Potential impact of (CET) carbon emissions trading on China's power sector: A perspective from different allowance allocation options

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Abstract:

In Copenhagen climate conference China government promised that China would cut down carbon intensity 40-45% from 2005 by 2020. Carbon emissions trading (CET) is an effective tool to reduce emissions. But because CET is not fully implemented in China up to now, how to design it and its potential impact are unknown to us. This paper studies the potential impact of introduction of CET on China's power sector and discusses the impact of different allocation options of allowances. Agent-based modeling is one appealing new methodology that has the potential to overcome some shortcomings of traditional methods. We establish an agent-based model (CETICEM) of introduction of CET to China. In CETICEM, six types of agents and two markets are modeled. We find that: (1) CET internalizes environment cost; increases the average electricity price by 12%; and transfers carbon price volatility to the electricity market, increasing electricity price volatility by 4%. (2) CET influences the relative cost of different power generation technologies through the carbon price, significantly increasing the proportion of environmentally friendly technologies; expensive solar power generation in particular develops significantly, with final proportion increasing by 14%. (3) Emission-based allocation brings about both higher electricity and carbon prices than by output-based allocation which encourages producers to be environmentally friendly. Therefore, output-based allocation would be more conducive to reducing emissions in the Chinese power sector.

Keywords: Agent-based model; Carbon emissions trading; Emission-based allocation; Output-based allocation

1. INTRODUCTION

The European Union (EU) emission trading scheme (ETS) directive was first published in 2003, aiming at helping its members prepare for carbon emission targets agreed in the Kyoto Protocol for the 2008 to 2012 trading period [1]. An emission-based allocation was available in EU ETS. From January 1, 2005, if enterprises of member states are about to emit carbon dioxide, they must gain the rights to do so, which can be received from their government or bought from the carbon trading market. The main reason for the introduction of ETS is that it can reduce emissions in a cost-effective way [2]. Since January 1, 2008, emission rights can be traded among EU countries.

With rapid economic development, China's energy consumption, especially electricity consumption, has grown rapidly. More than 75% of China's electricity power is thermal power. Coal-fired electricity generation has increased rapidly over recent years. From 1991 to 2005, the proportion of coal-fired generation in thermal power was maintained at 90%-96%, meaning large amounts of carbon emissions during that period. In 2005, carbon emissions from the Chinese power sector reached 38.73% of total emissions of primary energy [3]. The Chinese power generation sector has been liberalized, allowing competition. The current electricity pricing mechanism in China is mainly based on the up-grid electricity price management approach, implemented May 1, 2005. Two-part electricity prices are applied to the generation units. The capacity price is set by the government. The electricity price is determined through market competition. The specific price is set through consultations between the power generation and power grid companies, on the premise that generation cost can be compensated.

In this paper, we study the potential impact of introducing CET on China's power sector. This is because, on the one hand, carbon emissions from the power sector are large; and, on the other hand, because of regional division of the power market, cross-border and inter-regional electricity transmission is relatively small, subject to transmission capacity and line loss. According to China Energy Statistical Yearbook 2008, China's power imports in 2007 only accounted for 0.13% of the total electricity supply [4]. Introduction of CET will inevitably increase the companies' costs and weaken their international competitiveness. As was argued above, inter-connector capacity between China and neighboring countries is relatively low and it is not expected to increase dramatically. Therefore the physical supply of electricity will remain a regional product. That means that the model here is applicable for China power sector.

This paper attempts to establish an agent-based model on the introduction of CET into the Chinese power market, and attempt to answer the following questions:

(1) What would be the impact of CET on the electricity price and final portfolio of power plants?

(2) What would be the difference of emission-based allocation and output-based allocation? What is the micro mechanism behind it? Which allocation mechanism would be more suitable for China's domestic carbon market?

The results may shed light on the wisdom of the government's decision and even potentially cause a change in policy. Also, some conclusions may be the general rules of carbon market, which will be a contribution to existing literatures. The article is structured as follows: firstly, we will introduce the literatures relating to the carbon market mechanism and agent-based model; secondly, a CET-introduced Chinese electricity market simulation model is established; thirdly, we carry out simulations to answer the questions above; finally, a summary and some policy implications are given.

2. LITERATURE REVIEW

The literatures relating to CET mainly focuses on carbon market mechanism design and its applications between and within countries. Regarding carbon market mechanism design, Bohringer and Lange discuss emission-based and output-based allocations [5]. They find that in a closed-trade system, emission-based allocation is better; however, in an open-loop system, combination of the two allocations is better. Cramton and Kerr believe that the government should auction carbon emission rights, rather than allocating them for free [6]. They argue that auction can promote technological innovation and share cost effectively. Burtraw et al. compared auction, and emission-based and output-based allocations based on the Haiku electricity market model [7, 8]. They find that the social cost of auction is about half of the two free allocation types, and that emission-based allocation is more favorable to producers, while output-based allocation leads to the lowest electricity price and highest gas price.

Regarding inter-state trading of emission rights, Haurie and Viguier propose a computable stochastic equilibrium model to represent possible competition between Russia and China on the international market of carbon emissions permits [9]. They analyzed the impact of this competition on the pricing of emissions permits and on the effectiveness of the Kyoto and post-Kyoto agreements, without US participation. Carlén investigate market power in intergovernmental CET based on a simulation [10]. They find that (i) the presence of a large trader is not likely to create inefficiencies, and (ii) a large trader is not likely to be able to substantially influence prices to its advantage during end-period trading. Bosello and Roson explore the distributional consequences of alternative emissions trading schemes [11]. They find that the introduction of a competitive market for emissions permits, especially when this market includes non-Annex I countries (developing countries), would dramatically lower total abatement costs but, on the other hand, would primarily benefit the richest countries.

Regarding intra-state trading of emission rights, Keats et al. believe that as a result of introducing EU ETS, the net values of both a typical pulverized coal-fired (PC) power station and a more modern gas-fired combined cycle gas turbine (CCGT) would increase [12]. They also argue that in the future, a greater proportion of allowances can and should be auctioned. Szabó et al. developed a global dynamic simulation model of the cement industry, quantifying the benefit achieved from emission trading in different markets (EU15, EU27 and Annex B) and assessing the magnitude of the potential carbon leakage effect [13]. Chappin and Dijkema present an agent-based model to elucidate the effect of CET on the decisions of power companies in an oligopolistic market [14]. They find that that even after the introduction of CET, capacity expansion plans indicate a preference for coal. In power generation, the economic effect of CET is not sufficient to outweigh the economic incentives in choosing coal.

Agent-based modeling (ABM) is a typical bottom-up method. Nowadays, agent-based model have received increasing attentions from many researchers in the field of energy system modeling [15]. ABM is thought of as a powerful tool for studying complex adaptive systems.

The applications of agent-based methods in energy market reform and energy policy simulation are mainly focused on the study of electricity market. Bunn and Oliveira used an agent-based simulation of England and Wales electricity markets to analyze the market power and the market design [16]. Based on Sandia models, Ehlen et al. constructed a multi-agent model to simulate both uniform-price and real-time price (RTP) contracts of U.S. electricity wholesalers [17]. They found that RTP contracts made power loads move from peak to off-peak hours, increased wholesalers' profits, but also created susceptibilities to short-term market demand and price volatilities. Bunn and Oliveira developed a simulation model of technological evolution in electricity markets to analyze how the market performance depended upon the different technological types of plant owned by the generators

[18]. Hamalainen et al. did a simulation of consumer coalitions in Finnish electricity retail market to analyze the response of different types of consumers to Time-Of-Use (TOU) pricing [19]. Bernal-agustin et al. presented a realistic simulator of the day-ahead electricity market in mainland Spain, which was a good decision-making tool for the electricity market participants [20]. Cong and Wei examined whether carbon allowance auction should adopt a uniform-price or discriminatory-price format using an agent-based model [21]. They found that a discriminatory-price auction is more suitable in terms of maximizing revenue for the government, but an uniform-price auction is better in terms of fairness to bidders, especially small bidders.

The crisis of California electricity market in 2000 reminds us that a new market mechanism, if it is not fully tested before practice, can often produce the unexpected impact on the entire economy. Because CET is not fully implemented in China up to now [22], in order to analyze its potential impact on China power sector under an experiment framework which can be repeated, this paper constructed an agent-based model which is named as CETICEM (CET Introduced China Electricity Market) and consider electricity price elasticity and carbon market clearing in China, which are very important in intra-state CET. We also compare emission-based allocation and output-based allocation, which is of particular significance for domestic carbon market mechanism design.

3. METHODOLOGY: CETICEM

3.1 Model Settings

In the model, six types of agents are modeled: a power grid company, power producers, other industries, consumers, the government and a carbon market maker. And two markets, the electricity and carbon markets are also modeled (as shown in Fig. 1).

[Insert Fig.1]

3.2 The action rules setting

3.2.1 Power producers

Power producers aim to maximize their profits. The main actions of the power producers can be seen in Fig. 2. At the beginning of each period, power producers obtain carbon quotas and determine their electricity supplies. Based on the carbon needed for electricity generation, producers decide to buy or sell carbon quotas. At the end of each period, based on the supply and demand of the market and of the operations themselves, the producers make decisions to establish or close power plants.

[Insert Fig.2]

Which type of plant will be invested in is based on multi-criteria. The size of plant will be decided according to the criteria for meeting the electricity demand. The criteria include economic, environmental friendliness, nuclear fear, and the constraints of land and water resources.

The economic criterion indicates the expected profitability of a power plant. The expected profitability of producer i's plant j, $ep_{i,j}$, can be calculated in equation (1):

$$ep_{i,j}(t) = ((cer_{i,j}(t) \times cp(t) + capa_j \times p(t) - capa_j \times n_j \times fp_j(t) - capa_j \times m_j \times cp(t) - oc_j) \times \frac{1-(\frac{1}{1+infl})^{lt_j}}{1-\frac{1}{1+infl}} + sub_j - inco_j) / inco_j \tag{1}$$

Definitions of the parameters and variables in equation (1) are shown in Table 1 and Table 2. Expected profitability is based on the ratio of discounted net cash flows in each period and total investment costs. Different from previous studies, we consider the impact of carbon quota ($cer_{i,j}(t) \times cp(t)$) and capital rate ($infl$). In equation (1), carbon quota rights can be seen as revenue because it is free allocated by government.

[Insert Table 1]

[Insert Table 2]

At the same time, producers may prefer environmentally friendly electricity generation technology (for which m_j is smaller). The construction of nuclear plants does not only depend on producers' attitudes, but also on national policy. The construction of wind plants and hydropower stations depends on available land and water resources, respectively. The plants are graded, the ones with higher grade having a greater probability of being invested in.

We assume that there are three types of producers: profit-hunting producers, environmentally friendly producers and neutral producers, with weights of profit-hunting and environmental friendliness as follows: (0.7, 0), (0.3, 0.4) and (0.5, 0.2), respectively. For example, the weight on the expected profitability for profit-hunting producers is 0.7, while it is 0.3 for environmentally friendly producers. The weight on the expected profitability for neutral producers is 0.5, which means their relatively neutral attitudes to the economic criterion. In reality, profit-hunting producers may refer to private power companies whose objective is only profit maximization. Environmentally friendly producers may refer to public power companies. Not only profit maximization but also environmental protection is their objectives. Neutral producers fall in between two types of producers above.

While investing, producers will firstly decide their type of producer according to the probability vector $P_i = \{p_p, p_e, p_n\}$, where p_p, p_e, p_n represent the probabilities of turning to profit-hunting producers, environmentally friendly producers and neutral producers. They will then adjust their vectors at the end of each period based on the rules described in Table 3. For example, when producer's type is profit-hunting, if it can make profits, the probability of turning to profit-hunting is increased by Δ, the other two probabilities are decreased by $\frac{\Delta}{2}$.

[Insert Table 3]

The rules of probability adjusting are inspired by reinforcement learning theory where agents take actions to maximize their long-term utilities. So the action which can get larger utility is more likely adopted in the future. Through the reinforcement-learning mechanism mentioned above, we can study whether different market design will shift consumers' preferences.

3.2.2 Government

The government's main aim is to reduce emissions and stabilize the electricity price. Its actions include subsidizing environmentally friendly technology, laying the carbon allocation plan, setting the national nuclear policy and controlling the electricity price. Carbon allocation in our model focuses on two of these actions:

(Ⅰ) Emission-based allocation: The previous year's emission proportion is the standard used for setting emission quotas in the following year, which is the current quota allocation mechanism in the EU ETS. Producer i's emission quota, $cer_i(t)$, can be calculated in equation (2):

$$cer_i(t) = \frac{emi_i(t-1)}{\sum_i emi_i(t-1)} \times to\_cap(t) \times \gamma \tag{2}$$

where $emi_i(t-1)$ is producer i's carbon emissions in period t-1; $to\_cap(t)$ is total carbon quota in period t; and γ is the decrease in the rate of the quota.

$cer_{i,j}(t)$ in (1) is defined as equation (3):

$$cer_{i,j}(t) = \frac{m_j \times su_{i,j}(t-1)}{\sum_i \sum_j m_j \times su_{i,j}(t-1)} \times to\_cap(t) \times \gamma \tag{3}$$

where $su_{i,j}(t-1)$ is electricity supply of producer *i*'s plant j in period t-1.

(Ⅱ) Output-based allocation: The supply proportion of the previous year's electricity is the standard used for setting emission quotas for the following year, as shown in equation (4):

$$cer_i(t) = \frac{su_i(t-1)}{\sum_i su_i(t-1)} \times to\_cap(t) \times \gamma \tag{4}$$

$su_i(t-1)$ is producer i's electricity supply in period t-1. In this case, $cer_{i,j}(t)$ in (1) is defined as equation (5):

$$cer_{i,j}(t) = \frac{su_{i,j}(t-1)}{\sum_i \sum_j su_{i,j}(t-1)} \times to\_cap(t) \times \gamma \tag{5}$$

And the relationship between cer_i(t) and cer_i,j(t) is shown in equation (4):

$$cer_i(t) = \sum_j cer_{i,j}(t)$$

Although in the first phase of EU ETS, other allocation modes, such as auction, have been in practice. But there were only three countries (Ireland, Hungary and Lithuania) choosing auction. And the percentages of carbon allowances auctioned are relatively few. Therefore, we choose two free grandfathering allocations which drew the most attentions and try to compare them.

3.2.3 Industry

The industry's aim is to sell products to maximize profit. We use an agent to represent industry and assume its demand is determined by an exogenous scenario. Because power sector is our focus, industry agent's carbon demand is set exogenously here. We will expand our object of study in the future.

3.2.4 Power grid company

The action of the power grid company is setting the transmission and distribution tariff. In 2007, the average transmission and distribution tariff was 160.12 Yuan/KKWH, which accounted for 31.49% of the electricity price [23]. Therefore, in the model retail electricity price equals to 131.49% of average electricity price.

3.2.5 Consumers

According to different sale prices, we divide consumers into two categories: small and large electricity consumers. Small consumers need to bear the electricity price, and large consumers need to cover the electricity price and capacity price. We use two agents to represent consumers.

China's electricity demand is mainly driven by GDP. Meanwhile, as a commodity, its demand is certainly affected by its price. Therefore, we assume electricity demand is decided by GDP growth and its price changes accordingly. The consumers' decisions are shown in equation (6):

$$D(t)=D(t-1)\times [1+(\frac{GDP(t)}{GDP(t-1)}-1)\times \alpha]\times [1+(\frac{P(t)}{P(t-1)}-1)\times \beta] \tag{6}$$

where $GDP(t)$ refers to GDP in period t; $P(t)$ represents retail electricity price in period t; α is the GDP elasticity of electricity demand; and β is the retail price elasticity of electricity demand.

3.2.6 Carbon market maker

The primary function of the carbon market maker is to provide market liquidity and balance the supply and demand of the carbon market. The cumulative imbalance in period t, $pool(t)$, can be calculated as in equation (7):

$$pool(t) = pool(t-1) + car\_d(t) - car\_s(t) \tag{7}$$

where $car\_d(t)$ refers to total carbon demand in period t; $car\_s(t)$ is total carbon supply in period t; and $pool(t) > 0$ represents cumulative CO_2 demand is larger than CO_2 supply, and *vice versa*.

3.3 The market rules

3.3.1 Electricity market

A two-part electricity price system operates in China, comprising the electricity price and capacity price. The capacity price is based on the average investment cost of generating units, which aims to compensate for investment cost and finance charges. The electricity price is determined by the market. This paper sets the rules as follows: in period t, firstly, each plant decides the electricity supply, $w\_s_{i,j}(t)$. If the expected return of generation is less than selling the carbon quota, the electricity supply is zero; otherwise, the supply equals its capacity. The average market price, $bid\_ave(t)$, can be calculated in equation (8):

$$bid\_ave(t) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} w\_s_{i,j}(t) \times bid_{i,j}(t)}{\sum_{i=1}^{n}\sum_{j=1}^{m} w\_s_{i,j}(t)} \tag{8}$$

As shown in equation (8), the average market price is weighed to the capacity of the bids. The bid price of plant j owned by producer i is composed of cost and profit, shown in equation (9):

$$\begin{aligned} bid_{i,j}(t) = {} & [\, fp_j(t) \times capa_j(t) + oc_j(t) + capa_j(t) \times m_j \times cp(t)] \\ & \times (1 + mar_i \times ave\_mar) / capa_j(t) \end{aligned} \tag{9}$$

where ave_mar denotes the average profit rate of the electricity industry, which is set exogenously; and mar_i is the ratio of producer i's profit rate and the electricity industry's profit rate.

Based on the argument that the bidding price determines the amount of capacity sold, the actual supply of plant j owned by producer i is shown in equation (10):

$$s_{i,j}(t) = w\_s_{i,j}(t) \times \frac{D(t)}{\sum_{i=1}^{n}\sum_{j=1}^{m} w\_s_{i,j}(t)} \times \frac{bid\_ave_i(t)}{bid_{i,j}(t)} \quad (10)$$

In period t, the average electricity price, $ave\_ep(t)$, is shown in equation (11):

$$ave\_ep(t) = bid\_ave(t) \times e^{(\theta \times (to\_D(t) - \sum_{i=1}^{n}\sum_{j=1}^{m} w\_s_{i,j}(t)))} \quad (11)$$

where θ is a proportional coefficient, which reflects price fluctuations when there is an imbalance between supply and demand.

As mentioned above, the bids of power plants determine the frequency of their usage. In reality, the actual price received for the electricity produced by a specific power plant is related to the height of its bid price. The electricity price for each plant is shown in equation (12):

$$ep_{i,j}(t) = ave\_ep(t) \times \frac{bid_{i,j}(t)}{bid\_ave(t)} \quad (12)$$

Some validations of equations above can be found in Chappin’s research [24].

3.3.2 Carbon market

We assume that the carbon price is affected by carbon supply and demand. The current carbon price is affected by the total available quotas and emissions of the last period (current emission is not available). In period t, carbon price, $cp(t)$, is as shown in equation (13):

$$cp(t) = cp(0) \times e^{(\lambda \times (total\_emission(t-1) - total\_cap(t) + pool(t)))} \times (1 + \varepsilon_t), \varepsilon_t \sim N(0, 0.01^2) \quad (13)$$

where λ is a proportional coefficient. In addition, a random disturbance, ε_t, is also added to the model to explain other random factors and cp(0) is the initial value for the carbon price, which is set to 100 according to the EU ETS and exchange rate.

3.4 Model implementation

The software used here is NetLogo which is a cross-platform multi-agent programmable modeling environment. We created 90 agents as electricity power producers, each producer having a number of plants. Relevant parameters' value of power plants are shown in the appendix Table 1. The agents evolve over time by action and interaction. The total simulation length is 100 periods. The model procedure is repeated until the end of the simulated period is reached.

4. EXPERIMENT DESIGN AND ANALYSIS

The main assumptions underlying the model are an electricity market with perfect competition, a static number of electricity producers and a limited available power plant types. Main input data are listed in appendix Table 2.

4.1 Impact of carbon emission trading (CET) on electricity price

First of all, we explore the impact of introducing CET on the electricity price in China. The emission-based allocation, which was used in EU ETS, is chose here as the baseline scenario. We obtain different electricity prices corresponding to whether CET is introduced or not. With due consideration of availability of data, 2007 is chose as the base year. Data from China state electricity regulatory commission are used to calibrate the model. In 2007, average on-grid price for wind power is 617.58 Yuan/KKWH; for nuclear power is 436.23 Yuan/KKWH; for thermal power is 346.33 Yuan/KKWH; for hydro power is 244.04 Yuan/KKWH.

[Insert Fig.3]

We can see from Fig. 3 that compared to no CET, introducing CET has the following effects: increase in the level and fluctuation of the electricity price in most cases; at the end of 100 periods (here one period means one year), the electricity price is 1.23 times higher; and fluctuation of the electricity price is 1.04 times higher (see Table 4). Therefore, introducing CET internalizes costs and transfers the volatility of the carbon price to the electricity market.

[Insert Table 4]

Next, we study the impact of CET on the electricity price under different GDP growth rates. We do a simulation of the electricity price at the end of 100 periods corresponding to different GDP growth rates. The results are shown in Fig. 4.

[Insert Fig.4]

We can see from Fig. 4 that if no CET is introduced, when the GDP growth rate is low, the electricity price growth rate is high; and when the GDP growth rate is high, the electricity price growth rate shows a decreasing trend. On the one hand, economic development encourages electricity consumption and drives up the electricity price. On the other hand, increase in the electricity price suppresses consumption. Therefore, economic development has both positive and negative impact on electricity consumption, which in return reflects the trend of decrease in electricity price growth. However, electricity price growth shows an increasing trend when CET is introduced. This is because, in addition to the above impact, economic development also demands carbon, which pushes up the carbon price. The carbon price increase is reflected in the electricity price, pushing up the electricity price. Therefore, to address China's growing economy, the Chinese government should establish regulatory measures if CET will be introduced.

4.2 Impact of CET on power source structure

Next, we consider the impact of CET on China's power source structure. The emission-based allocation is also chose here.

[Insert Fig. 5]

[Insert Fig. 6]

We can see from Figs. 5 and 6 that introducing CET brings forward large-scale natural gas power generation. At the same time, we can see from the final power source structure (Table 5) that there is an increase in the proportion of environmentally friendly power generation technology (nuclear power, solar power and gas-fired power). Among them, solar power, which provides environmental protection but is expensive, develops a lot after introducing CET. Due to land and water constraints, the proportions of wind power and hydropower, respectively, do not increase after CET is introduced, although, the absolute amount of wind power increases slightly.

[Insert Table 5]

4.3 Comparison of emission-based allocation and output-based allocation

[Insert Fig. 7]

As can be seen from Fig. 7, the evolution of the electricity price and carbon price of the two allocation mechanisms is similar. However, the electricity price of output-based allocation is lower because of the lower carbon price. We would like to know what the micro mechanism for this macro phenomenon is and the difference of producers under both market mechanisms.

We analyze the final producers' proportions according to the type of allocation, i.e., emission-based and output-based allocations (initial proportions: economic producers, 0.3; environmentally friendly producers, 0.3; neutral producers, 0.4). The results are as follows:

[Insert Table 6]

[Insert Table 7]

As can be seen from Table 6, when emission-based allocation is introduced, the proportion of economic producers (0.394) is larger than the proportion when output-based allocation is introduced (0.328). As seen from Table 7, the probability of F is 0.544 for projected proportion of profit-hunting producers, which is insignificant at the 5% level. Thus, we believe that equal variances assumed under two allocations are not rejected. Next, let us look at the results corresponding to assumptions of equal variances. The value of t is 8.845, with probability is 0.000. The result rejects the null hypothesis and shows that there is a significant difference between the proportions of economic producers under the two allocation mechanisms.

We do a similar analysis on neutral and environmentally friendly producers (intermediate results are shown in Table 8 and 9). The robust test is also done for different initial proportion settings. The final results are shown in Fig. 8.

[Insert Table 8]

[Insert Table 9]

[Insert Fig. 8]

As seen in Fig. 8, when emission-based allocation is introduced, the proportion of economic producers (0.394) is higher compared to output-based allocation (0.328). In other words, emission-based allocation causes producers to turn to less environmentally friendly technologies. In essence, emission-based allocation allocates more carbon quotas to producers who emit more. This is an incentive for emissions. From a broader sense, emission-based allocation is designed for compensating bodies which are affected by emission control [25-27].

Output-based allocation encourages producers to be environment-friendly. Therefore, total emissions are lower, resulting in a lower carbon price. In this perspective, in the Chinese domestic carbon market, for the same sector, output-based allocation is more efficient for reducing emissions.

The results here may be different from the general opinion which was established in standard market theory that the method of allocation of a given number of emission certificates should not affect the equilibrium price. Because the producers in our model can shift their investment preferences in the two allowance allocations, output-based allocation makes producers tend to be environment-friendly, which will decrease total carbon demand and carbon price.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we studied the impact of introduction of CET on China's power sector using an agent-based model. The main findings are as follows:

(1) CET internalizes the external environmental cost, which increases the average electricity price (12%). At the same time, the volatility of the carbon market is also transferred to the electricity market (fluctuations excluding the impact of mean increases of 4%). When there is no introduction of CET, the electricity price shows a declining trend as the economy develops. However, introduction of CET significantly increases the electricity price. Therefore, to address China's high-speed development, the Chinese government should establish specific regulatory measures after introducing CET.

(2) CET influences the relative costs of different power generation technologies through the carbon price, which would have a significant impact on the power source structure. Introduction of CET would cause large-scale natural gas generation. The final proportion of environmentally friendly power generation technologies such as nuclear power and natural gas power would increase. Environmentally friendly solar power would develop significantly after CET is introduced (final

proportion, 14% increase). In contrast, the final proportion of coal-fired power, whose emissions are high, would decrease significantly by 18%.

(3) Emission-based allocation produces both a higher electricity price and higher carbon price, compared to output-based allocation. This is because under the latter allocation, producers would tend to be more environmentally friendly. Compared to emission-based allocation, output-based allocation would be more conducive to environmental protection. Therefore, output-based allocation should be considered in the design of the Chinese domestic CET market.

As we know, this paper is the first one which studied the potential impact of CET on China power sector in a computable framework. It will provide China government and related decision-makers a quantity tool for designing carbon market. This paper also firstly explains which free allocation is better and the micro mechanism behind it, which is a necessary supplement to existing literatures.

This paper does not endogenously model the Chinese fuel market. We also do not consider entry and quit mechanisms for producers. Demand elasticity of electricity is constant. These are left to address in future research.

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Table 1. Description of parameters

Parameter	Description	Parameter	Description
α	GDP elasticity of electricity demand	β	price elasticity of electricity demand
γ	the decrease in the rate of the quota	λ	proportional coefficient
θ	proportional coefficient	ave_mar	the average profit rate of the electricity industry
$capa_j$	Capacity of electricity plant j	$inco_j$	Investment cost for plant j
$Infl$	Capital interest rate	lt_j	Plant j's life
m_j	Carbon needed for plant j's unit of electricity	mar_i	the ratio of producer i's profit rate and the electricity industry's profit rate
n_j	Fuel needed for plant j's unit of electricity	oc_j	Operation cost for plant j in one period
sub_j	Subsidy for plant j, which is environmentally friendly		

Table 2. Description of variables

Variables	Description	Variables	Description
$ave\_ep(t)$	The average electricity price	$bid_{i,j}(t)$	The bid price of plant j owned by producer i in period t
$bid\_ave(t)$	The average market price	$car\_d(t)$	total carbon demand in period t
$car\_s(t)$	total carbon supply in period t	$cer_i(t)$	Producer i's emission quota
$cer_{i,j}(t)$	Carbon quota of producer *i*'s plant j	$cp(t)$	carbon price in period t
$D(t)$	electricity demand in period t	$emi_i(t)$	producer i's carbon emissions in period t
$ep_{i,j}(t)$	The electricity price for producer i's plant j	$fp_j(t)$	Fuel price for plant j
$GDP(t)$	GDP in period t	$P(t)$	Retail electricity price in period t
$pool(t)$	The cumulative imbalance in period t	$s_{i,j}(t)$	the actual supply of plant j owned by producer i in period t
$su_{i,j}(t)$	electricity supply of producer *i*'s plant j in period t	$\mathrm{su}_i(t)$	producer i's electricity supply in period t
$total\_cap(t)$	total available quotas in period t	$total\_emission(t)$	emissions in period t
$to\_cap(t)$	total carbon quota	$w\_s_{ij}(t)$	the electricity supply of producer i's plant j in period t

Table 3. The rules of probability adjusting

Producer's type when investing	Whether the plant can make profits?	Probability adjusting
Profit-hunting producers	Yes	$P \leftarrow \{p_p + \Delta, p_e - \frac{\Delta}{2}, p_n - \frac{\Delta}{2}\}$
	No	$P \leftarrow \{p_p - \Delta, p_e + \frac{\Delta}{2}, p_n + \frac{\Delta}{2}\}$
Environmentally friendly producers	Yes	$P \leftarrow \{p_p - \frac{\Delta}{2}, p_e + \Delta, p_n - \frac{\Delta}{2}\}$
	No	$P \leftarrow \{p_p + \frac{\Delta}{2}, p_e - \Delta, p_n + \frac{\Delta}{2}\}$
Neutral producers	Yes	$P \leftarrow \{p_p - \frac{\Delta}{2}, p_e - \frac{\Delta}{2}, p_n + \Delta\}$
	No	$P \leftarrow \{p_r + \frac{\Delta}{2}, p_e + \frac{\Delta}{2}, p_n - \Delta\}$

Table 4. Comparison of electricity prices under different mechanisms

Electricity price	CET introduced	No CET introduced	Ratio
Electricity price at the end of 100 periods （yuan/KKWH）	1162.6	947.26	1.23
Maximum electricity price （yuan/KKWH）	1170.38	965.61	
Minimum electricity price （yuan/KKWH）	486	486	
Average electricity price （yuan/KKWH）	876.44	780.72	1.12
Standard deviation （yuan/KKWH）	176.10	150.13	1.3
Standard deviation coefficient	0.20	0.19	1.04

Table 5. Comparison of power source structures under different schemes

		CET introduced	No CET introduced
The beginning period of large-scale gas power generation（Proportion > 8%）		2	34
Final portfolio (%)	Hydropower	6.83	11.13
	Solar power	24.27	16.51
	Wind power	0.31	0.50
	Solar power	25.25	11.10
	Coal-fired power	17.79	36.13
	Gas-fired power	25.53	24.64
The absolute amount (MW)	Hydropower	441477.8	453848.2
	Wind power	20225	20205.9

Table 6. Group statistics of economic producers

Type of producer	Mean	Std. deviation	Minimum	Maximum
Emission-based	0.394	0.053	0.3	0.6
Output-based	0.328	0.0534	0.2	0.5

Table 7. Independent sample t test for proportion of economic producers

		Levene's test for equality of variances		t-test for equality of means			
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference
Projected proporation of profit-hunting Producers	Equal variances assumed	0.369	0.544	8.845	198	0.000	0.0666
	Equal variances not assumed			8.845	197.989	0.000	0.0666

Table 8. Group statistics of environmentally friendly producers

Type of producer	Mean	Std. deviation	Minimum	Maximum
Emission-based	0.266	0.048	0.14	0.44
Output-based	0.327	0.051	0.21	0.48

Table 9. Group statistics of neutral producers

Type of producer	Mean	Std. deviation	Minimum	Maximum
Emission-based	0.339	0.051	0.19	0.456
Output-based	0.345	0.0538	0.22	0.49

Fig. 1 System structure

Fig. 2 Flow chart of power producers’ actions

Fig. 3 Electricity prices corresponding to different mechanisms (GDP growth, 3%; interest rate, 3%; reduction of quota, 2%)

Fig. 4 Electricity price at the end of 100 periods corresponding to different GDP growth rates

Fig. 5 Power source structure when CET is introduced

Fig. 6 Power source structure when CET is not introduced

Fig. 7 Electricity price and carbon price of two carbon quota allocations

Fig. 8 Impact of introducing CET on final producers’ proportions

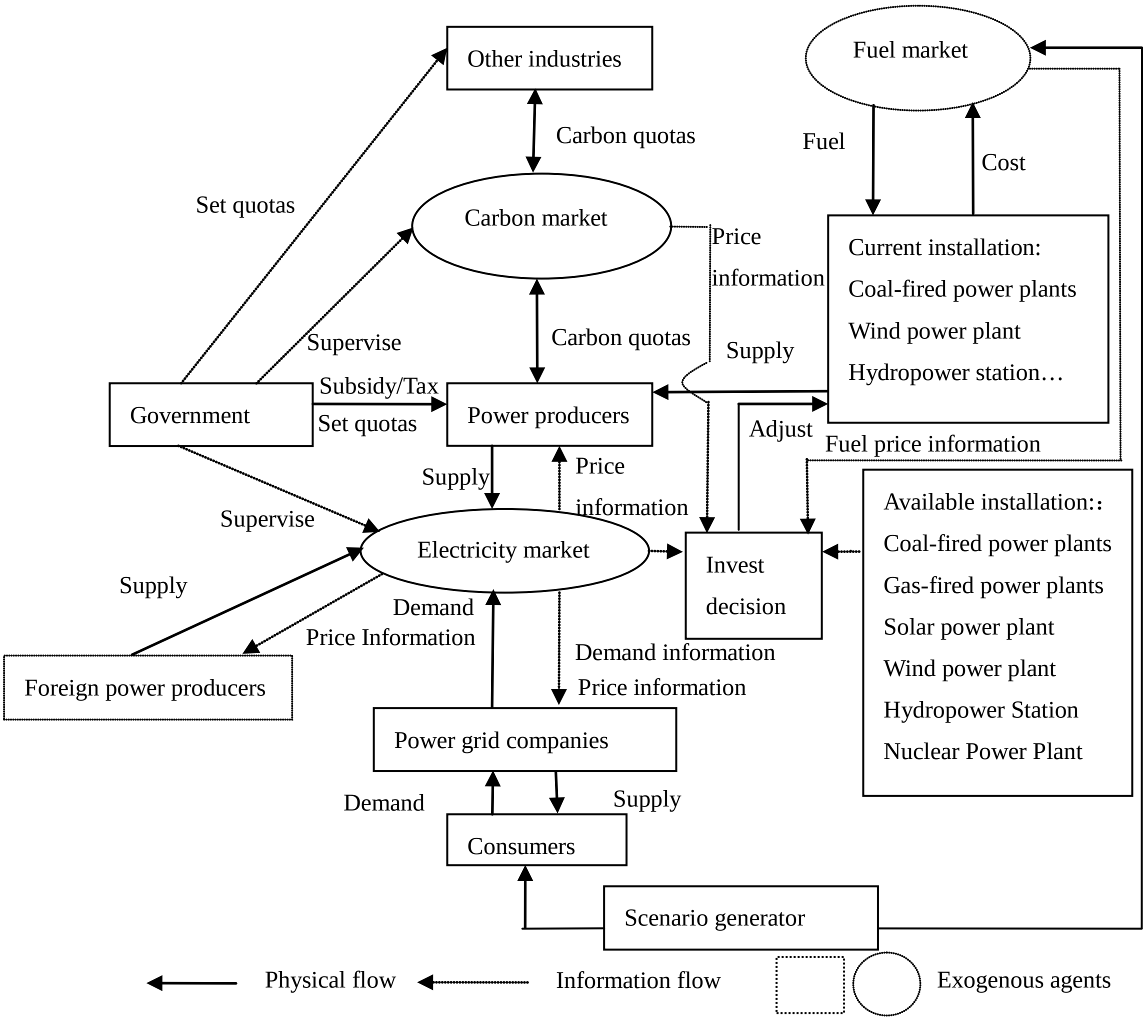

Fig. 1 System structure

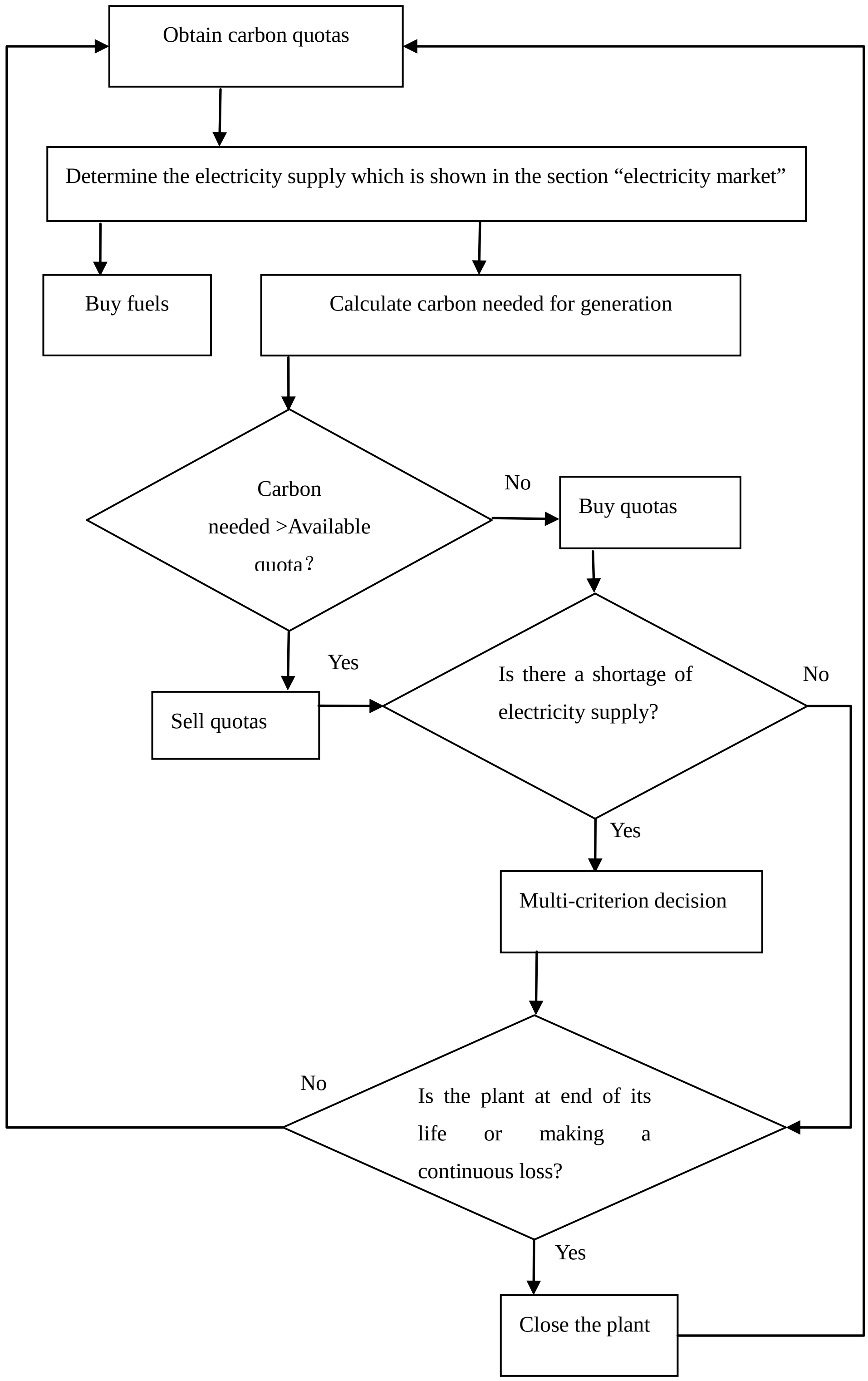

Fig. 2 Flow chart of power producers’ actions

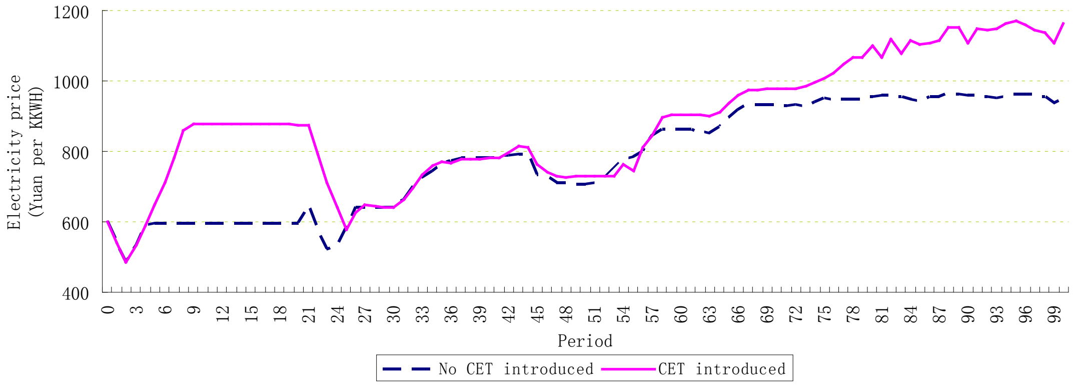

Fig. 3 Electricity prices corresponding to different mechanisms (GDP growth, 3%; interest rate, 3%; reduction of quota, 2%)

Note: we define GDP growth is 3%, because it will show the convergence trend in the long term. We also do the sensitivity analysis for different GDP and get the similar results.

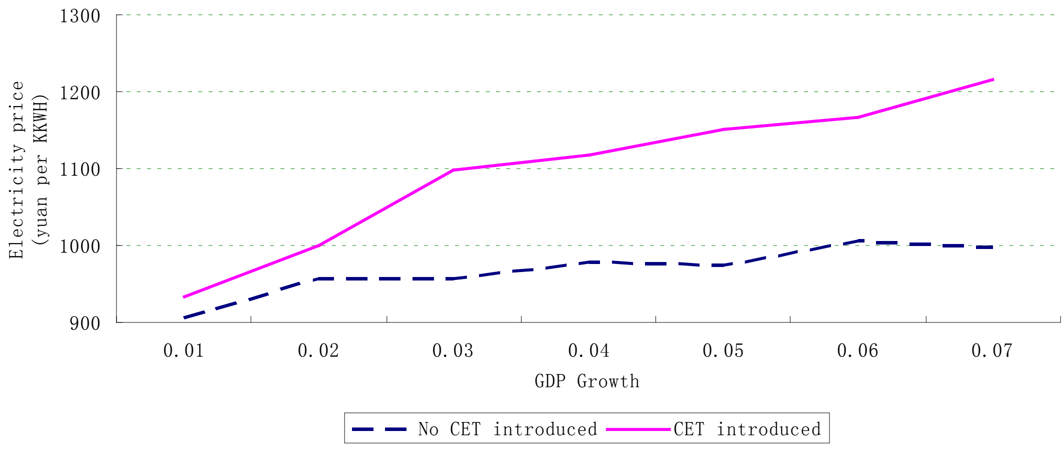

Fig. 4 Electricity price at the end of 100 periods corresponding to different GDP growth rates

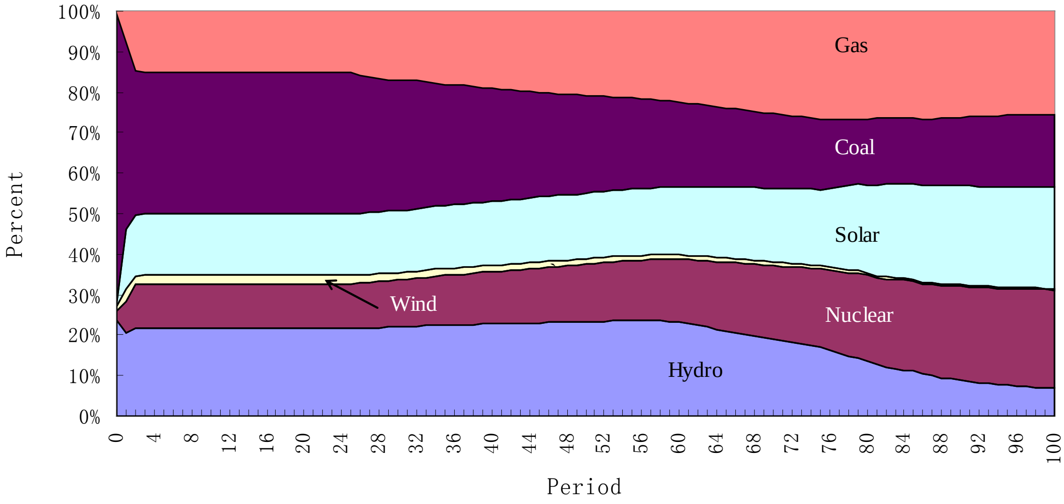

Fig. 5 Power source structure when CET is introduced

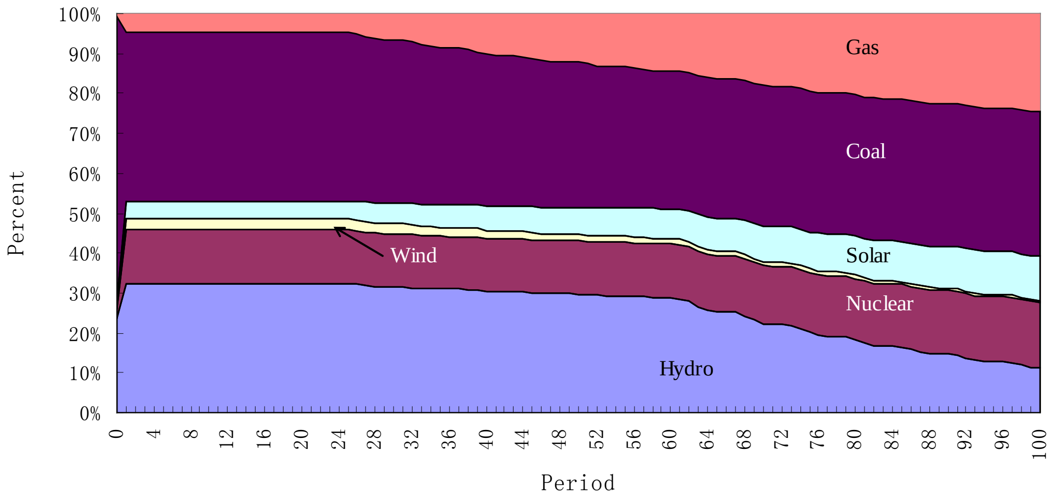

Fig. 6 Power source structure when CET is not introduced

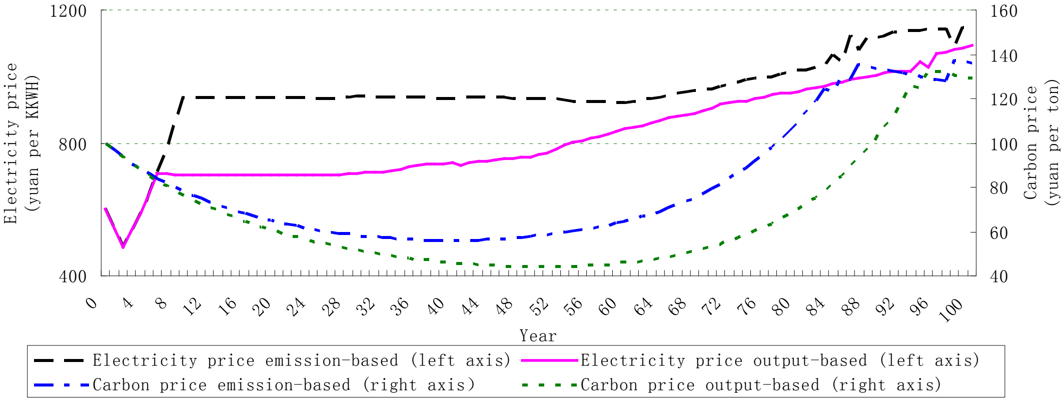

Fig. 7 Electricity price and carbon price of two carbon quota allocations

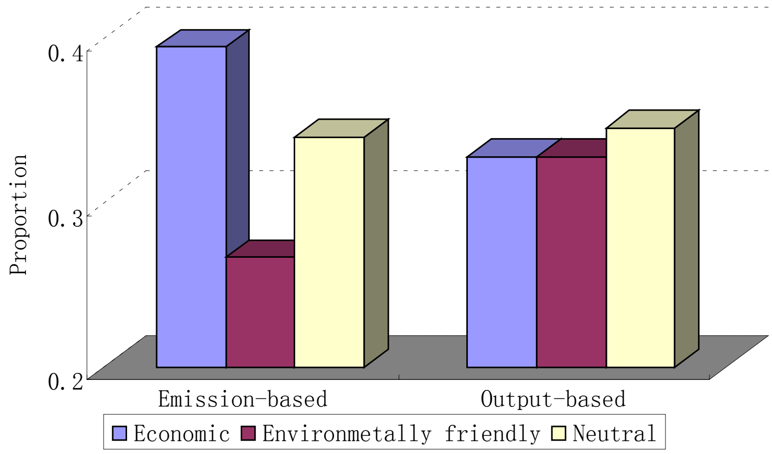

Fig. 8 Impact of introducing CET on final producers' proportions

Appendix Table 1. Parameters' values of power plants

Type	**Life** (lt_j)	**Installed capacity** ($capa_j$) (**MW**)	**Unit cost of power generation** ($fp_j(t) \times n_j$) **(yuan/KKWH)**	**Construction cost** ($inco_j$) **(yuan/KKWH)**	**Carbon emission** (m_j) **(ton CO2/KKWH)**
Hydrostation	30	600	240	6000	0
Nuclear plant	40	300	440	12000	0
Wind plant	20	10	620	8000	0
Solar plant	20	20	1900	10000	0
Coal-fired plant	20	300	350	4000	1.3
Gas-fired plant	20	120	800	4000	0.7

Source: [28, 29]. Some data are from the historical data of plants that have been established. Others are authors' calculations according to actual survey data from Chinese power plants**.**

Appendix Table 2. Main input data

Parameter	Value	Parameter	Value
α	0.8	β	-0.1
λ	0.005	γ	0.95
θ	0.001	ave_mar	0.1
$Infl$	0.03	mar_i	1
oc_j	0	sub_j	0
$cp(0)$	100		