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Stylized agent-based modeling on linking emission trading systems and its implications for China's practice

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ABSTRACT

China established a national emission trading system (ETS) to peak its carbon emission around 2030, building on the experience of pilot ETSs that are planned to be linked. Firms are the main entities that conduct carbon reduction and allowance trading. Due to the heterogeneity in the initial stock of technologies, firms' abatement costs differ, resulting in different abatement activities and the dynamics of the carbon price. Most of the studies on linking ETSs pay little attention to firms' behaviors, especially the interactions among firms' technology adoption strategies and their allowance trading strategies. In addition, whether linking ETSs can reduce carbon emission with lower system costs remains insufficiently explored. This study develops a stylized agent-based model (ABM) to explore the impact of linking two ETSs considering firms' heterogeneities and the interactions between their technology adoption strategies and allowance trading strategies. The model considers two ETSs, each of which includes energy-service-providing agents who are heterogeneous in the production scale and initial stock of technologies (and thus with different abatement costs), and attempts to minimize the total cost for a given output by adopting different technologies and trading emission allowances. The carbon price is dynamically affected by agents' willingness to pay, and a Walrasian auction is introduced to obtain the equilibrium. The results show that linking ETSs could be cost-effective to achieve carbon reduction commitment and creates a larger and more liquid carbon market; however, it also provides agents the opportunity to purchase more allowances rather than adopt low-emission technologies, which may result in more carbon emission. Adding restrictions on the linkage could somehow mediate this negative effect. Imposing strict exchange rate restrictions to the system with more balanced market shares of agents or quantitative restrictions would result in desirable results at the expense of increasing system costs. Moreover, restricted linkages could help alleviate the difficulties in initialing a linkage. The stylized ABM is mainly used for exploratory modeling purposes as a heuristic research device to examine in depth the effectiveness of unrestricted linkages and restricted linkages on adopting low-emission technologies at firms' level and the resulting carbon reduction. On the basis of the main findings of the ABM, we discuss the case if the Hubei pilot ETS links with the Guangdong pilot ETS, which could improve the understanding of the potential impact of linking ETSs on technology adoption and carbon reduction and provide policy implications for linking different ETSs.

1. Introduction

Today's booming global economy is causing increasingly serious environmental problems, among which climate change is one of the most concerning. Agreements and conventions have been proposed to reduce greenhouse gas (GHG) emissions to control global warming. For example, the Paris Agreement limits the global average temperature to well below 2 °C above preindustrial levels, possibly as low as 1.5 °C (IPCC, 2017; Wen et al., 2018). However, this task is challenging, and requires rapid and comprehensive changes in human activities (IPCC, 2018). According to the IPCC special report “Global Warming of 1.5°C”, human activities are estimated to have caused approximately 1.0 °C of global warming above the preindustrial level, and it will probably reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018). Therefore, it is urgent to accelerate actions to reduce GHG emissions to control global warming.

Carbon emission is the most prominent GHG emission (Xu et al., 2017). Adopting low-emission technologies is one of the most important ways to reduce carbon emission. Compared to traditional technologies, low-emission technologies usually require much higher investments, which is an obstacle to switching from traditional to low-emission technologies (Bondarev and Greiner, 2019; Fan et al., 2018). However, they usually have learning potential, which means

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their investment costs would decrease as the experience using them increases (Arrow, 1962; Arthur, 1989). This technological learning effect is considered an endogenous mechanism for the diffusion of low-emission technologies (e.g., Ma, 2010; Lin and Li, 2015; Chen and Zhou, 2019).

Carbon emission trading is a quantity-based policy instrument used by countries to fulfill their obligations as specified by the Kyoto Protocol (Wang et al., 2016; Qian et al., 2017), which helps internalize negative externalities in production and consumption activities (Diaz-Rainey and Tulloch, 2018). The negative externalities indicate that economic agents do not bear all the costs of their emission, which is a format of market failure (Fan et al., 2016). Within an emission trading system (ETS), each economic agent (e.g., a power plant company) is allocated certain emission allowances. When an agent finds that its economic activity might result in more emission than its allocated allowances, it can either adopt low-emission technologies with relatively high costs to reduce emission or purchase extra allowances from other agents in the same ETS. An ETS can be viewed as a complex adaptive system (CAS) (Holland, 1992) because agents' technology adoption strategies and allowance trading strategies interact, and they can adapt their strategies to the changes in costs of technologies and carbon price, which in turn result in the dynamics in the costs of technologies and carbon price.

Many studies have examined the design and operation of a single effective ETS (e.g., Cui et al., 2014; Tang et al., 2016; Zhang and Wei, 2010). Recently, interest has grown concerning the possibility of linking ETSs due to the variable opportunity for regions or countries to increase the effectiveness of their domestic or regional regimes (Borghesi et al., 2016). The linkages refer to the connections among ETSs that allow emission reduction efforts to be redistributed across systems. Such linkages are expected to help reduce the aggregate economic cost of abatement and create a larger and more liquid carbon market, thus reducing price volatility (Tuerk et al., 2009). Thus far, there are some examples of linkages in operation. For example, the linkage between the European Union Emission Trading System (EU ETS) and the credits originating from Joint Implementation (JI) and Clean Development Mechanism (CDM) projects, the linkage between the California Cap-and-Trade System and Quebec Cap-and-Trade System, and the linkages among the Regional Greenhouse Gas Initiative (RGGI). The linkages in operation might be one-way, two-way, or multi-way. The European Commission (2013) believed that the use of carbon credits from CDM and JI would increase the cost-effectiveness of achieving Europe's 2020 emission reduction goals. According to Purdon et al. (2014), although linking the California Cap-and-Trade System with the Quebec Cap-and-Trade System greatly decreases the carbon price in Quebec while slightly increases the carbon price in California, it could significantly reduce their compliance costs, which appeared to be a win-win result. However, although RGGI was smartly designed to raise money to fund clean energy programs, it does not promote the direct reduction of carbon emission in practice due to the relatively small carbon price (Ramseur, 2017). The aforementioned practices indicate linking ETSs could be successful but does not necessarily achieve the desired effect.

Many studies have explored the impact of linking ETSs from a macro perspective (Liu et al., 2013; Diaz-Rainey and Tulloch, 2018; Li et al., 2019; Ma et al., 2019; Holtsmark and Weitzman, 2020). However, firms are the main entities that conduct carbon reduction and allowance trading. Due to the heterogeneity in the initial stock of technologies, firms' abatement costs differ, resulting in different abatement strategies. The different abatement strategies then lead to the dynamics of the carbon price and in turn affect firms' abatement activities. Most studies on linking ETSs have paid little attention to firms' behaviors, especially the interactions among firms' abatement strategies and their allowance trading strategies. In addition, few studies have investigated whether linking ETSs can reduce carbon emission at lower system costs.

This study develops a stylized agent-based model (ABM) to explore these issues. The ABM considers two ETSs containing multiple economic agents (representing firms), each of which attempts to minimize the production cost (including the carbon cost) for a given output by adopting different technologies and trading emission allowances with others. The agents are heterogeneous in the production scale and initial capacities of technologies and thus have different carbon abatement costs. The carbon markets of these two ETSs are linked, and the emission allowances can be traded across ETSs. In the linked carbon market, the carbon price is dynamically affected by agents' willingness to pay (WTP) and a Walrasian auction (Bronfman et al., 2008) is introduced to obtain the equilibrium. Although the ABM is highly stylized, simulations could provide insights into the potential results of linking two ETSs.

Many researchers have argued that when considering the differences between the two ETSs to be linked, it is necessary to impose restrictions on allowance trading to maintain the effective operation of the linkage (e.g., Lazarus et al., 2015; Schneider et al., 2017). The restrictions already in practice are mostly quantitative restrictions (ICAP, 2019). For example, the EU ETS limits the total use of JI and CDM credits in phase 2 and phase 3 up to 50% of the overall reduction in that period. The California and Quebec Cap-and-Trade System limits the use of offset credits up to 8% of each entity's compliance obligation. The RGGI limits that 3.3% of an entity's liability can be covered with offsets. Other ETSs such as China's pilots ETSs, Japanese ETS, Korean ETS and Swiss ETS all limit the use of offsets. Researchers have also discussed exchange rate restrictions, but to the best of our knowledge, such types of restrictions have not been implemented. Will these restrictions be effective when implemented? With the ABM, we also explore this question with different restriction settings. We use the ABM methodology because ETSs are CASs, and ABM is a powerful tool to analyze the dynamics of such systems.

As the largest emitter, China launched a national ETS on December 2017. Before initialing the national ETS, eight pilot ETSs (Beijing, Chongqing, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin and Fujian) had been established, serving as the experimental stage for the national ETS. When the national ETS starts to operate effectively, these pilot ETSs would be linked, and the emission allowances could be traded across pilots. Given that the mechanism design, carbon price, trading volume and economic development vary across pilots, there are many concerns regarding the potential impact of linking these pilot ETSs.

Different ETSs may have different demands, reduction targets, allowance distribution and allocation rules, or different carbon policies, and the linkage could be very complicated. Most studies on linking ETSs assume that the total emission allowances of the linked ETSs should be discounted at the initial stage of the linkage to achieve more carbon reduction. It is quite challenging to design an appropriate discount. An ambitious discount might greatly increase the burden of some emission entities. In this study, we explore another mechanism, with which the total emission allowances of the linked ETSs are not discounted at the initial stage of the linkage, but will be reduced over time. We use the ABM as a heuristic research device to explore what could be the results with such a mechanism and the corresponding policy implications.

The linkage of ETSs is simplified based on two decisive variables, namely, intersystem and intrasystem trading volumes, and the complicated trading process is simplified with a Walrasian auction to obtain the equilibrium carbon price. Thus, the ABM in this study is not intended to be "realistic" and show economic and technological details. The model is deliberately kept highly stylized and mainly used for exploratory modeling purposes as a heuristic research device to examine in depth the effectiveness of unrestricted linkages and restricted linkages on adopting low-emission technologies at firms' level and the resulting carbon reduction. This study does not provide detailed policy designs for China's national ETS; instead, it provides insights into whether and how restrictions on linking different pilot ETSs should be implemented. Based on the main findings of the ABM, we then discuss the case if the Hubei pilot ETS links with the Guangdong pilot ETS, which could improve the understanding of the potential impact of linking ETSs on technology adoption in the power sector, the main industry that China's ETSs currently focus on, and provide policy implications for linking different ETSs.

The rest of this paper is organized as follows. Section 2 introduces the stylized ABM. Section 3 presents the process of solving agents' optimization problems of technology adoption considering allowance trading. Section 4 presents and analyzes the computational results of the model. Section 5 discusses the case if the Hubei pilot ETS links with the Guangdong pilot ETS based on the main findings of the computational experiments. Section 6 provides the concluding remarks.

2. The stylized model

2.1. The simplified economic system

For simplicity and transparency, we assume that there are two economic systems, system A and system B, the structures of which are deliberately kept simple. The economy demands one homogeneous good (e.g., electricity), and the exogenous demand increases over time. Both economic systems depend on one type of primary resource (e.g., coal), and the extraction cost of the resource will increase as a function of resource depletion. Three technologies can be used to produce goods from resources: the existing technology-T1, the incremental technology-T2, and the revolutionary technology-T3. The existing technology is assumed to be entirely mature. It requires a low initial investment cost and has low efficiency, and the carbon emission is high. With higher efficiency and lower emission, the incremental technology initially requires a higher investment cost. The revolutionary technology initially requires a much higher investment cost, but its efficiency is much higher, and it has almost no emission. As new technologies, incremental and revolutionary technologies have learning potential, which means their investment costs decrease as the cumulative experience with them increases.

In each system, the demand of the goods is satisfied by the production of all the agents in it. Agents are heterogeneous in the production scale and initial capacities of technologies; in other words, agents have different market shares and different initial stock of technologies (thus with different abatement costs). Each agent adapts its technology adoption strategy and allowance trading strategy to minimize the total cost for a given output while satisfying the carbon cap. Agents' carbon caps for the current period are set based on their last-period production scales and the carbon reduction plans of their domestic systems, and the annual initial allowances are allocated to agents for free and without reservation. An agent can sell the surplus allowances for profit if it controls its carbon emission below the carbon cap, or can purchase extra allowances to emit more.

From the perspective of the time frame, our model simulates the production and abatement phase with period T, which is divided into t $(t = 1,2,\ldots,T)$ decision intervals. In each decision interval, agents negotiate with each other with the tradable volume of allowances at every possible carbon price and adjust their technology adoption strategies accordingly. Due to heterogeneities, agents' acceptance of a carbon price will differ. To model this, agents' WTP is calculated, which characterizes the price intervals of agents acting as a buyer and a seller. Agents' technology adoption strategies affect their WTP and the subsequent allowance trading strategies, and agents' allowance trading strategies affect their technology adoption strategies.

2.2. Agents' technology adoption decisions

2.2.1. Without allowance trading

Suppose there are N heterogeneous agents in each economic system. Let $y_{i,n}^t$ denote agent n's $(n = 1,2,\ldots,N)$ newly installed capacity of technology $i (i = 1,2,3)$ at time t, then its total installed capacity of technology i at time t, denoted as $C_{i,n}^t$, can be calculated as

$$C_{i,n}^t = \begin{cases} \sum_{j=t-\tau_i}^{t} y_{i,n}^j & t > \tau_i \\ \sum_{j=1}^{t} y_{i,n}^j + \frac{\tau_i - t}{\tau_i} C_{i,n}^0 & t \le \tau_i \end{cases} \tag{1}$$

where $i = 1, 2, 3$ denotes the existing, incremental and revolutionary technology, respectively; τ_i denotes the plant life of technology i; $C_{i,n}^0$ denotes agent n's initial capacities of technology i.

At each decision interval, agent n's cumulative experience with technology i at time t can be represented as its cumulative production with technology i by time t, as shown in Eq. (2).

$$E_{i,n}^t = E_{i,n}^0 + \sum_{j=1}^{t} x_{i,n}^j \tag{2}$$

where $E_{i,n}^t$ denotes agent n's cumulative experience with technology i at time t; $E_{i,n}^0$ denotes agent n's initial experience with technology i; $x_{i,n}^j$ denotes agent n's production using technology i at time j.

The unit investment cost of the existing technology is assumed to be constant since it is mature, and those of the incremental and revolution technologies will decrease with technological learning, as denoted in Eq. (3).

$$CF_{i,n}^t = \begin{cases} CF_{i,n}^0 & i = 1 \\ CF_{i,n}^0 \cdot \left(E_{i,n}^{t-1}\right)^{-b_i} & i = 2,3 \end{cases} \tag{3}$$

where $CF_{i,n}^t$ denotes agent n's unit investment cost for technology i at time t; $CF_{i,n}^0$ denotes agent n's initial unit investment cost for technology i; $1 - 2^{-b_i}$ is the learning rate of technology i, which indicates the percentage reduction of the future unit investment cost for every doubled total experience; 2^{-b_i} is the process ratio, which denotes the speed of learning.

Agent n's total resource consumption at time t is a function of its production, which can be obtained with Eq. (4).

$$R_n^t = \sum_{i=1}^{3} \frac{x_{i,n}^t}{\eta_i} \tag{4}$$

where R_n^t denotes agent n's total resource consumption at time t and η_i denotes the efficiency of technology i.

Agent n's cumulative resource consumption by time t, denoted as $\overline{R}_n^t$, can be presented as

$$\overline{R}_n^t = \sum_{j=1}^{t} R_n^j \tag{5}$$

The unit resource extraction cost, denoted as CE_n^t, is assumed to be linearly correlated with agent n's cumulative resource consumption, as shown in Eq. (6).

$$CE_n^t = CE_n^0 + k\overline{R}_n^t \tag{6}$$

where CE_n^0 denotes agent n's initial unit resource extraction cost and k denotes the sensitivity of the extraction cost to the cumulative resource consumption.

The demand is exogenous and increases over time with the annual growth rate, as shown in Eq. (7).

$$D^t = D^0(1+\alpha)^t \tag{7}$$

where D^t denotes one economic system's total demand at time t; D^0 denotes the initial total demand of the system; α denotes the annual growth rate of the total demand.

Agents are assumed to have heterogeneous production scales, or market shares. Let w_n denote agent n's market share in its system, then we have $\sum_{i=1}^{n} w_i = 1$. In each decision interval, agents make technology adoption decisions simultaneously. Without allowance trading, each agent optimizes its technology adoption with the following model:

$$\min \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} CF_{i,n}^t \cdot y_{i,n}^t + \frac{1}{(1+\delta_r)^t} CE_n^t \cdot R_n^t + \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} COM_i \cdot x_{i,n}^t \quad (8)$$

$$\text{s.t.} w_n D^t \le \sum_{i=1}^{3} x_{i,n}^t \quad (9)$$

$$x_{i,n}^t \le C_{i,n}^t, \forall i \quad (10)$$

$$x_{i,n}^t \ge 0, \forall i \quad (11)$$

$$y_{i,n}^t \ge 0, \forall i \quad (12)$$

$$\sum_{i=1}^{3} \frac{\lambda_i}{\eta_i} x_{i,n}^t \le Cap_n^t \quad (13)$$

where
δ_r denotes the discount rate; COM_i denotes the operation and maintenance cost of technology i; λ_i denotes the carbon emission coefficient of technology i; Cap_n^t denotes agent n's carbon cap at time t, which equals its allocated initial free allowances.

The objective function is the total cost, including investment cost, resource extraction cost and operation and maintenance (OM) cost. Constraint (9) indicates that an agent's production must satisfy its market share of the total demand; Constraint (10) indicates that an agent's production cannot exceed its installed capacities of technologies; Constraints (11) and (12) indicate that the decision variables cannot be negative; Constraint (13) indicates that an agent's emission cannot exceed its carbon cap.

2.2.2. With allowance trading

a) Before linking two ETSs. With certain given initial allowances, an agent could sell its surplus allowances to make profit or buy allowances from others if it wants to emit more. Thus, for agent n at time t, without linking ETSs, its optimization model can be written as

$$\min \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} CF_{i,n}^t \cdot y_{i,n}^t + \frac{1}{(1+\delta_r)^t} CE_n^t \cdot R_n^t + \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} COM_i \cdot x_{i,n}^t - \frac{1}{(1+\delta_r)^t} p^t Q_n^t \quad (14)$$

$$\text{s.t.} \sum_{i=1}^{3} \frac{\lambda_i}{\eta_i} x_{i,n}^t + Q_n^t \le Cap_n^t \quad (15)$$

and constraints (9) ~ (12) where
p^t denotes the carbon price at time t; Q_n^t denotes the trading volume of agent n at time t, $Q_n^t > 0$ indicates agent n is a seller of allowances, and $Q_n^t < 0$ indicates agent n is a buyer.

The objective function is the total cost after allowance trading. Constraint (15) indicates that an agent can sell the surplus allowances to make profit if it controls its carbon emission below the carbon cap, or can purchase extra allowances to emit more.

b) After linking two ETSs. In general, the linkage between ETSs can be divided into two categories: direct linkage and indirect linkage. With a direct linkage, one system recognizes the other's allowances for compliance, and the allowances can be traded across systems directly. In general, direct linkages can be one-way (unilateral) or two-way (bilateral or multilateral) (Jaffe et al., 2015). With an indirect linkage, the supply and demand of allowances in one system may affect the supply and demand of allowances in the other system through linkages with a common system.

This study explores the situation of bilateral direct linkage. With a bilateral direct linkage, each agent can buy or sell allowances not only in the domestic system but also in its linked foreign system. The trading volume Q_n^t can be expressed as $Q_{n,\,Intra}^t + Q_{n,\,Inter}^t$, where $Q_{n,\,Intra}^t$ denotes the intrasystem trading volume, and $Q_{n,\,Inter}^t$ denotes the intersystem trading volume. Thus, for agent n at time t, after linking ETSs, its optimization model becomes

$$\min \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} CF_{i,n}^t \cdot y_{i,n}^t + \frac{1}{(1+\delta_r)^t} CE_n^t \cdot R_n^t + \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} COM_i \cdot x_{i,n}^t - \frac{1}{(1+\delta_r)^t} p^t \left(Q_{n,Intra}^t + Q_{n,Inter}^t\right) \quad (16)$$

$$\text{s.t.} \sum_{i=1}^{3} \frac{\lambda_i}{\eta_i} x_{i,n}^t + Q_{n,Intra}^t + Q_{n,Inter}^t \le Cap_n^t \quad (17)$$

and constraints (9) ~ (12)

The objective function is the total cost after linking ETSs. Constraint (17) indicates that an agent can buy or sell allowances not only in its domestic ETS but also in the linked foreign ETS.

2.3. Dynamics of the carbon price

Although great contributions have been made in analyzing the impact of carbon emission trading mechanism on technology adoption (e.g., see in Cong and Wei, 2010; Tang et al., 2015; Zhao et al., 2009; Liu et al., 2016), most studies ignore the dynamics of the carbon price. Carbon price changes with agents' marginal abatement costs and influences agents' adoption strategies. For example, if the carbon price exceeds an agent's marginal abatement cost, the agent will not buy any allowances but perform its own carbon reduction; if the carbon price is lower than an agent's marginal abatement cost, the agent will not sell any allowances.

In our ABM, the dynamic carbon price is obtained based on agents' WTP. WTP calculates the lowest price at which each agent is willing to sell (hereinafter referred as the "selling price") and the highest price at which each agent is willing to buy (hereinafter referred as the "buying price"), which can be formulated by using the following model:

$$\min \pm p \quad (18)$$

$$\text{s.t.} \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} CF_{i,n}^t \cdot y_{i,n}^t + \frac{1}{(1+\delta_r)^t} CE_n^t \cdot R_n^t + \sum_{i=1}^{3} \frac{1}{(1+\delta_r)^t} COM_i \cdot x_{i,n}^t - \frac{1}{(1+\delta_r)^t} p^t Q_n^t \le Cost_{NT} \quad (19)$$

and constraints (9) ~ (12), (15) where the objective function is the selling price or the buying price of each agent; it is min$p$ if agent n is a seller or min $-p$ if agent n is a buyer. $Cost_{NT}$ denotes the total cost of agent n without allowance trading. Constraint (19) indicates that the total cost after allowance trading should not exceed the total cost without allowance trading presented in Eq. (8).

3. Process of obtaining the solutions

In this section, we present the process of solving agents' optimization problems of technology adoption considering allowance trading.

As mentioned in Section 2.1, in each decision interval, agents negotiate with each other with the tradable volume of allowances at every possible carbon price and adjust their adoption strategies accordingly. Due to heterogeneities in the production scale and initial capacities of technologies, agents' abatement costs will differ, resulting in heterogeneous acceptance of the carbon price. Some agents tend to sell allowances because their abatement costs are sufficiently low, and some

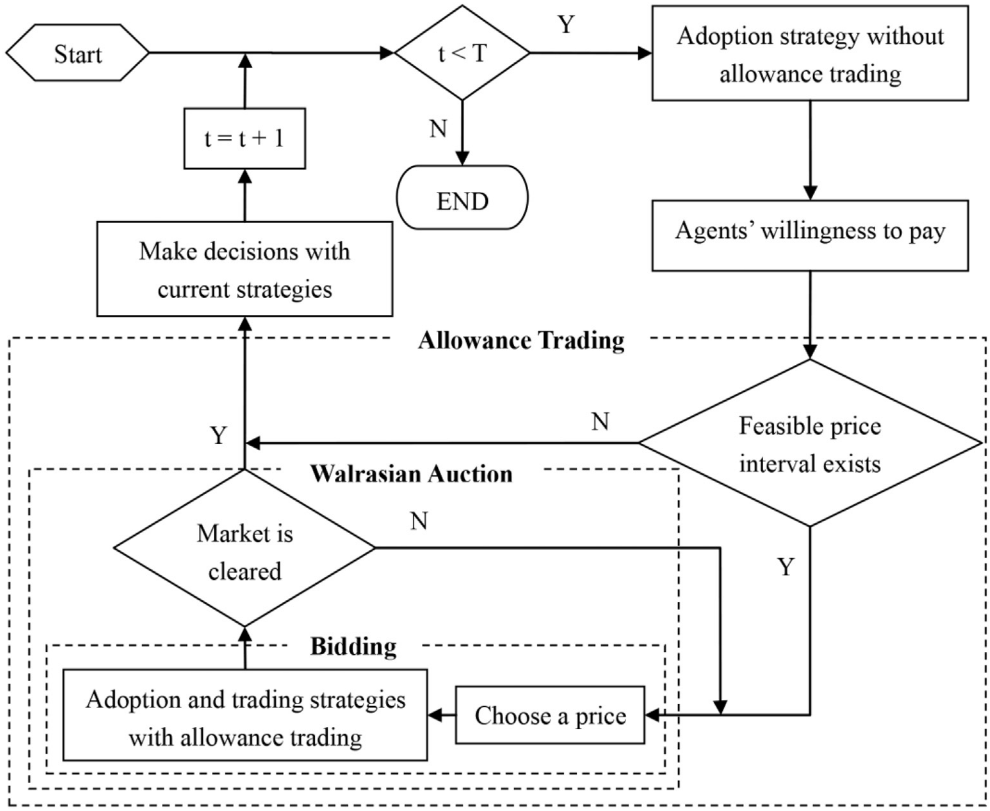

Fig. 1. Model structure.

agents tend to buy allowances because they have high abatement costs. However, we have no information in advance which agents will be the sellers and the buyers. Thus, agents' WTP is calculated first by the model presented in Section 2.3 to characterize the price intervals of agents acting as a buyer and a seller. After obtaining the buying price and selling price of each agent, the feasible interval for carbon price changes is determined accordingly, where at least one seller and one buyer exist. The reasonable carbon price is located in the interval between the minimum selling price and the maximum buying price (Stańczak and Bartoszczuk, 2010; Sabzevar et al., 2017).

In the feasible price interval, each agent calculates its allowance demand or supply and makes the first bid (e.g., with a combination of price, volume and trading direction), and a costless auctioneer collects all the bids and declares if trade occurs; if not, agents then adjust their demand or supply of allowances and make the second bid. The previous bidding information is public to all agents. Trade occurs if and only if a market-clearing price is formed to balance supply and demand. In the simulation, we use a Walrasian auction (Bronfman et al., 2008) to simulate the bargain process and obtain the equilibrium carbon price because it can perfectly match the supply and demand of a trading market, which is a basic assumption of our model. With this auction, each agent calculates its demand or supply of allowances with models presented in Section 2.2.2 (before or after linking the two ETSs), and its trading direction is also determined (e.g., $Q > 0$ indicates selling allowances and $Q < 0$ indicates buying allowances). The equilibrium price is obtained when the total demand across all agents equals the total amount of supply. The flow chart of the model structure is shown in Fig. 1.

As suggested by Walras, equilibrium is achieved through “trial and error”, a form of hill climbing; however, it is a time-consuming method. In our practice, we use the binary search, a commonly used algorithm to find specific elements in an ordered array. For example, we choose the midpoint of the price interval as the current search point and judge whether the market is cleared; if not, we replace the low bound with the current search point; otherwise, we replace the upper bound with the current search point. In the new price interval, the midpoint is used again for the next search. This process continues until the accuracy of the price interval is satisfied. The process of obtaining the solutions of the model can be described in the following steps:

Step 1: Initialize parameters. Let $t = 0$ and go to Step 2;

Step 2: Calculate agents' total costs without allowance trading $Cost_{NT}$ and the corresponding technology adoption strategies TA with the model presented in Section 2.2.1 and go to Step 3;

Step 3: Calculate agents' WTP p_{sell} and p_{buy} with the model presented in Section 2.3 and go to Step 4;

Step 4: If $\min(p_{sell}) > \max(p_{buy})$, agents make decisions as strategies TA and go to Step 8; otherwise, let $[p_{low}, p_{upper}] = [\min(p_{sell}), \max(p_{buy})]$ and go to Step 5;

Step 5: $p = (p_{low} + p_{upper})/2$. Calculate agents' tradable volumes of allowances and the corresponding technology adoption strategies TA' with models presented in Section 2.2.2 (before or after linking the two ETSs) and go to Step 6;

Step 6: If allowances are in short supply, let $p_{low} = p$; otherwise, let $p_{upper} = p$. Go to Step 7;

Step 7: If $p_{upper} - p_{low} \leq \varepsilon$, agents make decisions as strategies TA' and go to Step 8; otherwise, go to Step 5;

Step 8: $t = t + 1$. If $t \leq T$, go to Step 2; otherwise, END.

4. Computational experiments

4.1. Initialization of the model

In our simulations, the problem scale is assumed to be 100 years (e.g., from 2010 to 2110) with 10-year decision intervals. For both systems, we assume that each contains 10 agents that are heterogeneous in terms of the production scale and initial capacities of technologies. In

Table 1
Initial value of parameters.

Parameters	Existing technology	Incremental technology	Revolutionary technology
Initial investment cost (US\$/kW)	$CF^0_{1,n} = 1000$	$CF^0_{2,n} = 2000$	$CF^0_{3,n} = 40000$
Efficiency (%)	$\eta_1 = 30$	$\eta_2 = 40$	$\eta_3 = 90$
Plant life (year)	$\tau_1 = 30$	$\tau_2 = 30$	$\tau_3 = 30$
O + M cost (US\$/kW)	$COM_1 = 30$	$COM_2 = 50$	$COM_3 = 50$
Learning rate	$1-2^{-b_1} = 0$	$1-2^{-b_2} = 20\%$	$1-2^{-b_3} = 30\%$
Carbon emission coefficient (Metric ton/kW)	$\lambda_1 = 0.8$	$\lambda_2 = 0.6$	$\lambda_3 = 0.1$
Other parameters			
Initial demand (kWyr)	$D^0 = 30000$	Annual growth rate of demand (%)	$\alpha = 2.6$
Initial extraction cost (US\$/kW)	$CE^0_n = 20$	Extraction cost coefficient	$k = 10^{-9}$
Discount rate (%)	$\delta_r = 5$		

each system, agents' production scales randomly range from 0 to 1, with the sum of 1. For simplicity, the system with more balanced market shares (i.e., production scales) of agents is denoted as system A, and the system with less balanced market shares of agents is denoted as system B.[1] As the existing technology, T1 is assumed to account for over 70% of the initial technology capacities, and as new technologies, T2 and T3 are assumed to account for no more than 20% and 10%, respectively. Each agent adapts its technology adoption and allowance trading strategies to minimize the total cost for a given output while satisfying the carbon cap. Agents' carbon caps for the current period are set based on their last-period production scales and the carbon reduction plans of their domestic systems. We assumed that both systems have the same reduction target of 6% for every 10 years. The annual initial allowances are allocated to agents for free and without reservation, and one-unit allowance is equivalent to one metric ton of carbon dioxide emission.

To explore technology adoption and carbon reduction influenced by linking ETSs, we assume that all agents have the same resource consumption function, the same demand dynamics, the same technological learning rate, and that all adoption decisions are made simultaneously. Table 1 lists the initial value of parameters used in our simulations, for each of the two systems, which mainly follows previous studies on technology adoption considering technological learning (e.g., Ma, 2010; Chen and Ma, 2017).

4.2. Inequality of emission intensity of each system

Different technologies have different emission coefficients. In our simulation, the emission coefficient of T1, T2 and T3 are 0.8, 0.6 and 0.1, respectively. Due to the heterogeneity in initial capacities of technologies, agents' initial emission intensities differ. Here, the emission intensity denotes the carbon emission for producing one-unit good. Based on agents' initial emission intensities, we measure the intensity inequality of each system by using the Gini coefficient (Gini, 1912). For system k, the Gini coefficient is calculated as

$$G_k = \frac{\sum_{i=1}^{n_k}\sum_{j=1}^{n_k}\left|s_i - s_j\right|}{2n_k\sum_{i=1}^{n} s_i} \tag{20}$$

where n_k denotes the number of agents in system k and s_i denotes agent i's initial emission intensity in system k.

In our simulations, we consider four different levels of inequality of emission intensity of each system, i.e., $G_k = 0.01\text{\textasciitilde}0.04$, and explore the impact of linking ETSs under different combinations of systems' intensity inequalities.

[1] The variance of agents' market shares of system A is 0.0092, and that of the system B is 0.0314.

4.3. With linkage vs. without linkage between two ETSs

In this subsection, we compare the cases with and without linking ETSs in terms of technology adoption, total cost, cumulative carbon emission, carbon price and total trading volume.

Fig. 2 compares the share of T3 – the revolutionary technology with little emission – by 2080 with and without linkage. We choose this period because T3 is adopted at a high rate (e.g., to over 80%) from 2010 to 2080. As can been seen, linking ETSs reduces the adoption of T3 in system A. For system B, linking with a small Gini coefficient is more likely to promote the adoption of T3, and linking with a large Gini coefficient will lower its adoption of T3. For the entire system (i.e., "system A + system B"), when linking ETSs, a small Gini coefficient of system B is more likely to promote the adoption of T3, and a large one will lead to lower adoption of T3.

Fig. 3 compares the total cost with and without linkage. As can be seen, although linking ETSs may increase the total cost of system A, it is more likely to result in a cost decrease in system B and thus lead to a lower total cost of the entire system. Thus, for the entire system, linking ETSs seems to be a cost-effective way to achieve carbon reduction commitment. However, the stability of the linkage may be threatened because no one expects to achieve the same reduction target at a higher cost. In the cases with Gini coefficient pair as (0.01,0.02), (0.01,0.03), (0.01,0.04), (0.03,0.03), (0.03,0.04) and (0.04,0.03), linking ETSs reduces both systems' total costs simultaneously, which contributes to improving the stability of a linkage. Moreover, for comparison of the cumulative carbon emission with and without linkage (see Fig. A.1 in the Appendix), results show that linking ETSs does not result in emission reduction in both systems simultaneously. For the entire system, linking ETSs most often results in more carbon emission, except for the case with Gini coefficient pair as (0.01,0.01). In this case, the total carbon emission after linking ETSs will be below that without linkage but is at the expense of increasing at least one system's total cost. Therefore, although linking ETSs seems to be a cost-effective way to achieve carbon reduction commitment, it might not reduce total carbon emission; conversely, it allows the transfer of emission allowances between systems and results in more total carbon emission.

For carbon price and total trading volume (see Fig. A.2 and Fig. A.3 in the Appendix), the results show that linking ETSs most often increases carbon price in one system and reduces it in the other, and it is more likely to contribute to more allowance trading and create a larger and more liquid carbon market when both systems' Gini coefficients are large.

To explain the aforementioned results, we compare the cumulative utilization rate of allowances in the entire system with and without linkage (see Fig. A.4 in the Appendix). The results show that linked systems have higher utilization of allowances than unlinked systems. This is why linking ETSs causes more carbon emission than without linkage.

Since technological learning could benefit agents in the future, compared to the agents with small market shares, agents with large market shares will be more willing to be technical leaders. Moreover, agents'

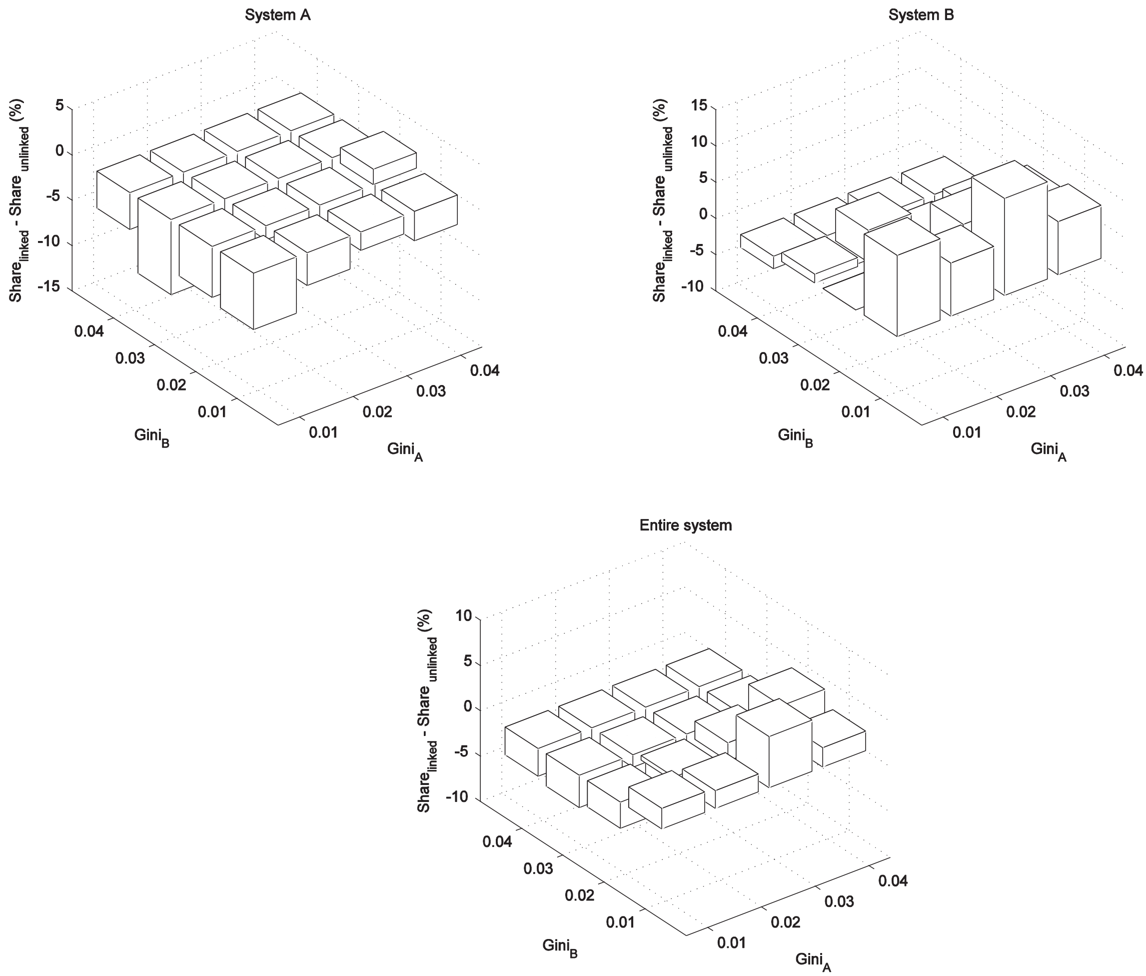

Fig. 2. Comparison of the share of T3 by 2080 with and without linkage.

market shares in system B are not as balanced as those in system A; thus, technical leaders are more likely to appear in system B when linking these two ETSs. The early adoption lowers technical leaders' abatement costs and benefits them in allowance trading. Thus, system B is the export system of allowances and the monetary inflow system.

For the export system (i.e., system B), linking ETSs provides agents the opportunity to export more allowances, thus promotes cost reduction. Moreover, a small Gini coefficient indicates that agents tend to make similar adoption strategies, thus results in less intrasystem trading and promote the adoption of T3. However, when the Gini coefficient is large, agents conduct more intrasystem trading; thus, the technical laggards have little motivation to adopt T3, and the diffusion of T3 in system B will be reduced due to the great decrease in the technical laggards' adoption of T3. This is why linking ETSs reduces the total cost of system B, and a small Gini coefficient of system B is more likely to promote the adoption of T3 while a large one leads to lower adoption of T3.

For the import system (i.e., system A), linking ETSs provides agents the opportunity to import allowances, which might reduce agents' motivation to adopt T3. As carbon reduction plan proceeds, it is impossible for system A to achieve the carbon reduction target solely through importing allowances; thus, agents have to adopt T3. A large imported volume in the initial period decreases system cost but keeps agents' abatement costs at a high level, leading to the increase in import cost and adoption cost in the later period. A small imported volume in the initial period promotes the early adoption of T3 and increases system cost. However, due to technological learning, agents' abatement costs decrease rapidly, which helps to reduce import cost and adoption cost in the later period. This is why linking ETSs reduces the adoption of T3 in system A and might have an unpredictable impact on the total cost of system A.

In summary, for the entire system, linking ETSs could be a cost-effective way to achieve carbon reduction commitment and create a larger and more liquid carbon market, which may help reduce price volatility; however, it might result in more total carbon emission than without linkage and slow the adoption of the low-emission technology.

4.4. Linking ETSs with restrictions

4.4.1. Introduction to restrictions

The aforementioned simulation is based on full bilateral direct linkage; thus, agents in both systems can trade with each other without restrictions. In practice, a full linkage is difficult to establish, especially when both systems have different demands, reduction targets, allowance distribution and allocation rules, or carbon emission policies. In general, two approaches can be used to alleviate the difficulties in initializing a linkage (Quemin and Perthuis, 2017): connecting to a common hub and imposing restrictions on allowance trading. In this study, we consider the second approach and explore the impact of restricted linkages on technology adoption and carbon reduction.

In the following simulations, we consider two types of restrictions: exchange rate restriction and quantitative restriction. The exchange rate restriction denotes setting a ratio of substituting one-unit allowance in a foreign system with allowances in the domestic system. For example, an exchange rate restriction of 2/1 indicates that the value of

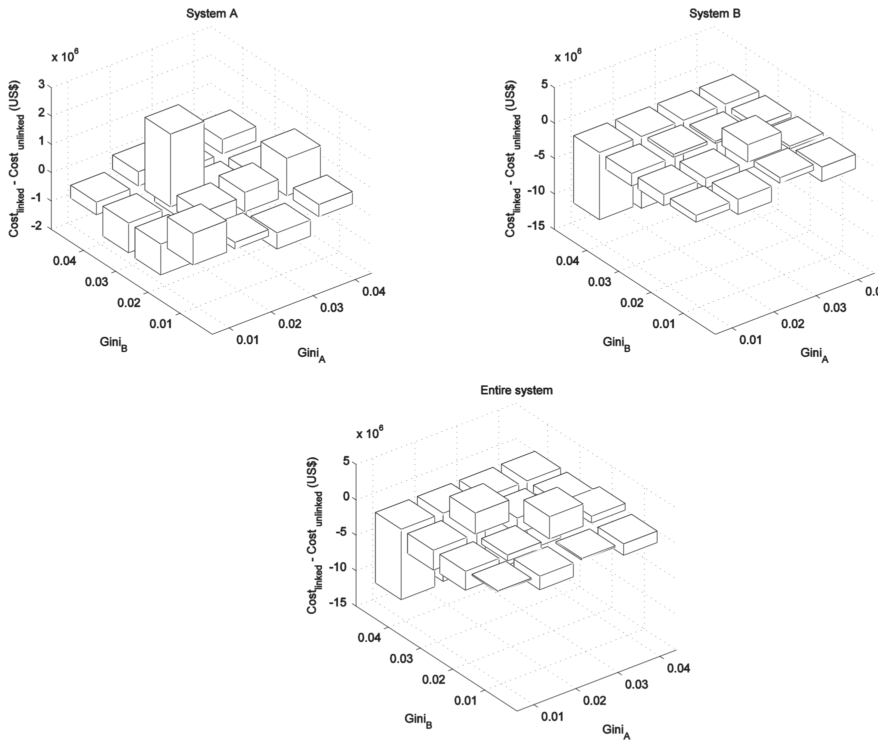

Fig. 3. Comparison of the total cost with and without linkage.

two-unit allowances in system A equals the value of one-unit allowance in system B. Thus, if system A imports allowances from system B, it is required to import only half the required volume, and if system B imports allowances from system A, it is required to import twice the volume. The quantitative restriction denotes that the maximum volume of allowances each system can obtain through intersystem trading in every single period is limited. For example, a quantitative restriction of 1/2 means the maximum volume of allowance that agents in system A (or system B) can import is 50 units if system B (or system A) can offer 100 units. To explore how restricted linkages work, in the following simulations, we keep all the parameter values the same as the simulations presented in Section 4.3 and impose different restrictions.

4.4.2. Linking ETSs with exchange rate restrictions

In this subsection, we explore the impact of linking ETSs with different exchange rate restrictions on the adoption of T3 and carbon reduction. Simulations with exchange rate restrictions as 1/5, 1/1 and 5/1 will be conducted. Here, $E_r = 1/5$ means a strict exchange rate restriction to system A and a loose exchange rate restriction to system B, and $E_r = 1/1$ means the equality of allowance values in both systems, denoting the unrestricted linkage discussed in Section 4.3, and we use it as the baseline to compare the impact of different exchange rate restrictions.

Fig. 4 shows the share of T3 by 2080 with different exchange rate restrictions. As can been seen, imposing a strict exchange rate restriction to system A is more likely to promote the adoption of T3 and imposing a loose one to system A is more likely to slow the adoption of T3. Moreover, the total adoption of T3 in the entire system after imposing a strict exchange rate restriction to system A may even be more than that without linkage. Thus, when linking ETSs with exchange rate restrictions, in terms of promoting the adoption of T3, it is better to treat the allowances in system A as more valuable and impose a strict exchange rate restriction to it.

Fig. 5 compares the total cost with different exchange rate restrictions. As can be seen, imposing exchange rate restrictions most often either increases the total cost of one system and reduces that of the other, or increases the total costs of both systems simultaneously. Only in several cases with, e.g., Gini coefficient pair as (0.01,0.02) and exchange rate restriction as 1/5, restricted linkage results in lower system costs than unrestricted linkage. As shown in Fig. B.1 in the Appendix, imposing a strict exchange rate restriction to system A will result in lower carbon emission than unrestricted linkage and imposing a loose exchange rate restriction to system A is more likely to result in more carbon emission, with exception of the case with Gini coefficient as (0.03,0.04). In this case, a loose exchange rate restriction to system A will also result in lower carbon emission than unrestricted linkage. Therefore, compared to unrestricted linkage, restricted linkages most often could not achieve reduction in total carbon emission with lower system costs. However, there are some exceptions, for example, in the cases with Gini coefficient pair as (0.01,0.02) and exchange rate restriction as 1/5, restricted linkages reduce total carbon emission with lower costs of both systems, which are very desired results. Compared to loose exchange rate restrictions, strict ones are more likely to result in such desired results. When imposing strict exchange rate restrictions to system A, the technical laggards tend to adopt T3 much earlier, which reduces their abatement costs and thus may benefit them in the later period. When imposing loose exchange rate restrictions to system A, the technical laggards tend to import more allowances to fulfill the carbon reduction target rather than adopt T3, which keeps their abatement costs at a high level and increases the adoption cost and import cost in the later period.

As shown in Fig. B.2 and Fig. B.3 in the Appendix, imposing a strict exchange rate restriction to system A will result in an increase in initial carbon price, and imposing a loose exchange rate restriction to system A will result in a decrease in initial carbon price. Not surprisingly, imposing exchange rate restrictions is more likely to shrink the carbon market.

As shown in Fig. B.4 and Fig. B.5 in the Appendix, system A is more likely to be the net inflow system of allowances, and the monetary is more likely to flow to system B from system A. This indicates that in the linked carbon market, system A is more likely to be the importer,

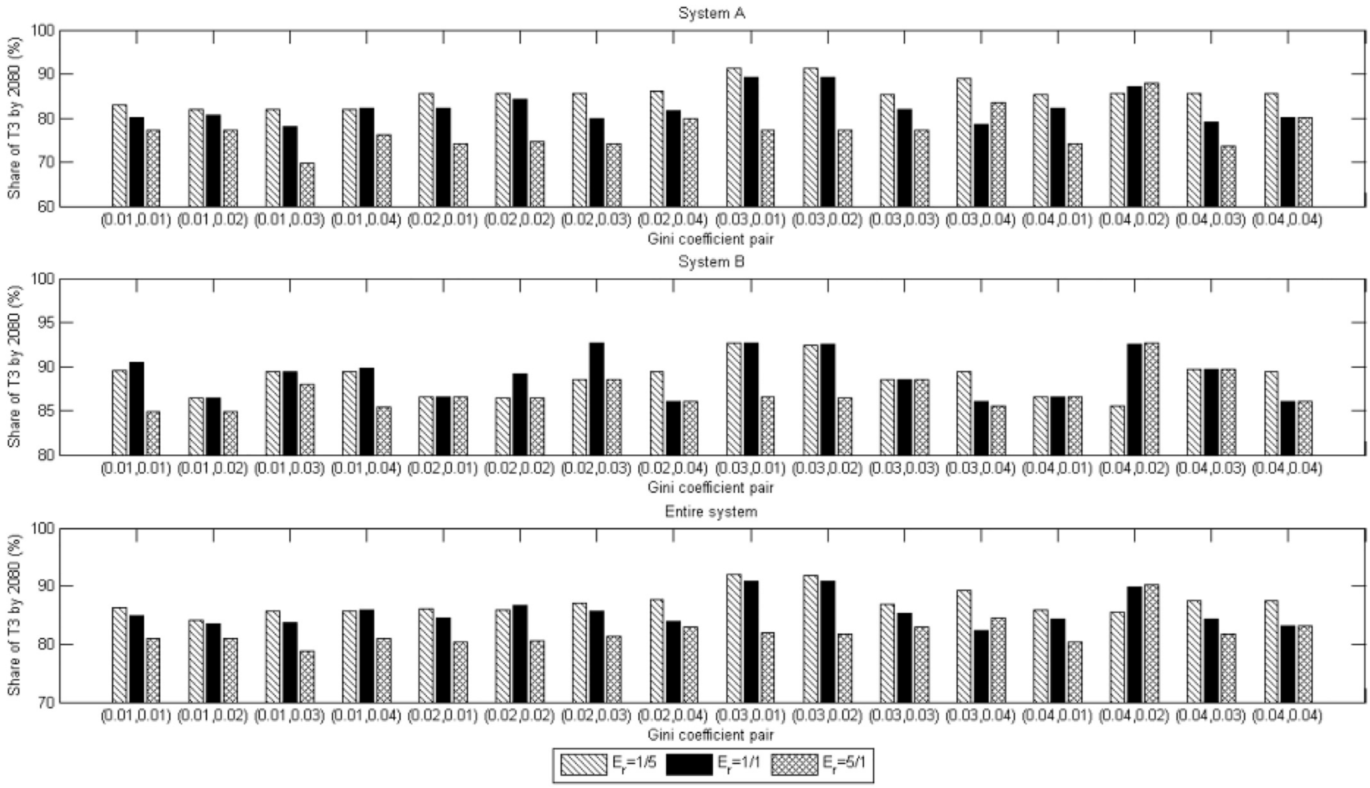

Fig. 4. Share of T3 by 2080 with different exchange rate restrictions.

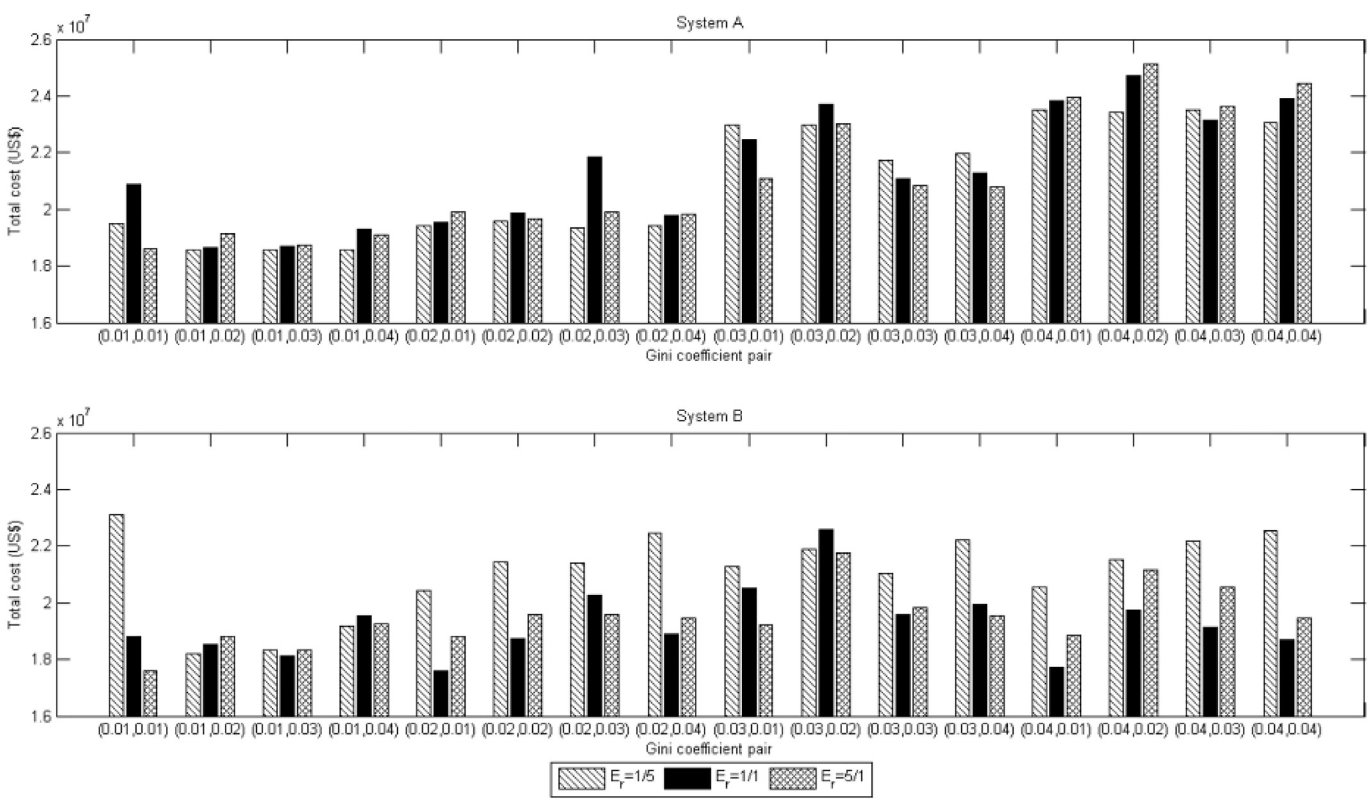

Fig. 5. Total cost with different exchange rate restrictions.

and system B is more likely to profit from intersystem trading. This is because agents' market shares in system B are not as balanced as those in system A, and technical leaders are more likely to appear in system B due to technological learning, which could benefit from early adoption. In general, imposing exchange rate restrictions on the linkage between ETSs could decrease intersystem trading volume and monetary flow.

As shown in Fig. B.6 in the Appendix, imposing a strict exchange rate restriction to system A is more likely to result in lower utilization of allowances than unrestricted linkage, and this explains why the carbon emission with a strict exchange rate restriction to system A is lower than that in unrestricted linkage. In addition, although imposing a loose exchange rate restriction to system A may also lead to lower utilization of allowances than unrestricted linkage, due to the multiplied increase in carbon emission caused by using allowances from system B in system A, the total carbon emission in the entire system does not decrease. That is why imposing a loose exchange rate restriction to system A may lead to lower utilization of allowances but still results in more carbon emission than unrestricted linkage.

As the exchange rate restriction is more loosed to system A, agents in system A are required to import fewer allowances to offset the same emission, thus the adoption of T3 will be reduced. However, for system B, the utilization rate is not 100% and the surplus allowances could be further used without causing more adoption of T3; thus, its adoption of T3 is not as sensitive to the changes in exchange rate restrictions as that in system A. This is why imposing a strict exchange rate restriction to system A is more likely to promote adoption of T3 and a loose exchange rate restriction to system A is more likely to slow the adoption of T3.

A strict exchange rate restriction to system A indicates that agents in system A have to import more allowances to offset the same emission. Thus, agents will reduce the demand of imported allowances by adopting more T3. As long as the cost decrease caused by importing fewer allowances exceeds the cost increase caused by adopting more T3, the total cost of system A will decrease; otherwise, it will increase. For system B, this restriction is loose and encourages agents to adopt more T3 to export more allowances. However, due to the decline in allowance demand, system B could not export as many allowances as that in the unrestricted case; thus, its total cost will increase. Agents then will adopt fewer T3 to reduce allowance supply and cost. As long as the cost decrease caused by adopting fewer T3 exceeds the cost increase caused by exporting fewer allowances, the total cost of system B will decrease; otherwise, it will increase. Moreover, a loose exchange rate restriction to system A indicates that agents in system A require fewer imported allowances to offset the same emission, which seems to help reduce the cost of system A. For system B, this restriction is strict and means that agents could only export fewer allowances than in the unrestricted case, which may result in a cost increase. However, agents will adopt fewer T3 to reduce allowance supply. With the decrease in allowance supply, agents in system A have to adopt more T3; thus, the total cost of system A may not decrease. As for system B, as long as the cost decrease caused by adopting fewer T3 exceeds the cost increase caused by exporting fewer allowance, its total cost will decrease; otherwise, it will increase. This is why it is difficult to predict the cost change of each system caused by imposing an exchange rate restriction.

In summary, compared to unrestricted linkage, imposing exchange rate restrictions most often could not reduce total carbon emission and promote the adoption of T3 with lower system costs. Restricted linkages shrink the intersystem trading volume and thus reduce the monetary flow between systems, which can somehow alleviate the difficulties in initialing a linkage. The most important finding of our simulations with different exchange rate restrictions is as follows. When imposing exchange rate restrictions, in terms of promoting the adoption of low-emission technologies and carbon reduction, it is better to treat the allowances in the system with more balanced market shares of agents (i.e., system A in the simulations) as more valuable. Such mechanisms promote firms to invest more in adopting low-emission technologies.

4.4.3. Linking ETSs with quantitative restrictions

In this subsection, we explore the impact of linking ETSs with different quantitative restrictions on the adoption of T3 and carbon emission. For simplicity, we only consider cases in which both systems have the same quantitative restriction, which means the quantitative restrictions are equal for both the importer and exporter. For example, if the maximum trading volume system A can import from (or export to) system B is restricted to 1/3, the maximum trading volume system B can export to (or import from) system A is also be restricted to 1/3.

In the following simulations, we explore cases with quantitative restrictions being 1/3, 2/3 and 1. Here, $Q_r = 1/3$ and $Q_r = 2/3$ indicate that only a discounted volume of allowances can be traded between the two systems. $Q_r = 1$ indicates no quantitative restriction on intersystem trading, which denotes the unrestricted linkage discussed in Section 4.3, and we use it as the baseline to compare the impact of different quantitative restrictions.

Fig. 6 compares the share of T3 by 2080 with different quantitative restrictions. As can be seen, imposing quantitative restrictions most often promotes the adoption of T3, and a strict quantitative restriction is more likely to result in more adoption of T3.

Fig. 7 compares the total cost with different quantitative restrictions. As can be seen, imposing quantitative restrictions most often either increases the total cost of one system and reduces that of the other, or increases the total costs of both systems. There are several exceptions, for example, with Gini coefficient pair as (0.01,0.01) and quantitative restriction as 1/3, restricted linkage results in lower system costs than with unrestricted linkage. As shown in Fig. C.1 in the Appendix, imposing quantitative restrictions most often results in lower carbon emission than unrestricted linkage. However, in the cases with Gini coefficient pair as (0.01,0.01) and (0.01,0.04), a strict quantitative restriction results in more carbon emission than unrestricted linkage, and in the cases with Gini coefficient pair as (0.01,0.04), (0.02,0.03) and (0.04,0.02), a loose quantitative restriction results in more carbon emission than unrestricted linkage. In summary, compared to unrestricted linkage, restricted linkages most often could not achieve reduction in total carbon emission with lower system costs. An exception is that with Gini coefficient pair as (0.03,0.02), imposing a strict quantitative restriction could reduce total carbon emission with lower system costs, which is a desired result.

As shown in Fig. C.2 and Fig. C.3 in the Appendix, imposing a quantitative restriction results in the increase in initial carbon price and is more likely to shrink the carbon market. As shown in Fig. C.4 and Fig. C.5 in the Appendix, system A is more likely to be the net inflow system of allowances, and the monetary is more likely to flow to system B from system A. In general, imposing a quantitative restriction could decrease intersystem trading volume and monetary flow.

As shown in Fig. C.6 in the Appendix, imposing a quantitative restriction most often leads to lower utilization of allowances than unrestricted linkage, except for the cases with Gini coefficient pair as (0.01,0.01), (0.01,0.04), (0.02,0.03) and (0.04,0.02). It can be inferred that imposing a quantitative restriction reduces the tradable volume of allowances in the carbon market and is more likely to promote the adoption of T3 in system A, which reduces the allowances required for the production in system A to a certain extent (because T3 produces less carbon emission than the other two technologies). However, the allowance demand decreases with the adoption of T3, which means that system B is only required to adopt fewer T3 to satisfy the allowance demand; thus, the allowances required for the production in system B increase. As long as the increase in the utilization of allowances in system B exceeds the decrease in the utilization of allowances in system A, the total utilization rate will increase. This is why imposing a quantitative restriction most often results in lower carbon emission than

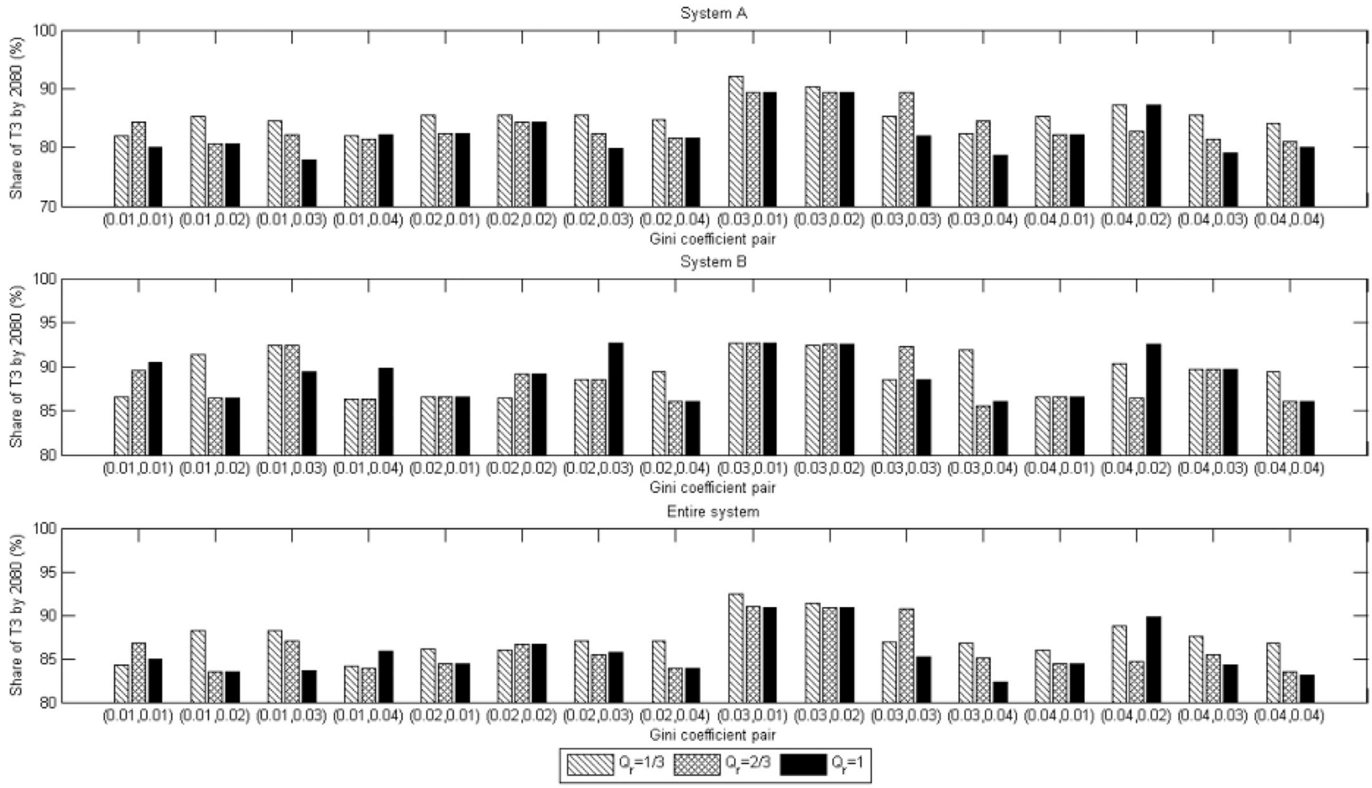

Fig. 6. Share of T3 by 2080 with different quantitative restrictions.

unrestricted linkage while in some exceptional cases it may lead to more carbon emission.

As the quantitative restriction is more loosed, agents in system A could import more allowances, thus the adoption of T3 will be reduced. However, for system B, the utilization rate of allowances is not 100% and the surplus allowances could be further used without causing more adoption of T3; thus, its adoption of T3 is not as sensitive to the changes in quantitative restrictions as that in system A. This is why imposing quantitative restrictions most often promotes the adoption of T3, and a strict quantitative restriction is more likely to result in more adoption of T3.

For system A, imposing a quantitative restriction indicates that agents could import fewer allowances than in the unrestricted case

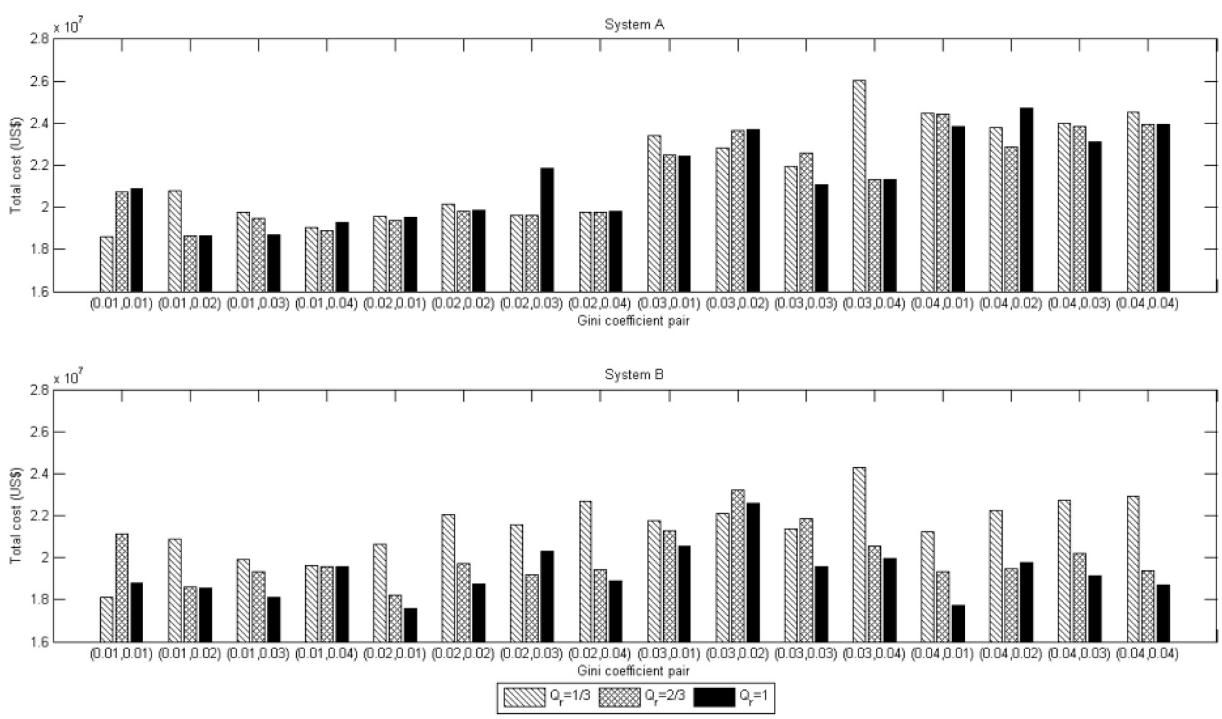

Fig. 7. Total cost with different quantitative restrictions.

and have to adopt more T3 to achieve the carbon reduction commitment, which may result in a higher cost. However, the import cost decreases as the imported volume decreases. Thus, although the total cost of system A is more likely to increase, it may also decrease as long as the cost decrease caused by importing fewer allowances exceeds the cost increase caused by adopting more T3. For system B, imposing a quantitative restriction reduces the tradable volume agents could export, resulting in a cost increase. However, agents will adopt fewer T3 to reduce allowance supply. Thus, although the total cost of system B is more likely to increase, it may also decrease as long as the cost decrease caused by adopting fewer T3 exceeds the cost increase caused by exporting fewer allowances. This is why it is difficult to predict the cost change of each system caused by imposing a quantitative restriction.

In summary, compared to unrestricted linkage, imposing quantitative restrictions most often could not reduce total carbon emission and promote the adoption of T3 with lower system costs. Restricted linkages shrink the intersystem trading volume and thus reduce the monetary flow between systems, which can somehow alleviate the difficulties in initialing a linkage. The main finding of our simulations with different quantitative restrictions is that compared to unrestricted linkage, imposing a strict quantitative restriction is more likely to contribute to more diffusion of low-emission technologies and thus reduce carbon emission, but at the expense of higher system costs.

5. Implications for China's practice – with Hubei and Guangdong as examples

In this section, we will discuss the implications of the theoretical study presented above for China's practice in linking different pilot ETSs, with the linkage between the Hubei pilot ETS and Guangdong pilot ETS as an example. As planned, China launched its establishment of the national ETS on December 2017 based on the experience of eight pilot ETSs. After the national ETS starts to operate (roughly scheduled on 2020), the current pilot ETSs will be linked, and the emission allowances can be traded across systems. However, linking these pilot ETSs is not easy work, which requires long-term negotiations and practices because these pilot ETSs are heterogeneous in mechanism design, market scale and economic development. Thus, based on the main findings of simulations, we briefly discuss the case if the Hubei pilot ETS links with the Guangdong pilot ETS and analyze the potential impact on technology adoption and carbon reduction in the power sector, which is the main sector that China's ETSs focus on.

The two pilot ETSs can be viewed as the two systems, and the power-generation companies in these two pilots can be viewed as heterogeneous agents with different production scales and different initial capacities of technologies in our ABM. According to the data from China Industrial Enterprise Database, firms' market shares in Hubei are more balanced than those in Guangdong; thus, Guangdong is more likely to be the inflow system of allowances and Hubei is more likely to be the outflow system of allowances if these two pilot ETSs are linked. According to the data from Hubei Emission Exchange and Guangzhou Emission Exchange, the average carbon prices of these two pilots in 2018 are 23.06 Yuan/t and 12.46 Yuan/t, respectively, and the trading volume in Guangdong is over three times that of Hubei. Thus, linkage will result in a decrease in Hubei's carbon price and an increase in Guangdong's carbon price and lead to more monetary flow to Hubei.

Linking the two ETSs will create a larger and more liquid carbon market, which may help reduce price volatility. This will benefit the power generation companies in Guangdong and Hubei in terms of a more stable power generation cost. As shown in our simulations, it could be a cost-effective way to achieve carbon reduction commitment from the perspective of power generation companies. However, from the perspective of the central government, it might result in more total carbon emission than without linkage and slow the adoption of low-emission technologies. According to China Electric Power Yearbook 2018, thermal power generation in Guangdong accounts for over 70% of the total installed capacities, and the share in Hubei is less than 40%. The linkage may reduce the motivation of power generation companies in Guangdong to adopt clean power generation technologies since it provides firms the opportunity to buy more allowances than in the unlinked case. Thus, it is most likely that the total carbon emission of Guangdong and Hubei might be higher than that without linkage. In addition, at the initial stage of the linkage, the government of Guangdong might have the monetary flow-out problem before the purchased allowance returns more revenue.

Imposing restrictions on the linkage provides a substitute way to alleviate the negative effect of unrestricted linkage. According to the findings of our simulations, it is better to value the emission allowances in Guangdong more when linking these two pilots with exchange rate restrictions, so that the carbon reduction could be put into practice at the expense of increasing system costs. Quantitative restrictions are also essential for an efficient initial linkage to reduce the intersystem trading volume and the monetary flow, which can somehow reduce Guangdong government's concern regarding monetary flow-out in the carbon market.

As found in our simulations, it is most likely that the total allowances of Guangdong and Hubei will be more used with the linkage (although imposing restriction might restrain such effect) and thus results in more total carbon emission than without linkage. This suggests that the central government needs to reconsider (most likely reduce) the total allowances allocated to Hubei and Guangdong if the aim is to control the total carbon emission below that without linkage.

Although Guangdong might have monetary flow-out in the carbon market, the power generation companies might reduce their cost in adopting more low-emission technologies or obtain more revenue by enlarging production scales. How to balance the monetary flow-out and the revenues among actors in Guangdong is a new issue that might need to be addressed after the linkage, which the local government of Guangdong should be well prepared before the linkage.

6. Concluding remarks

This paper develops a stylized ABM to explore the impact of linking two ETSs considering firms' heterogeneity and the interactions among firms' technology adoption and allowance trading strategies. Although the simulations are highly stylized, they can still provide insights into how linkages and restrictions on the linkages will influence the adoption of low-emission technologies and carbon reduction. The main findings and policy implications of this study are as follows:

(1) Linking ETSs could be a cost-effective way for the entire system to achieve carbon reduction commitment and create a larger and more liquid carbon market, which may help reduce price volatility; however, it might restrain the diffusion of low-emission technologies and result in more total carbon emission since the allowances allocated to each ETS (before linking) will be used more. This implies that the allowances to each ETS should be redesigned (mostly reduced) to ensure that the total emission does not exceed that before linkage. In the case of China, the central government can play such a role because different pilot ETSs are in the same country. However, in the case of linking ETSs in different countries, such work is more difficult because it has no organization with the authority over the ETSs planned to be linked.

(2) The government should be aware that linking ETSs most likely cannot achieve carbon reduction with lower system costs. In some cases, it could reduce total carbon emission at the expense of increasing the cost of at least one ETS. In such cases, the government could consider subsidizing the more burdened ETS to make the linkage more stable. Again, this is much easier if the ETSs to be linked are under the same authority.

(3) Restricted linkages could reduce intersystem trading volume and monetary flow between systems, which can somehow alleviate the difficulties in initializing a linkage. When imposing exchange rate restrictions, in terms of promoting the adoption of low-emission technologies and carbon reduction, it is better to treat the allowances in the system with more balanced market shares of agents more valuable and impose a strict exchange rate restriction to this system because such mechanisms will promote firms to invest more in adopting low-emission technologies.

Although the models and simulations provide the aforementioned insights into the impact of linking ETSs, we acknowledge that this study has limitations that should be addressed in the further work. First, the current model does not consider that government can auction allowances to emitters and reserve a certain amount for market intervention. Second, the current model does not consider banking allowances for later use. Third, agents in the current model are short-sighted and optimize their adoption and allowance trading decisions only for each single period. Due to technological learning, investments in low-emission technologies will benefit the future, thus agents may have long foresight to balance the short-term expenditures and future returns.

Acknowledgment

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Appendix A

Fig. A.1Comparison of the cumulative carbon emission with and without linkage

Appendix B Fig. B.1Cumulative carbon emission in the entire system with different exchange rate restrictions.

Appendix C Fig. C.1Cumulative carbon emission in the entire system with different quantitative restrictions.

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