t \leq Permit.demand_t \\ (1-\alpha)pc_t, & Permit.supply_t > Permit.demand_t \end{cases}. \quad (24)$$

For a clear explanation, Fig. 3 describes the main decision variables of a firm's ETS-related activities and the ETS markets, together with their relationships.

2.4. Data descriptions and model calibration

All sectors (or commodities) in China's economic system are aggregated or disaggregated into 14 sectors according to different characteristics of energy intensity and carbon emissions intensity

Table 2
Codes of sectors (or commodities).

ID	Code	Full title of the sector (or commodity)
Sector 1	AGR	Agriculture
Sector 2	M_C*	Coal
Sector 3	M_O*	Crude oil
Sector 4	M_G*	Natural gas
Sector 5	MIN	Other Mining
Sector 6	MAF	Manufacture
Sector 7	OIL*	Processing oil
Sector 8	COK*	Coke
Sector 9	ELE*	Electric power and heat power
Sector 10	GAS*	Gas
Sector 11	WTR	Water
Sector 12	CNS	Construction
Sector 13	TRP	Transportation and information services
Sector 14	OSR	Other services

Notes: "*" denotes the energy sector (or commodity).

(Tang et al., 2015), as listed in Table 2. Seven energy sectors are especially investigated due to their different properties of carbon emissions intensity and energy efficiency, amongst which electric power and heat power (ELE) is secondary energy, while the other six resources are primary energies (or fossil energies).

For model initialization, the initial values of various decision variables are specified based on the latest real data for China's economy (Tang et al., 2015). In particular, the sectoral outputs in the base period $TsX_{i,t=0} = \sum_{j=1}^{n_i} X_{i,j,t=0}$ are derived from the Chinese national input-output (IO) data for the year 2007, and the number of firms in sector i, n_i, is obtained from the China Statistical Yearbook 2013 and the related official news. The initial output of firm j in sector i is assumed to follow a normal distribution, i.e., $X_{i,j,t=0} \sim N(u_i, \sigma_i^2)$, where the mean $\mu_i = Ts\_X_{i,t=0}/n_i$ and the variance σ_i^2 are calculated based on the real data for the main firms. The initial values for other decision variables of firms are generated in a similar way. The initial income of the government and various tax rates are obtained from the China Fiscal Statistical Yearbook 2013. For the ETS policy, the initial total
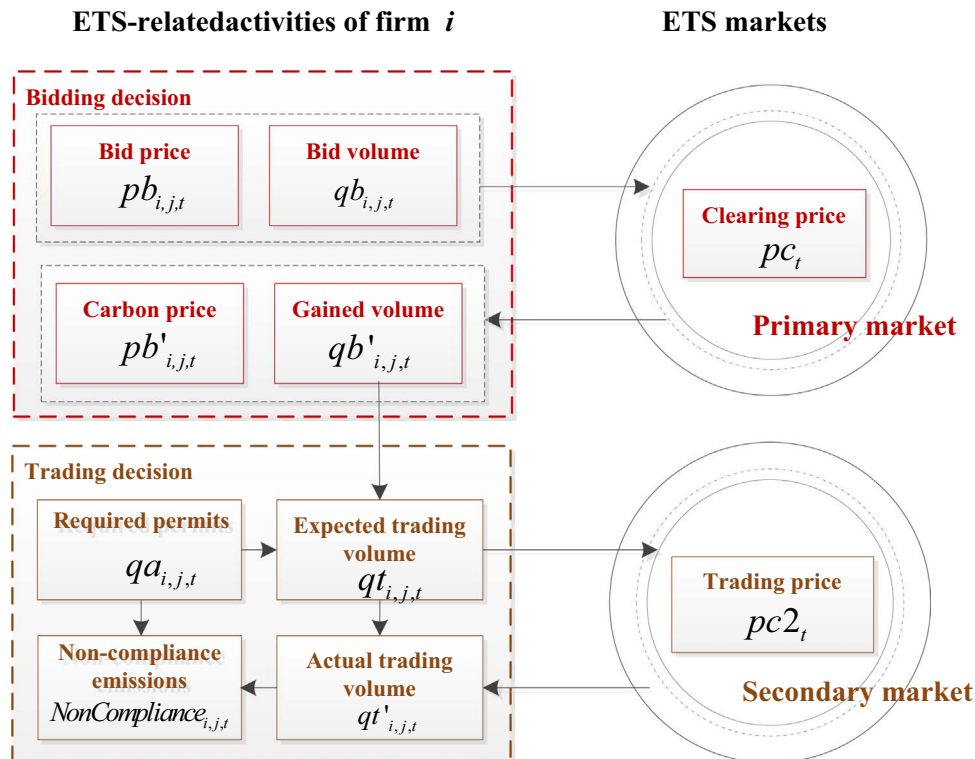
ETS-relatedactivities of firm *i*   ## ETS markets

Fig. 3. The main decision variables of a firm's ETS-related activities and the ETS markets.

allowance supply $TotPermit_{t=0}$ is set to 60% of the total national carbon emissions, and the penalty rate is experimentally set to three times of carbon market clearing price based on existing ETS markets.

As for model calibration and parameter settings, the share parameters and scale parameters are calibrated based on the Chinese national IO data for 2007. The other parameters, e.g., the substitution elasticity parameters, are specified according to the related studies (Bao et al., 2013; Tang et al., 2015). The factors in carbon emissions computation are obtained from the Intergovernmental Panel on Climate Change (IPCC).

3. Experimental analysis

Based on the proposed multi-agent-based ETS simulation model, the impacts of the ETS policy with different auction-based allowance allocations on China are thoroughly studied, for exploring appropriate auction designs in China's ETS. First, different policy scenarios with different auction designs are set in Section 3.1. Second, the simulation results are analyzed in detail in Section 3.2.

3.1. Scenario settings

To investigate the ETS policy in China, the baseline case without ETS is first run by the model, designated as business as usual (BAU). Then, a set of ETS policies with different carbon auction designs are simulated, in terms of different auction forms and allowance supplies. The impacts of different ETS designs are estimated in terms of the differences in the simulation results between the BAU and various ETS policy scenarios.

As for auction form in the primary ETS market, two popular auction rules are especially introduced, i.e., the uniform-price rule and the discriminative-price rule. In particular, the uniform-price auction was adopted in the pilot ETS program of Guangzhou, China during 2013–2015, and the static sealed auction was employed in EU ETS during the first phase. Therefore, the two most typical sealed auction forms are considered in this paper, i.e., the uniform-price form and discriminative-price form, labelled as Scenarios A1 and A2 respectively. Based on different auction forms, the prices of carbon allowances are determined in different ways, according to Eq. (3) for the uniform-price form and Eq. (5) for the discriminative-price form.

As for allowance supply, the mitigation rate η in Eq. (1) is suggested to be about 3% per year, according to China's current carbon emissions level and carbon reduction goal. During the third phase of EU ETS (2013–2020), the allowances were expected to decrease by 1.74% per year. According to the RGGI, the decrease rate of carbon allowances is advised to be 2.5% per year to relieve the extra supply beyond the actual demand in carbon market. Accordingly, four scenarios with different total allowance supplies in the primary carbon auction market are designed, i.e., Scenarios B1-B4 respectively with the mitigation rate η=0.5%, 1.5%, 2.5% and 3.5%.

To sum up, a total of six policy scenarios are designed, as listed in Table 3. It is worth noticing that due to the randomness stemming from

Table 3
ETS policy scenarios with different carbon auction designs.

Policy exploration	Scenario	Auction form	Mitigation rate
Without ETS	BAU	–	–
Auction form	A1	Uniform-price form	0.010
	A2	Discriminative-price form	0.010
Allowance supply	B1	Uniform-price form	0.005
	B2	Uniform-price form	0.015
	B3	Uniform-price form	0.025
	B4	Uniform-price form	0.035

initial solution generation and certain parameter settings in the multi-agent-based model, all policy scenarios are run 20 times, and the average values are calculated as the final results. Moreover, the model is recursively run up to the 10th year after the ETS policy is implemented, to capture its dynamic impacts on China's economy and carbon emissions.

3.2. Simulation results

Based on the multi-agent-based ETS simulation model, the impacts of different ETS policies with different auction designs on China are estimated by comparing Scenarios BAU (a baseline case without ETS) and various policy scenarios (see Table 3). In particular, the impacts of different auction forms (i.e., the uniform-price form and the discriminative-price form) are evaluated in Section 3.2.1, and Section 3.2.2 investigates the allowance supply provided in the primary carbon auction market. Finally, some interesting policy implications can be drawn from the simulation results, as discussed in Section 3.2.3.

3.2.1. Impacts of auction form

3.2.1.1. A general review. The comparison results between different auction forms, in term of the impacts on China's economy and carbon emissions, are displayed in Fig. 4. The simulation results indicate that the ETS policy with any auction form (the uniform-price form or discriminative-price form) would have a negative impact on China's gross domestic product (GDP) and total carbon emissions. However, compared with the uniform-price rule, the discriminative-price rule seems to be much more aggressive, in terms of a much larger damage on China's economy and also a much more effective mitigation effect on the carbon emissions (see Fig. 4). For example, in the 10th year, GDP will be decreased by about 0.646% under Scenario A1 and by about 0.974% under Scenario A2 relative to Scenario BAU, and total carbon emissions will be similarly reduced by about 1.393% under Scenario A1 and by about 2.348% under Scenario A2.

The downturn in GDP and significant reduction in carbon emissions are directly attributed to higher costs of high carbon-intensive energies. Accordingly, confronted with the rising costs, all firms adjust their production decisions and input decisions to adapt to the ETS policy, not only through cutting down their outputs due to the decrease in profits, but also through improving energy structures into much cleaner ones and adopting emissions reduction techniques, e.g., the carbon capture and storage (CCS) techniques.

When comparing the two auction forms, the uniform-price form might lead to much smaller effects in both economic damage and emissions reduction than the discriminative-price form. The main hidden reasons can be summarized into the following two aspects:
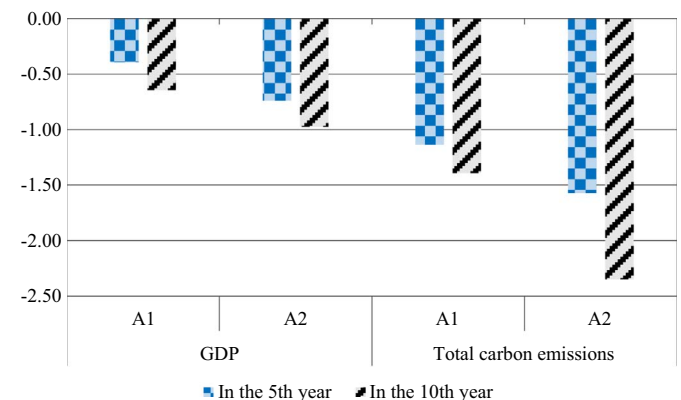

Fig. 4. Impacts of ETS on China's GDP and total carbon emissions with different auction forms (%).
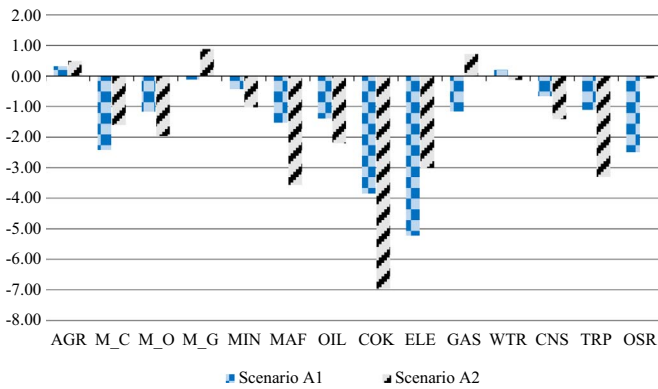
Fig. 5. Impacts of ETS on China's sectoral outputs with different auction forms in the 10th year (%).

Fig. 6. Impacts of ETS on China's energy structure with different auction forms in the 10th year (%).

carbon cost and risk expectation. First, as for carbon cost, since each firm pays the carbon credits at a same price under the uniform-price form, i.e., the equilibrium price (the lowest bid price of all winning bidders), the losses cut by ETS might be much smaller than those of the discriminative-price form (with different prices all above or at least equal to the equilibrium price). Accordingly, under the uniform-price form leading to smaller losses, firms can better adjust to the ETS policy with relatively moderate negative impacts on their productions and hence on the total economy system, compared with the discriminative-price form. Second, as for risk expectation, the discriminative-price form might expose bidders to a much larger strategic risk, due to the difficulty in evaluating the equilibrium price (Cramton and Kerr, 2002), which yields higher volatility in the carbon auction market and thus enhances the risk expectation for the future market. Therefore, due to higher carbon cost and risk expectation, the discriminative-price form will suppress the outputs more strongly and thus lead to a much greater damage on GDP and a more obvious mitigation effect on carbon emissions, compared with the uniform-price form.

3.2.1.2. Sectoral perspective. The impacts of different ETS designs with different auction forms on sectoral outputs in China are illustrated in Fig. 5. Four interesting conclusions can be drawn from the simulation results. First, the outputs of most sectors in China will shrink, as ETS directly increases the production costs. Second, the impacts differ across sectors. In particular, for the majority of the energy sectors, the outputs will be significantly reduced by ETS, mainly due to their intrinsic relationships with carbon emissions. For example, the outputs of the energy sectors with high carbon-intensities, e.g., COK, will be reduced the most due to ETS, by approximately 3.843% under Scenario A1 with the uniform-price form and 6.963% under Scenario A2 with the discriminative-price form, respectively, in the 10th year after the ETS implementation. For the sectors with high energy-intensities, the outputs would also be cut down greatly. For example, the outputs of sectors ELE, MAF and TRP will be reduced by approximately 5.219%, 1.523% and 3.568% under Scenario A1 with the uniform-price auction, and 3.010%, 1.106% and 3.301% under Scenario A2 with the discriminative-price auction, in the 10th year. Third, due to the substitution effect, the sectors with relatively low carbon-intensities (e.g., AGR and OSR) and the cleaner energy sectors (e.g., M_G and GAS) will otherwise increase the outputs under the ETS policy. Finally, the changing directions due to the ETS designs with the uniform-price auction and discriminative-price auction appear similar trends in most sectors, even to different extents.

3.2.1.3. Energy structure. The impact of ETS with different auction forms on China's energy structure is displayed in Fig. 6. Two main interesting conclusions can be found. On the one hand, China's energy
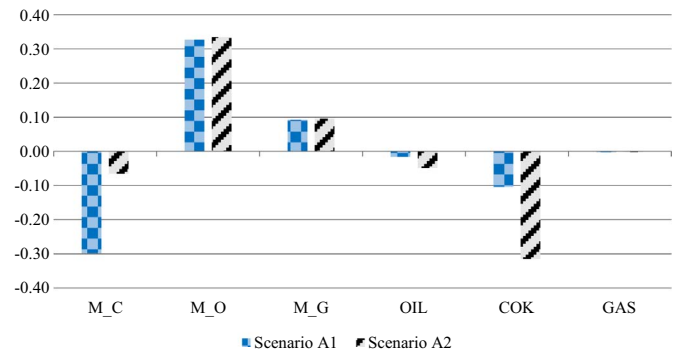
structure will be significantly improved into a much cleaner one due to ETS, with an increase in demands for the energy resources with relatively lower carbon-intensity (e.g., M_O and M_G) and a decrease for energy resources with higher carbon-intensity (e.g., M_C and COK). In particular, the emissions factors of M_O, M_G, M_C and COK are respectively about 20.0kgC/GJ, 15.3 kgC/GJ, 25.8 kgC/GJ and 29.2 kgC/GJ, according to IPCC. On the other hand, both auction forms show a same trend in terms of changing directions in energy demand shares, even with a slight difference in extents. For example, the shares of M_O and M_G in total energy demand will be increased by about 0.327% and 0.093% under the uniform-price auction (Scenario A1), and 0.334% and 0.096% under the discriminative-price auction (Scenario A2). In contrast, the shares of M_C and COK in total energy demand will be otherwise decreased by about 0.298% and 0.065% under Scenario A1, and about 0.104% and 0.315% under Scenario A2.

3.2.1.4. Carbon price in primary ETS market. Under different auction forms, the market clearing price displays different features, as the results shown in Fig. 7 and Table 4. Three main implications can be drawn. First, compared with the discriminative-price auction, the uniform-price auction generates a slightly higher level of market clearing price for carbon allowances. The main reason might lie in that since each winner pays credits at a same market clearing price (i.e., the lowest bid price amongst all winners) under the uniform-price auction rather than its own bid price under the discriminative-price form, the firm may strategically submit a relatively higher bid price beyond the true value to win the bids, which further enhances the market clearing price. In contrast, under the discriminative-price auction, since bidders should pay at the prices that they bid, the firms are more likely to provide bid prices at possibly low levels for avoiding extra costs, which largely suppresses the clearing market price
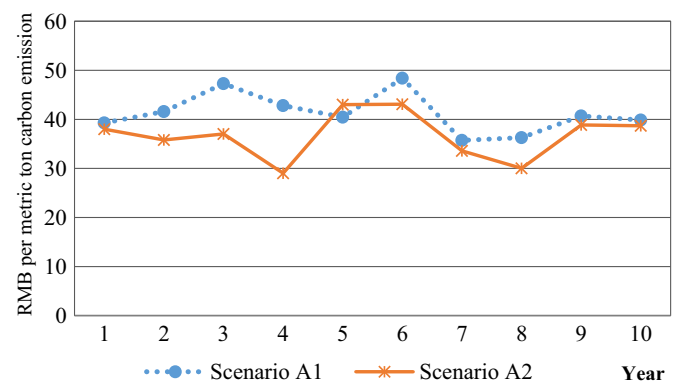

Fig. 7. Market clearing prices for carbon allowances in primary ETS market with different auction forms.

Table 4

Statistical analysis of market clearing carbon prices in primary ETS market with different auction forms.

Auction form	Mean	Standard deviation
Uniform-price auction form	41.236	16.909
Discriminative-price auction form	36.709	22.783

(Cramton and Kerr, 2002).

Second, the volatility of market clearing price under the discriminative-price form is much higher than that of the uniform-price form, since the standard deviation is much higher (see Table 4). The main reason can be referred to the risk expectation, as mentioned above. In particular, the discriminative-price form might expose bidders to a much larger risk expectation, since the firms cannot exactly know the true value of carbon allowances (i.e., the market clearing price) (Cramton and Kerr, 2002), which certainly yields higher volatility in the carbon auction market. In contrast, under the uniform-price form, in which all winners should pay at the market clearing price (or the equilibrium price), the firms can provide a bid price around the true value of carbon allowances for the next period, which largely promotes the convergence of market clearing price toward the true value.

Third, the difference between the two auction forms in terms of carbon prices tends to become increasingly smaller as time goes. In particular, the carbon prices fluctuate on the range of 30–50 RMB yuan per metric ton of carbon dioxide emission and move toward 40 RMB yuan after several rounds. It is worth noticing that the simulation results for the carbon price in this study are quite consistent with not only the similar studies on China's ETS policy but also China's existing ETS markets, in terms of fluctuation range and general trend. As for similar studies, by conducting an experimental study, Cong and Wei (2012) showed that the carbon auction price in China's carbon allowance market might fluctuate on the range of 20–50 RMB yuan per metric ton. Based on the CGE model, Cui et al. (2014) suggested the carbon price to be 53 RMB yuan in China's nationwide ETS mechanism. Tang et al. (2015) proposed a multi-agent-based model for China's CET design and recommended a benchmarking carbon price of 40 RMB yuan. As for existing ETS markets, the mean carbon prices of Beijing, Shanghai, Tianjin, Shenzhen, Chongqing, Guangdong and Hubei are 52.28, 19.60, 18.95, 43.92, 24.00, 17.66 and 27.50 RMB yuan for the year 2015, respectively.

3.2.2. Impacts of allowance supply

The impacts of the ETS policy with different mitigation rates in allowances supply on China's GDP and total carbon emissions are reported in Fig. 8. We can observe that as the mitigation rate becomes gradually higher (from 0.005 to 0.035 with the step length of 0.010),
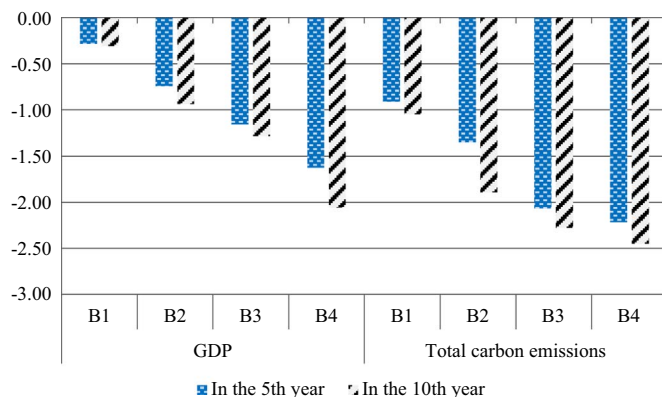

Fig. 8. Impacts of ETS on China's GDP and total carbon emissions with different mitigation rates in allowance supply (%).

the negative impact on GDP becomes stronger due to the increasingly smaller allowance supply. For example, China's GDP will be decreased due to ETS by 0.284%, 0.742%, 1.157% and 1.628% in the 5th year and 0.311%, 0.936%, 1.283% and 2.061% in the 10th year, under Scenarios B1-B4 with the mitigation rate of 0.005, 0.015, 0.025 and 0.035, respectively. As to the impact on carbon emissions, a similar conclusion can be drawn that a higher mitigation rate in allowance supply will generate a larger effect in carbon emissions reduction. For example, the total carbon emissions in China will be cut down due to ETS by about 0.912%, 1.351%, 2.068% and 2.317% in the 5th year and 1.044%, 1.898%, 2.278% and 2.451% in the 10th year, under Scenarios B1-B4 with the mitigation rate of 0.005, 0.015, 0.025 and 0.035, respectively.

The main hidden reasons for these above results can be summarized into the following three points. First, the decrease in total supply of the primary carbon auction market will certainly enhance the difficulty in acquiring enough allowances to support productions, and thus stimulate the carbon price. Second, the higher carbon price will further suppress the outputs due to the increase in production costs. Therefore, due to such an income effect, the overall output and total carbon emissions mainly generated during production process will be cut down significantly. Third, such higher costs for carbon emissions will meantime inspire the firms to improve the energy structures and energy techniques to reduce the production costs and avoid the penalties. These factors will further improve China's environment in terms of carbon emissions reduction.

3.2.3. Policy implications

The above simulation results can provide helpful insights into China's ETS policy, which can be summarized into the following four aspects.

Generally, the ETS policy will effectively reduce the total carbon emissions and improve the energy structure in China, with a relatively small negative impact on economy. The results further indicate that the ETS policy can be used as one quite promising tool for carbon emissions reduction.

When comparing the two typical auction forms, the uniform-price form is relatively moderate in economic damage as well as emissions reduction, while the discriminative-price one is quite aggressive. Accordingly, to avoid heavy damage to the economy, the uniform-price form is strongly recommended, especially at the beginning stage of ETS. In contrast, the discriminative-price one can be introduced in the later stages, to guarantee an effective curb on carbon emissions.

As for carbon price, the uniform-price auction might generate a slightly higher market clearing price than the discriminative-price auction. Under both the two auction forms, the carbon prices will fluctuate on the range of 30–50 RMB yuan per metric ton of carbon dioxide emission, and move toward 40 RMB yuan after several rounds.

As for allowance supply, the government should carefully balance the economic growth and carbon reduction, to determine an appropriate mitigation rate. If the mitigation rate is set too high, the economy could be largely damaged. If the mitigation rate is set too low, the environment is sacrificed for economic development.

Finally, to both enhance the emissions mitigation effect and reduce the negative economic effect, some other auxiliary policies can be employed accompanied with ETS, e.g., investment subsidies for energy-saving technologies and CCS techniques.

4. Conclusion and policy implications

This paper proposes a nationwide ETS simulation model via a multi- agent-based approach, in which the auction-based allowance allocation method is especially analyzed for China's ETS investigation. In particular, two types of agents, i.e., the government (the ETS implementer and supervisor) and firms (the main economic agents in China's economic system and the ETS targets), are involved in the proposed model. Under the ETS policy, all agents would make various

decisions individually according to their own goals, and interact with each other through three main markets, i.e., the traditional commodity market, the primary ETS market (i.e., carbon auction market) and the secondary ETS market (i.e., carbon trading market).

Generally, the main innovations of this paper can be summarized into the following three aspects. First, since the ETS policy is a market-driven mitigation instrument, the most typical bottom-up analysis technique, i.e., the multi-agent-based model, is implemented to effectively capture the activities and interactions among various heterogeneous agents under the ETS. Second, different from most existing numerical models focusing on certain ETS-related sectors, the novel simulation model covers various sectors in China's economic system to allow a general analysis from the macroscopic perspective. Third, different auction designs, in terms of different auction forms (e.g., the uniform-price and discriminatory-price rules) and different allowance supplies, are introduced into the ETS formulation, which can offer helpful insights into China's ETS policy design.

The simulation results demonstrate the effectiveness and robustness of the proposed model, and provide some useful policy implications for China's ETS auction design. First, generally, the ETS policy will effectively reduce the total carbon emissions and improve the energy structure in China, with a relatively small negative impact on economy from both general and sectoral perspectives. Second, as for auction forms, the uniform-price design is relatively moderate in economic damage as well as emissions reduction, while the discriminative-price one is quite aggressive. Third, as for carbon price, the uniform-price auction might generate a slightly higher market clearing price than the discriminative-price auction, and the prices under both two auction rules fluctuate around 40 RMB yuan per metric ton of carbon emission. Finally, as for carbon cap, the total allowances in the carbon auction market should be carefully set to well balance economic growth and environmental protection.

However, according to existing ETS mechanisms, a combined allowance allocation scheme coupling both historical-based and auction-based methods may be an even more effective design for China's ETS policy, which should be carefully designed in the future. Moreover, besides China's ETS formulation, the proposed model can be extended to other ETS mechanisms for verifying its generalization and availability. These above interesting issues may be the main focuses of the future research.

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