Identifying Strategic Traders in China's Pilot Carbon Emissions Trading Scheme

Lei Zhu,[a,b] Xu Wang,[a] and Dayong Zhang[c]

ABSTRACT

This paper uses a sample of 1,867 firms that participate in the "Top-10,000 Energy-Consuming Enterprises Program" in China and aims to identify strategic traders in its pilot emissions trading scheme. Firms included in the ETS can exert their market power and manipulate allowance prices to achieve low compliance costs, which will consequently influence the effectiveness of this platform. This is of great importance to regulators or designers of this system in identifying these strategic traders and understanding their impact. We follow the basic principle proposed by Godal (2005) and develop a simple and implementable empirical procedure to study firm-level data from seven pilot programs in China. The results show that strategic traders exist with clear regional and sectoral differences. As a consequence of strategic trading by these firms, the overall volume of trading falls remarkably, with a clear increase in total compliance costs.

Keywords: Emissions trading scheme, Full market model, Marginal abatement costs, Strategic traders

https://doi.org/10.5547/01956574.41.2.lzhu

1. INTRODUCTION

In order to cope with global warming and achieve its greenhouse gas (GHG) emissions target, China has established seven pilot emissions trading schemes (ETS)[1]. A nationwide ETS was also launched in late 2017, but only covers power generation sector in its first stage of operation. China's ETS platform, to a large extent, follows the European Union emissions trading system (EU ETS) to create a market for emissions rights or permits (Goulder et al., 2017). The seven pilot ETS programs involve 3,051 firms, and at the end of 2018, the total trading volume reached 105.1 million tons. Significant variations are found in allowance prices; for example, the Beijing ETS has the highest average price, at around RMB 50 per ton (approximately 7.5 US dollars), whereas lower prices of around RMB 20 per ton can be found in the Hubei, Tianjin, and Chongqing ETSs.

The theoretical foundation of ETS is firstly given by Coase (1960), who suggests that the market equilibrium price should be independent of the initial allocation of allowances in the ETS in competitive market, and trading in a well-conceived market can reduce emissions to a target level cost effectively. Montgomery (1972) also shows that, in theory, such a system can effectively lower

1. Seven pilot ETS in China includes Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei and Shenzhen. The eighth pilot program was established in Fujian, but only recently in the late 2016, and thus it is not included in our study.

a School of Management, China University of Mining and Technology, China.
b School of Economics and Management, Beihang University, China
c Corresponding author. Research Institute of Economics and Management, Southwestern University of Finance and Economics, 555 Liutai Avenue, Chengdu, China, 611130. E-mail: dzhang@swufe.edu.cn.

emissions, and an optimal equilibrium price can be achieved through a market competition mechanism. The effectiveness of ETS has also been proved in a series of relevant studies (e.g., Muller and Mestelman, 1994; Linn, 2008; Frey 2013; Holland et al., 2015). However, in practice, firms with market power can trade strategically and manipulate permit prices (Montero, 2009) to their own benefit, which potentially compromises the effectiveness of this platform, and, as a consequence, the optimal solution cannot be reached.

As most firms that actively participate in emissions trading are from monopolistic industries (e.g., electricity suppliers), they can easily gain market power. For example, Montero (2009) points out that, between 1995 and 1999, 43% of the permits were allocated to the four largest firms in the US sulfur market. Ellerman et al. (2010) report that one-third of the cap was assigned to only 10 firms in the EU ETS. The capacity of these large players to trade and influence permit prices gains them market power (Burniaux, 1999). When these firms exert their market power in the permit trading market, manipulation is possible, which consequently affects the system. Goulder et al. (2017) suggest that firms with government ownership tend to gain market power naturally, moreover, local government has the incentive to protect local competitive power. Regulation and legislation support to avoid such issues are therefore important (Zhang et al., 2017; Karplus and Zhang, 2017) to ensure healthy development of the ETS. Zhang et al. (2015) suggest that the firms' decision in the ETS is affected by the rules of permit allocation, which gives stronger roles to the regulators. In general, it is therefore important for the designers of an ETS or regulators to pay attention to the decisions and strategic trading behaviors of firms in the ETS.

The first and probably the most important issue here is identifying strategic traders in the market and then understanding how these traders act individually or collectively to move prices and affect the system. Hahn (1984) designs a model to study the role of market power in the permit trading market, which is then followed by extensive studies. The existing literature, mainly theoretical, provides a good description of how strategic traders may behave in the permit market. However, it offers no explicit guidance on how to identify strategic traders empirically (Godal, 2011).

Theoretically, we follow the principle developed by Flåm and Jourani (2003), Flåm and Godal (2004) and Godal (2005) to establish the basic analytical framework. The paper is then set up an empirical strategy to identify strategic traders in the permit market with application to the pilot programs in China. China's plan to establish its own nationwide trading scheme seems too ambitious. Many questions arise in such a vast market with many political implications. Strategic trading is more likely, and it can have a significant impact on the effectiveness of China's ETS. Therefore, it is important for Chinese policy makers and market designers to understand the system better.

Another reason for conducting an empirical investigation of the pilot programs in China is the availability of data. In 2011, the National Development and Reform Commission (NDRC) set up an interesting program to achieve the strategic goals in energy savings and emissions reduction outlined in the twelfth five-year plan. The NDRC proposed the "Top-10,000 Energy-Consuming Enterprises Program" which requires all those responsible for the largest carbon emissions to participate. A total of 1,867 firms in the program are from the pilot regions, and rich information on these firms is available for our empirical study (also used in Wang et al., 2018).

The remainder of this paper is organized as follows: section 2 reviews the theoretical background and relevant studies. Section 3 explains our analytical framework and elaborates our empirical approach. Section 4 describes the data and presents some preliminary analysis of the sample firms. Section 5 discusses our empirical results, and then the last section concludes.

2. RELEVANT LITERATURE

Market imperfection in the tradable pollution permit market is introduced formally by Hahn (1984). In a static framework, he builds a model around a large dominant firm and its competitors. These firms are assumed to be price takers in the market, and permits are allocated freely. The model shows that initial distribution of permits can lead to market inefficiencies. Restricting all trades with a single price is the main difference from Coase (1960), who shows that initial allocation does not matter. Hahn and Stavins (2011) further prove the importance of initial distribution of permits. The dominant firm can obtain direct benefits through minimizing abatement costs (Bueb and Schwartz, 2011); and it can also gain indirectly in the product market through "exclusionary manipulation" (Misiolek and Elder, 1989). Malueg and Yates (2009) and Westskog (1996) extend the Hahn (1984) model to allow for two or more strategic actors. Montero (2009) also considers more than one large firm, and these firms may interact in the market. One special characteristic of the permit market is that firms can retain the current permit for future use, therefore a dynamic framework is needed. Hagem and Westskog (1998) first introduce dynamics via a two-period framework to the Hahn (1984) model. Liski and Montero (2010) and Montero (2009) extend this to a multiperiod permit market. The general idea is that an emissions trading market is developing, and it is expected that emissions limits will be tightened in the future.

Another strand of the literature investigates the role of strategic trading at the country/regional level (e.g., Bohringer and Loschel, 2003; Bohringer et al., 2007; Carlen, 2003; Helm, 2002; Sartzetakis, 1997). Bohringer and Rosendahl (2009), for example, show potential efficiency losses due to strategic allowance allocation in the EU ETS. Most of these studies focus on theoretical investigation or draw conclusions based on numerical simulation in the computable general equilibrium (CGE) model. Price has important signaling effects, though distortions can exist. For example, under the assumption of incomplete information, Sengupta (2012) considers how firms' investment in cleaner technology is affected by the stringency of regulation, price can signal the market when regulation is weak. Zhang et al. (2015) find that emissions reduction efforts can be affected by price, awareness and government subsidies. Electricity market is perhaps the most relevant sector when considering market power in emission trading. Amundsen and Bergman (2012) show that the Nordic electricity companies can manipulate electricity market using market power in green certificate market. Others such as Pahle et al. (2013) and Limpaitoon et al. (2014) discuss strategic trading in electricity market and its impact on emission trading schemes.

In general, an extensive number of studies show that, in theory, manipulation or strategic trading can take place in the permit trading market, and the impacts are well established. The empirical literature on how strategic trading affects an ETS, however, is relatively limited. One significant gap is the estimation and calibration of firm-level MAC curves. Following a bottom-up approach, an enormous survey has to be conducted to collect sufficient information on energy savings, emissions abatement costs, and the adoption of abatement technology at each firm, and it is difficult to do this if the firm sample is large (Hyman et al., 2003). Betz et al. (2010) has estimated four representative installations' bottom-up MAC functions to present their empirical study on the coverage of EU-ETS among installations with a trading fee, in which all the firms were assumed to face perfect competition. Ma and Hailu (2016) use a non-parametric approach to estimate MAC of emissions in China.

The classical Hahn-Westskog type models assume a large dominant strategic trader (or a group of large dominant traders) in advance, whereas other firms are assumed to be price takers. The price-taker fringe must be numerous enough for the model to work well (Montero, 2009); otherwise, no effective market-clearing device exists. But this strand of models provides no clear guidance on how to identify these strategic actors. Intuitively, it might be simple for a firm with small trading volumes to be considered a price taker, and its behavior has a negligible impact. In light of Flåm and Jourani (2003) and Flåm and Godal (2004), Godal (2005) explores whether the equilibrium of the Hahn-Westskog type models is sensitive to the classification/misclassification of players. And he suggests that the impact on equilibrium, if one exists, can be substantial when one player, even if a small one, decides to change their positions (e.g. from strategic trader to price taker). His simulation results using a multi-country example show that when more countries are considered strategic players, trading volumes and total costs will be significantly affected.

To address the classification issue, Godal (2005) proposes an alternative approach that assumes that all agents can be considered to be strategic in the first stage of a two-stage game. With others set up the same as the Hahn-Westskog model, Godal (2005) describes the characteristics of both price takers and strategic traders in his Proposition 1. The identity of strategic traders can only be observed in the second stage. For example, a strategic seller (buyer) has a final MAC that is lower (higher) than the equilibrium permit price, whereas the final MAC for all price takers equals the permit price. Moreover, strategic traders bring less/more than their endowment to the second stage. Apart from solving the stability issue, this approach has another notable value, which is to provide an efficient way to identify strategic traders in an ETS.

A number of recent studies have also been relevant and helpful in the setting up our empirical frameworks (e.g., Flåm, 2016; Flåm, Gramstad, 2017; Wang et al., 2018). It is also worth to note that collusion is possible, in other words, sellers can form a cartel (Godal and Meland, 2010) in response to strategic traders. Some earlier studies (e.g., Springer, 2003; Klepper and Peterson, 2005) discuss this issue in the national level, though Bohringer et al. (2007) suggest that the cartel solution is not stable and there are always incentives to deviate and lead to market equilibrium.

3. ANALYTICAL FRAMEWORK

3.1. The Theoretical Model

The theoretical foundation of our empirical analysis is mainly the model proposed in a series of works by Flåm and Godal (2004), Godal (2005), and Godal and Klaassen (2006). Among them, Godal's (2005) working paper has a detailed description relevant to our study here. The key modelling framework can also be seen in Flåm and Gramstad (2017), Wang et al. (2018), and Wang et al. (2019).

First, we assume that an economy has n firms, and these firms are included in an ETS with a target level of emissions. Each firm is endowed with an initial allowance (permit) e_i, for $i \in I$, then the cap is given by $e = \sum_{i=1}^{n} e_i$. A firm makes a decision to emit the amount x_i, which then incurs the emissions cost $c_i(x_i)$. The cost function is continuous and twice differentiable and decreasing at an increasing rate or, in mathematical form: $c_i' < 0$ and $c_i'' > 0$.

Firms in the set I are part of either a non-empty subset of competitive fringe (F) or a possibly empty set of strategic traders (S). The first subset of firms is also called price takers. In a two-stage game, firms choose the amount of emissions x_i in the first stage, and then price is determined with a market-clearing condition in the second stage.

The original Hahn-Westskog model assumes that the market-clearing price (p) depends on the choices of strategic traders, and thus equals to the MAC of fringe firms in equilibrium, such as:

$$-c_i'(x_i) = p \text{ for } i \in F \quad (1)$$

and the MAC for strategic traders is

$$-c_i'(x_i) = p + p'(x_i - e_i) \text{ for } i \in S \tag{2}$$

where $\mathbf{p}' = \frac{\partial p}{\partial x_i} = \frac{1}{\sum_{i \in F} \frac{1}{c_i''(x_i)}}$, given that $c_i'' > 0$, p' is also positive.

Godal (2005) proposes an alternative approach to the Hahn-Westskog model. His approach keeps the two-stage structure as the original Hahn-Westskog model, but allows all agents to participate in both stage, thus he calls it a full market model. Specifically, in the first stage, all firms (including those in the competitive fringe) decide the amount of z_i to be carried to the second stage. Buyers can choose to bring more permit (i.e. $z_i > e_i$) to the market to push the price down, whereas sellers can choose to bring less (i.e. $z_i < e_i$) to the market to drive the price up. The choice is made in a non-cooperative fashion but the total permits cannot exceed the cap ($\sum_{i=1}^{n} z_i \le e_i$).

In the second stage, all firms (including strategic traders) join a coalition to clear the market. Defining y_i as the amount of permits each firm gets in the second stage, they minimize their final costs by solving:

$$\begin{aligned} &\min_{z_i} c_i(e_i - z_i + y_i) + \rho \cdot (y_i - z_i) \\ &s.t. \sum_{i=1}^{n} z_i = e \end{aligned} \tag{3}$$

where ρ is a Lagrange multiplier or the shadow price. With the assumption that price takers treat the shadow price and y_i independent of z_i, and also $e_i = z_i$, the equilibrium condition for price takers can be solved as:

$$-c_i'(e_i - z_i + y_i) = -c_i'(y_i) = \rho \text{ for } i \in F \tag{4}$$

and for the strategic traders, ρ is a function of z_i, or $\rho = -c_i'(z_i)$.

$$-c_i'(e_i - z_i + y_i)(1 - y_i'\rho') = \rho(1 - y_i'\rho') - \rho'(y_i - z_i) \text{ for } i \in S \tag{5}$$

where $y_i' = -\frac{1}{c_i''(y_i)}$ and $\rho' = -\frac{1}{\sum \frac{1}{c_i''(y_i)}}$.

The new equilibrium conditions in Godal (2005) are reflected in his Proposition 1, which is essentially the key to our procedure to distinguish strategic traders from price takers. It clearly indicates the characteristics of price takers and strategic traders. For price takers, the results are essentially the same as the original Hahn-Westskog model, in that the equilibrium permit price equals their final MAC. The characteristics of the strategic traders, however, depend on whether the firm is a net seller or buyer. A net strategic seller brings less than his endowments ($z_i < e_i$) to the second stage and has a lower MAC than the equilibrium permit price. In other words, strategic sellers can use their market power to increase the equilibrium allowance price whereas strategic buyers aim to reduce the equilibrium price.

3.2 Estimating Firm-specific MAC Curves

According to the equilibrium conditions described above, the key to identifying strategic traders in a market is estimating MAC for each firm. However, as mentioned above, estimating the firm-specific MAC requires detailed information that is not available in our sample. As an alternative, we extend the method used in Fan and Wang (2014), adopting an aggregated approach based on the CGE model to estimate MAC for each sample firm. It consists of three steps.

The first step is estimating sectoral MAC curves at the national level. The discrete information on MAC and its associated emissions reduction for each industrial sector in China can be acquired through a simulation in the energy environmental version of the Global Trade Analysis Project (GTAP)[2]. A semi-logarithmic form (Nordhaus, 1991) to describe the MAC curve in sector j can be written as

$$MAC_j = \beta_j \ln\left(1 - R_j\right) \tag{6}$$

where MAC is marginal abatement costs, j is a particular industrial sector, R is the percentage of emissions reduction, and β is a constant, which can be estimated using the least squares method.

The second step is to find regional MAC for each sector. We define E as the total carbon emissions level and Y as output, and $e_j = \frac{E_j}{Y_j}$ represents the carbon intensity of sector j, which measures the level of emissions. $e_{ij} = \frac{E_{ij}}{Y_{ij}}$ represents carbon intensity of sector j in region i, in other words e_j can be treated as the weighted average of regional carbon intensities e_{ij}.

Let r_{ij} represent the relative position of region i's carbon intensity to that of the sectoral average, in which $r_{i,j} = 1 - e_{i,j}/e_j$ if $e_{i,j} < e_j$, or $r_{i,j} = e_j/e_{i,j} - 1$ if $e_{i,j} > e_j$. The MAC curve for regions with low carbon intensity (i.e., $e_{ij} < e_j$) is steeper along the national MAC curve. Regions with high carbon intensity are associated with flatter MAC curves (negative value of r_{ij}). Figure 1 plots regional MAC curves following the arguments above along with a national MAC curve.

Denote R_{ij} as the ratio of carbon reduction in region i and sector j, then the MAC curve for region i and sector j can be calculated as:

$$MAC_{ij}\left(R_{ij}\right) = MAC_j(R_{ij} + r_{ij}) - MAC_j\left(r_{ij}\right) = \beta_j \ln\left(1 - \frac{R_{ij}}{1 - r_{ij}}\right) \tag{7}$$

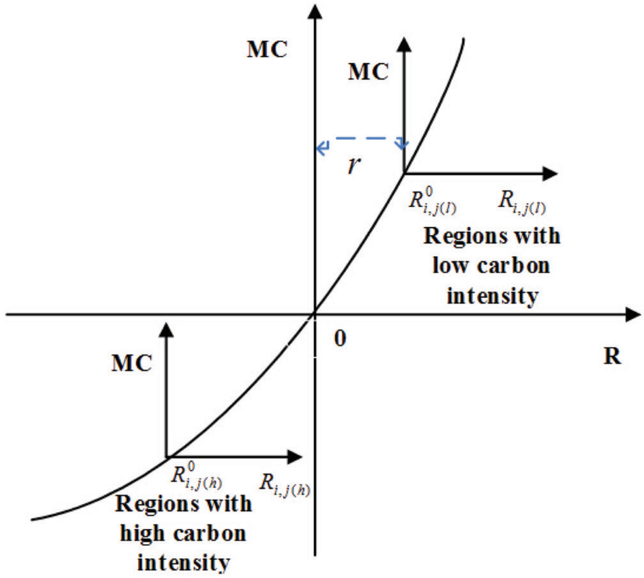
As the sectoral MACs in different regions are all derived from the national curves, an adjustment to β is needed to ensure that the total abatement costs at the national level are consistent when the reduction target is set. In other words, the total abatement costs calculated by sectoral MACs or by within-region sectoral MACs should be the same after aggregating them to the national level. Therefore, a region-specific factor β_{ij} should be constructed to satisfy:

$$\int_0^{R_j} MAC_j = \sum_i \int_0^{R_{ij}} MAC_{ij} \tag{8}$$

The third step is following a similar logic to estimate firm-level MAC curves. For firm k at region i in industry j, carbon intensity can be written as $e_{ijk} = \frac{E_{ijk}}{Y_{ijk}}$ and $r_{i,j,k} = 1 - e_{i,j,k}/e_{i,j}$ if

2. The latest reference year of GTAP model is 2011, which raises the question to our estimation as the economic structure in China has changed substantially since. The specification of certain parameters can have some impacts to the results, it should not change the main results for a couple of reasons. First, the emission reduction target is set in the 12th five-year plan according to emission level in 2010, which sets up the foundation of these pilot programs (Fan and Wang, 2014). Second, these pilot programs mainly located in those well-developed regions in China. Although industrial structure in China may experience substantial change, the development in these regions should be reasonably stable. We sincerely appreciate an anonymous referee for his insightful comments and do acknowledge the needs to take this into consideration when possible.

Figure 1: Regional MAC curves



$e_{i,j,k} < e_{i,j}$, or $r_{i,j,k} = e_{i,j} / e_{i,j,k} - 1$ if $e_{i,j,k} > e_{i,j}$. The firm-specific MAC function for firm k is therefore:

$$MAC_{ijk}\left(R_{ijk}\right) = \beta_{ij} \ln\left(1 - \frac{R_{ijk}}{1 - r_{ijk}}\right) \tag{8}$$

The sectoral MAC curves in our study are estimated via a CGE model (for more details, see Cui et al., 2014; Fan and Wang, 2014). This aggregated approach is not a perfect estimation of firm-specific MAC. Nonetheless, it provides a feasible alternative when data issues have generally existed in similar studies (see Wang et al., 2018 for a more detailed description of the estimation algorithm).

3.3. Identifying Procedures

One of the major objectives of this paper is establishing an implementable empirical procedure to realize the Godal (2005) model and identify strategic traders in an ETS. In light of the analytical framework discussed above, we propose the following four-step procedure.

Step 1. Estimating firm-level MACs. The key to identifying strategic firms is estimating their MACs. The top-down approach explained in the previous subsection is adopted to find out the MAC for each sample firm.

Step 2. Sorting firms according to their market power. Several indicators have been used in the existing literature to measure firms' potential market power. For example, Hahn (1984) uses each firm's share of total emissions; Godal (2005) suggests using the market share of each firm to serve as a benchmark; Bohringer et al. (2014), by contrast, suggest that the ability to shift the MAC from the allowance price could reflect market power in the international ETS. In this paper, we use price impacts to measure market power. The idea is to set each individual firm as the sole strategic trader (as in the full market model, and all other firms are price takers) and simulate its price impact (relative to the allowance in a scenario of perfect competition). The benefit of using this new measurement is that it is not predetermined and it is consistent with the underlying model.

Step 3. Finding out equilibrium allowance prices. After ranking all firms according to their simulated market power, we can then add them successively to the strategic set *S* described in the full market model, which results in a series of equilibrium market prices.

Step 4. Identifying strategic traders. The simulated price change sequence is then compared with a predefined convergence criterion (threshold value). Firms causing price changes above the criteria are classified as strategic traders, firms with increasing market equilibrium prices are considered strategic sellers, and those with decreasing equilibrium market prices are strategic buyers. After the absolute price change is lower than the value, we can then conclude that the remaining firms are price takers.

4. DATA DESCRIPTION

4.1. Data for Estimating Firm-specific MACs

The data used to estimate firm-specific MACs are collected from various sources, which are listed in Table 1.

Table 1: Data Sources

Data	Source
Regional and sectoral gross domestic product	*China Statistical Yearbook* 2011 and regional statistical yearbooks
Regional and sectoral energy consumption	*China Energy Statistical Yearbook* 2011 and regional statistical yearbooks
Emissions factor of each fuel type	Intergovernmental Panel on Climate Change (IPCC, 2006)
Sample firms' information	Top-10,000 Energy-Consuming Enterprises Program
Value added in sample firms	Chinese industrial enterprises database (2011)

The base year is 2010. We use the energy consumption–based accounting approach to calculate sectoral carbon dioxide (CO_2) emissions. Firms are sorted into sectors based on four-digit standard industrial classification (SIC) codes. The distribution of our sample firms in regions/sectors is listed in Table 2. It is clear that the firms are unevenly distributed across regions and sectors. Hubei and Guangdong, at the provincial level, have more firms in the chemical products sector and nonmetallic products sector included in their pilot programs than others.

Table 2: Sample firms' distribution across regions and industrial sectors

Sectors	Beijing	Tianjin	Shanghai	Chongqing	Hubei	Guangdong	Shenzhen	Total (sector)
Coal	1	0	0	7	0	0	0	8
Petroleum and natural gas	2	3	1	1	1	1	2	11
Processing of fuels	6	6	7	4	6	13	0	42
Mining	2	2	0	2	6	5	1	18
Foods and tobacco	14	11	13	7	72	55	2	174
Textile	1	4	7	5	52	68	0	137
Wood	1	0	0	0	9	6	1	17
Paper and printing	2	2	3	4	26	60	0	97
Chemical products	10	32	39	36	128	63	1	309
Nonmetallic mineral products	26	9	24	48	90	227	5	429
Metals	1	35	11	27	42	60	2	178
Metal products	2	6	3	0	2	1	0	14
Transport machinery	7	5	17	10	41	11	1	92
Other machinery	8	11	33	3	29	53	23	160
Electricity supply	20	23	23	16	25	50	11	168
Water	3	1	3	1	1	3	1	13
Total (region)	106	150	184	171	530	676	50	1,867

Given the fact that no detailed emissions information is available on the sample firms, they are approximated using total sectoral emissions in each region. Firms participating in the "Top-10,000 Energy-Consuming Enterprises Program" account for more than 60% of China's total energy use, where industrial sectors account for about 70% of total national emissions during the twelfth FYP (2011–2015) period. In this program, participating enterprises first report their energy-saving potentials to local governments based on the past consumption level, and then the local governments submit a proposed target to central government. After a review and renegotiation process, a final target is determined, which also lead to each firm's energy saving target. Given that emission and energy consumption are directly linked, we can effectively assume a firm's share in the energy saving targets is a reflection of its share of emissions of the total sectoral emissions in its location. Following this assumption, each firm's emission can be calculated based on its share and the local sectoral total emissions (available from regional statistical yearbooks). The regional emissions reduction targets during the twelfth FYP period are used as the cap for each pilot program.

4.2. Market Structure in Seven Pilot Regions

Prior to the empirical tests, Table 3 reports some basic information on the market structure in each pilot program. Three commonly used measures are included, namely, the Herfindahl-Hirschman Index (HHI), the CR_4 index, and the CR_8 index. CR_4 and CR_8 are alternative measures of concentration, which shows the accumulated share of the top four and top eight firms in one region. The higher these indices are, the higher the level of market concentration or the less competitive the market is. If we denote s_i is the share of firm i in one pilot region with a total of n firms, the HHI can be calculated as

$$H = \sum_{i=1}^{n} s_i^2. \quad (8)$$

Normally, when the concentration ratio is less than 40%, the market is considered competitive; and when the ratio is over 40%, it is considered monopolistic. Clearly, the Shanghai pilot region has the highest level of market concentration, whereas Guangdong has the most competitive market in all the regions.

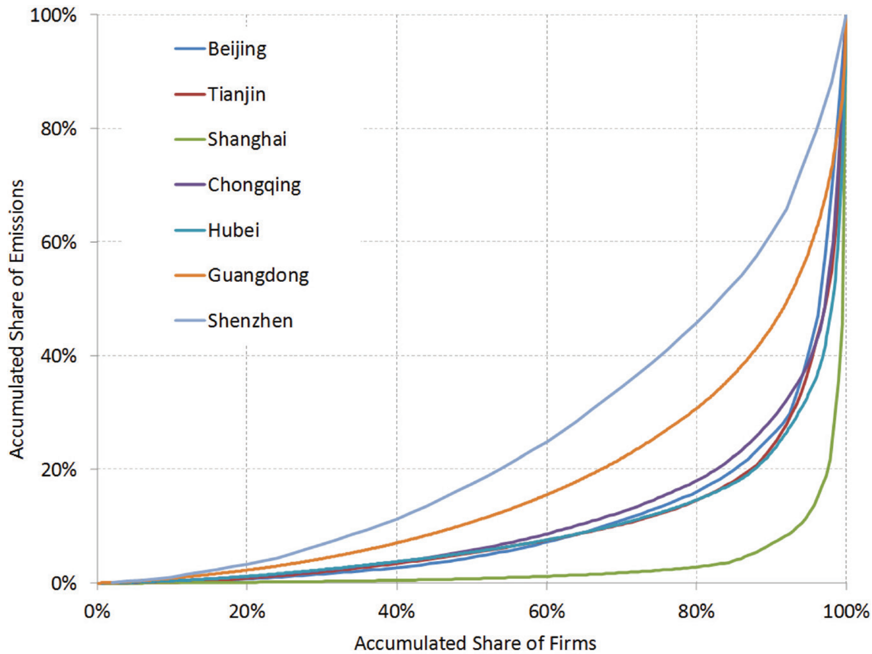
Table 3: Sample firms' distributions in seven pilot regions

Regions	No. of firms	HHI	CR_4	CR_8
Beijing	106	8.06%	52.95%	70.23%
Tianjin	150	8.73%	50.36%	63.78%
Shanghai	184	31.87%	78.30%	86.34%
Chongqing	171	6.56%	45.91%	60.16%
Hubei	530	3.49%	30.89%	46.61%
Guangdong	676	0.96%	15.07%	20.62%
Shenzhen	50	4.48%	34.21%	48.67%

Figure 2 plots the accumulated distribution of emissions for firms in seven pilot regions. Again, Shanghai has the most unevenly distributed pattern and more than 80% of the emission is due to less than 5% share of firms.

The shares of carbon emissions in each industry and for all pilot regions are reported in Table 4. Clearly, the distribution of emissions shares is different from the distribution of sample firms and shows significant regional/sectoral differences. For example, the coal sector alone in Chongqing (which consists of only seven firms) are responsible for around one-quarter of emissions in this

Figure 2: Distribution of emissions for firms in seven pilot regions (2010)



region. The metal sector accounts for 38.93% and 33.15% of total carbon emissions in Tianjin and Shanghai, respectively. In general, the metal sector and electricity supply sector are responsible for the most among all sectors in all seven pilot regions.

Table 4: Shares of carbon emissions in each industry and for all pilot regions

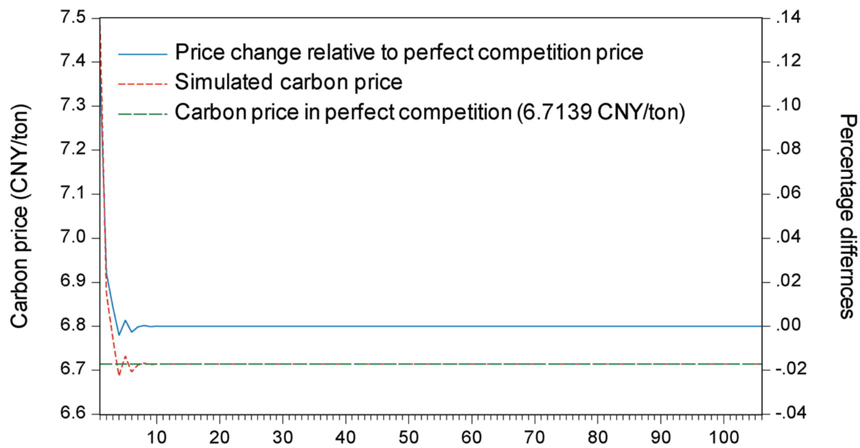
Sectors	Beijing	Tianjin	Shanghai	Chongqing	Hubei	Guangdong	Shenzhen	Total (sector)
Coal	0.03%	0.00%	0.00%	25.72%	0.00%	0.00%	0.00%	3.69%
Petroleum and natural gas	0.20%	2.28%	1.04%	0.06%	0.00%	0.21%	1.63%	0.90%
Processing of fuels	2.26%	1.08%	13.26%	0.73%	0.09%	6.55%	0.00%	6.81%
Mining	11.30%	0.08%	0.00%	0.52%	0.28%	0.49%	0.40%	1.80%
Foods and tobacco	1.31%	1.12%	0.12%	0.57%	2.05%	2.92%	0.70%	2.60%
Textile	0.18%	0.35%	0.16%	0.38%	0.52%	6.89%	0.00%	3.44%
Wood	0.02%	0.00%	0.00%	0.00%	0.08%	0.57%	0.33%	0.31%
Paper and printing	0.37%	0.20%	0.08%	1.41%	0.93%	4.36%	0.00%	2.60%
Chemical products	2.32%	13.39%	2.18%	6.70%	12.12%	9.23%	0.26%	12.88%
Nonmetallic mineral products	3.37%	2.32%	0.30%	7.63%	7.62%	13.89%	2.45%	11.28%
Metals	0.22%	38.93%	33.15%	5.53%	5.93%	7.97%	4.28%	21.90%
Metal products	0.22%	1.04%	0.05%	0.00%	0.23%	3.19%	0.00%	1.73%
Transport machinery	0.88%	0.89%	0.11%	0.80%	1.32%	1.10%	0.51%	1.44%
Other machinery	0.23%	1.71%	0.31%	0.28%	0.75%	8.16%	27.47%	6.45%
Electricity supply	19.36%	0.55%	8.89%	18.33%	28.92%	6.73%	5.96%	21.86%
Water	0.04%	0.01%	0.00%	0.00%	0.01%	0.48%	0.94%	0.30%
Total (region)	42.31%	63.95%	59.65%	68.66%	60.85%	72.74%	44.93%	100.00%

5. EMPIRICAL RESULTS

5.1. Sorting Firms according to their Market Power

The first step in our empirical analysis is to estimate firms' MAC and then simulate firms' market power by assuming that each firm is the sole strategic trader in one market and compare its price impact to that of the perfect competition case. Taking Beijing as an example, the carbon price in the perfect competition case is RMB 6.7139 per ton. Figure 3 plots firms' ranking in the Beijing pilot program.[3] It indicates that most of the 106 firms have no price impact. The firms with the highest market power (if it is considered the sole strategic trader in the full market model) can cause prices to increase by 11.47%; effectively, only nine firms can cause price impacts of more than 0.01%.

Figure 3: Firm rankings using market power: Beijing

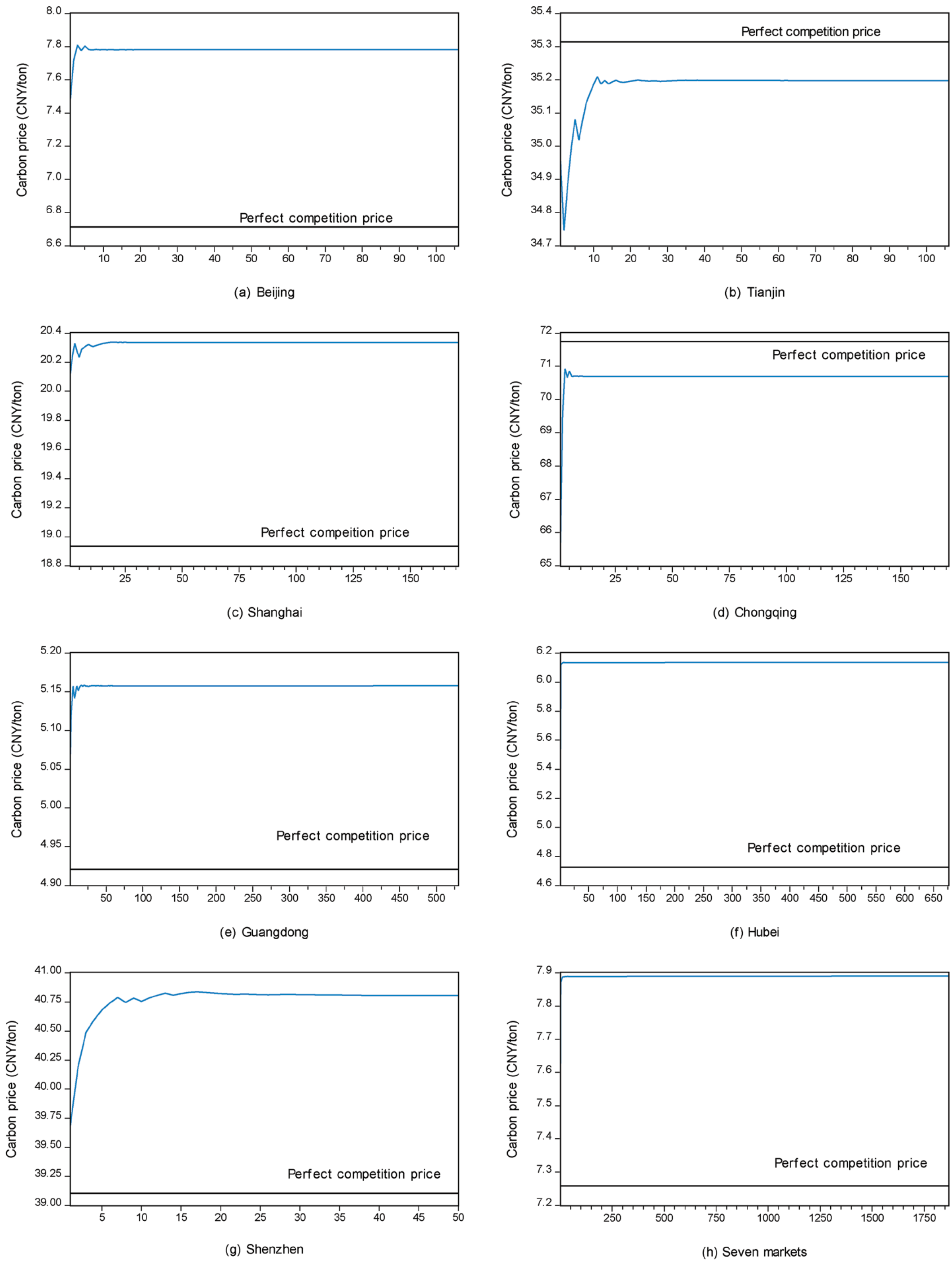


5.2. Calculating Equilibrium Allowance Prices

After the rankings of firms become available, they can be added successively to the strategic set *S* to calculate the sequence of equilibrium market prices. The results are reported in Figure 4 for seven pilot markets and a hypothetical case of linking seven markets together (Figure 4h). The majority of the firms are expected to be price takers in the market, which causes almost zero price changes at the market equilibrium. The most powerful firms' (ranked higher) trading can change prices, but when more firms are added, prices reach an equilibrium level, whereas any additional firms (price takers) do not have any price impact. Another observation is that the market equilibrium price can vary significantly across markets. It goes as high as more than RMB 70.70 per ton for Shanghai to as low as RMB 5.16 per ton in Hubei. Note that the equilibrium price in our model is calculated via MAC, Shanghai is quite a special case in terms of its industrial structure. Being the most advanced city in China (Wu et al., 2014), Shanghai has the highest carbon emission efficiency (Du et al., 2016) or the least reduction potential. In other words, marginal costs of emission reduction in Shanghai are higher.

3. Ranking information for other firms is also available from the author on request.

Figure 4: Simulated equilibrium allowance price sequence (Horizontal axis: number of firms)



Referring to the analytical model, the perfect competition price equals the MAC, as predicted by the Hahn-Westskog model. Strategic sellers increase equilibrium prices, whereas strategic buyers reduce equilibrium prices. Figure 4 shows two markets, namely Tianjin and Chongqing, that behave differently from other markets. The firm with the highest market power in both markets are strategic buyers; their trading behaviors drive down equilibrium prices (relative to the MAC). For all other markets, firms with the highest market power are strategic sellers, which drives prices higher than perfect competition value. Furthermore, the price sequences in these markets are not monotonic, indicating the existence of both strategic buyers and sellers in each market. In the case of a hypothetical linkage over 7 markets (Figure 4h), we can draw some implications to the unified national program. Carbon prices are substantially lower in the linked market than those in 4 out of the seven pilots, which raises question about how to resolve regional imbalances in development. Strategic traders with smaller numbers relative to the aggregation of individual markets can drive market price up significantly relative to the price with perfect competition.

5.3. Identify Strategic Traders

After estimating the sequence of market equilibrium prices, we can then use the sequential relative price changes to identify strategic traders. A firm is classified as a strategic trader if its inclusion in the *S* set change previous equilibrium prices by a level that is higher than the convergence criteria. Whenever adding an additional firm does not change the equilibrium price, the remaining firms including this additional firm are price takers. In the absence of clear instructions on how to set the convergence criteria, as a rule of thumb, we choose 0.01% as the cutoff point.[4]

Across all markets, there are a total of 102 identified strategic traders, of which 70 are strategic sellers and 32 firms are strategic buyers. The number of strategic traders and their distribution vary significantly across markets and are unevenly across sectors (see Table 5). In general, strategic sellers dominate, which is consistent with the observation from Figure 4. The situation is more unbalanced in Guangdong with 7 strategic sellers against 1 strategic buyer and Chongqing (14 against 2), whereas Shanghai (4 against 3) and Beijing (6 against 4) are more balanced. The results may also reflect differences in the regional economic structure and sectoral distribution of industries.

It is also interesting to look at the sectoral distribution across these pilot systems. The results show clear sectoral concentrations of both strategic sellers and buyers. The electricity supply sector has 12 strategic buyers, and the metals sector has 10 strategic buyers, which together account for around two-thirds of the strategic buyers. Although every sector has strategic sellers, the top three sectors (other machinery, transport machinery, and nonmetallic products sector) together account for over 60% of the strategic sellers.

For Beijing, strategic traders are mainly from electricity sector, which has stronger government presence and normally with large size. It is also found that Beijing ETS has insufficient market liquidity (Hu et al., 2017) and much lower cap (Fan and Todorova, 2017). Together these can induce larger price distortions, which explain the high price difference for Beijing.

5.4. Estimating the Impacts of Strategic Trading

Given the confirmation that strategic traders are present in China's seven pilot ETSs, it is natural to ask how much they affect each ETS. To address this question, we further simulate three potential impacts of strategic trading (relative to the perfect competition case): total compliance costs, allowance prices, and total volume of trading in the ETS. The results are reported in Table 6.

4. A higher value can be set, such as 0.001, to relax the restrictions a bit, but firms with high market power will remain. The results are available from the authors upon request.

Table 5: The number of strategic traders and their distribution across markets & sectors

Sectors	Beijing	Tianjin	Shanghai	Chongqing	Hubei	Guangdong	Shenzhen	Total (sectors)
Coal				(4/2)				(4/2)
Petroleum and natural gas			(1/0)				(0/1)	(1/1)
Processing of fuels			(1/2)					(1/2)
Mining	(2/0)							(2/0)
Foods and tobacco	(1/0)	(2/0)		(1/0)	(1/0)		(1/0)	(6/0)
Textile				(1/0)	(1/0)	(2/0)		(4/0)
Wood							(1/0)	(1/0)
Paper and printing	(1/0)			(1/0)				(2/0)
Chemical products		(3/2)		(1/0)	(2/0)			(6/2)
Nonmetallic mineral products		(1/0)		(5/0)	(1/0)	(2/0)	(2/0)	(11/0)
Metals		(1/4)	(0/1)	(0/1)	(0/1)	(0/1)	(0/2)	(1/10)
Metal products		(1/0)						(1/0)
Transport machinery		(1/0)			(8/0)	(1/0)	(1/0)	(11/0)
Other machinery		(2/0)				(2/0)	(8/3)	(12/3)
Electricity supply	(2/4)		(2/0)	(1/1)	(1/6)		(0/1)	(6/12)
Water							(1/0)	(1/0)
Total (regions)	(6/4)	(11/6)	(4/3)	(14/4)	(14/7)	(7/1)	(14/7)	(70/32)

Notes: Numbers in parentheses are (No. of strategic sellers/No. of strategic buyers)

The impacts on allowance prices are somehow more obvious than what is illustrated in the previous subsection. Negative price impacts apply only to Shanghai and Tianjin, as the firms with the highest market power are strategic buyers in these two markets. Strategic trading can push prices up quite significantly, for example, by 29.82% over the benchmark price (Guangdong). Total compliance costs are generally higher; trading volumes are lower in all markets. With a price impact in Shanghai of only –1.46%, the trading volume can fall up to –18.84%, which is significant and should not be ignored by policy makers. Of course, we have to acknowledge that the impacts on certain markets (e.g., Tianjin, Hubei, and Shenzhen) are relatively small. And the impacts on total compliance costs are generally small as well. It is notable that the current ETS is still in its trial stage, in which both the number of firms and trading volume are limited and clearly vary across markets.

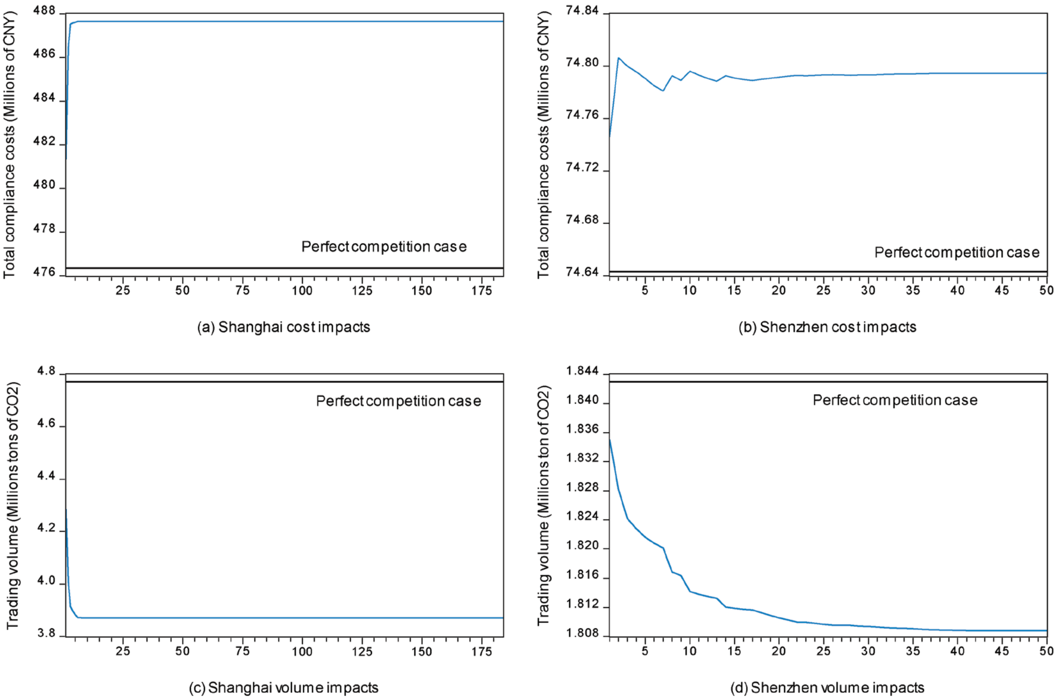
Table 6: The impacts of strategic trading across markets

	Beijing	Tianjin	Shanghai	Chongqing	Hubei	Guangdong	Shenzhen
Impacts on allowance price	15.91%	–0.33%	–1.46%	7.38%	4.81%	29.82%	4.36%
Impacts on total compliance costs	1.89%	0.16%	2.37%	0.88%	0.49%	4.36%	0.20%
Impacts on volume of trading	–5.18%	–4.65%	–18.84%	–4.47%	–2.44%	–4.87%	–1.78%

To further illustrate the scenario in which more firms are added to each ETS, we plot the cost impacts and trading volume in Figure 5,[5] with Shanghai (negative price impact) and Shenzhen (positive price impact) as examples. The results show the trend in impacts when more firms are included. It is obvious that the first strategic firm (the one with the highest market power) has the highest impact. The results here also confirm that changing the rule of thumb of using 0.01% as a criterion for identifying strategic firms will not have a significant impact on the results in this paper. Relaxing the criterion will not affect the findings of major strategic traders and therefore the impacts should be robust.

5. The price impact is shown in the previous subsection.

Figure 5: Impacts of strategic trading on volume and costs: Shanghai and Shenzhen (Horizontal axis: number of firms)



5.5. Differences between the Hahn-Westskog and the Full Market Models

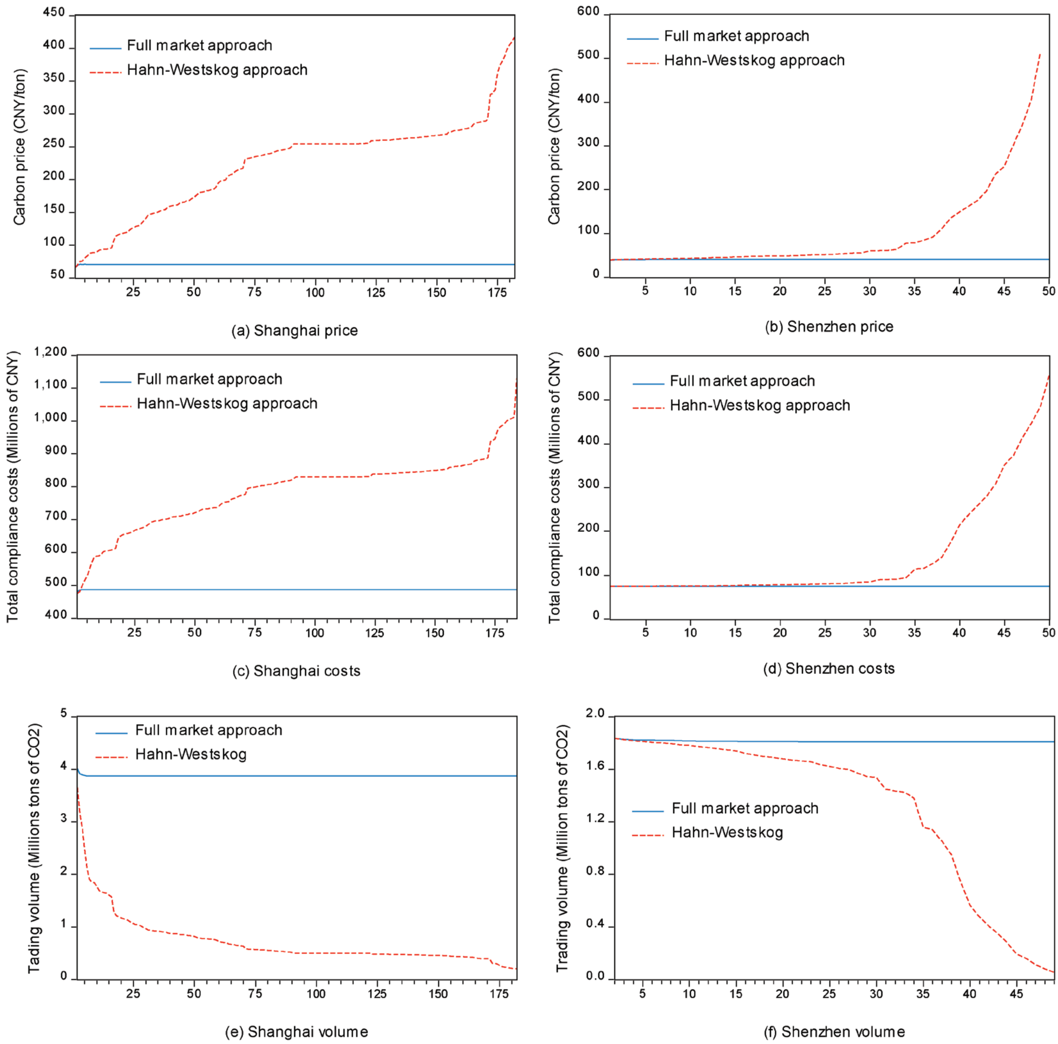
The full market model has a clear advantage in theory, but it is also interesting to see how the alternative model (Hahn-Westskog) performs using real data. Again, we use Shanghai and Shenzhen as two special cases to show how much the Godal (2005) full market approach differs from the Hahn-Westskog model. The price impacts, volume impacts, and impacts on total compliance costs are plotted in Figure 6 for these two markets.

The differences across these two models are significant. Whereas the full market approach converges for all three factors, a monotonic increasing/decreasing pattern is found for all cases using the Hahn-Westskog model. It is clearly unrealistic to find that smaller firms (in terms of market power) can have such a significant impact, thus, the results further reinforce our results using the full market approach.

5.6. Further Discussion on Carbon Prices

Although the model in this paper is not designed to directly comment on price levels in actual carbon markets, it nonetheless enables us to make a direct comparison to actual trading prices in the market. Table 7 shows the price comparison of the predicted equilibrium prices and the actual trading prices in the seven pilot programs. Apart from Chongqing and Shenzhen, differences are clearly noticeable across most of the markets. The differences may be due to market factors, such as government intervention. The model used in this paper covers only industrial participants; commercial facilities, universities, and other non-industrial institutions with large energy consumption in the pilot programs are not considered here, which could also contribute to the price gaps. Moreover,

Figure 6: Cross-model comparison: Shanghai and Shenzhen (Horizontal axis: number of firms)



according to Hu et al (2017), Fan and Todorova (2017) and others, the development of China's pilot ETS has lots of problems that lead to large variation of prices and/or price distortions. For example, firms have less incentive to participate. Market turnover rate are generally low (Deng and Zhang, 2019), which associates with high liquidity risk. Policy uncertainties may also be a problem that lead to price uncertainties.

Table 7: Price comparisons with actual trading prices (in RMB/ton)

	Beijing	Tianjin	Shanghai	Chongqing	Hubei	Guangdong	Shenzhen
Perfect competition price	6.71	35.31	71.75	18.94	4.92	4.72	39.10
Full market model equilibrium price	7.78	35.20	70.70	20.33	5.16	6.13	40.81
End of 2016 spot price	53.30	15.05	26.55	9.96	18.17	13.34	32.82
Historical average price	50.65	25.66	25.45	17.35	21.98	25.27	50.00

Note: End of 2016 spot price is taken from the last available trading day in 2016.

Although the actual trading carbon prices for Beijing, Hubei, and Guangdong are clearly higher than predicted by our model, the prices for Shanghai and Tianjin are significantly lower than predicted by theory. These two markets are the only ones in which strategic traders can put downward pressure on equilibrium prices. The direction of price differences, in this respect, is consistent with the prediction of our full market approach and provides evidence that strategic traders can manipulate market prices and cause large market distortions.

6. CONCLUSIONS

This paper aims to empirically identify the strategic traders included in the pilot ETS in China. The analytical framework is based on the full market approach, and we introduce a simple and implementable four-step approach to identify firms that trade strategically in the ETS. Using 1,867 industrial firms participating the "Top-10,000 Energy-Consuming Enterprises Program" in China and included in the pilot ETS, we illustrate the feasibility of this empirical method. A direct comparison shows that the full market model has more stable behavior than the traditional Hahn-Westskog approach with actual data.

There is clear evidence of strategic traders (buyers/sellers) in the pilot programs. However, the distribution of these traders differs significantly in each pilot ETS market. This shows that the most powerful strategic traders in Shanghai and Tianjin market are strategic buyers, which will reduce equilibrium allowance prices, whereas other markets have the opposite findings with higher equilibrium prices relative to the perfect competition case. Strategic traders are mainly in highly energy-intensive sectors. Strategic buyers are concentrated mainly in the metal and electricity power supply sectors, whereas sellers are mainly in nonmetallic mineral products and the machinery (transport and others) manufacturing sectors.

In general, our simulation results show that the impact of strategic trading not only can affect market prices but also tends to increase total compliance costs and reduce trading volumes in the market. These results are important for policy makers in China, as a unified national ETS system has implemented. Forming proper policy so as to avoid the negative impact of strategic trading is crucial for the success of its national ETS. It is also very important to realize that the regional imbalances across China can impose great challenges to the unified program. Strategic traders can execute their market power and achieve substantial gains from the national program, which causes more trouble to the whole system.

A number of shortcomings of this paper and implications for future research works are worth to mention here[6]. First, the empirical analysis is based on simulation rather than statistical analysis, thus unable to provide statistical inference. Second, there are other issues/market factors that can affect carbon prices. It is worth to statistically investigate how much different factors contribute to price distortions in the ETS, for example, turnover rates, energy prices, and policy uncertainties. Third, firm level characteristics such as government ownership can affect their behaviors and cause different responses to policies. With more data available, this is another major issue to be addressed.

ACKNOWLEDGMENTS

We thank James Smith for his insightful comments on the first draft of this paper, the editor David Broadstock and three anonymous referees for their constructive comments and insightful

6. We thank an anonymous referee for these insightful suggestions and further investigation on these issues are definitely worth to be explored.

suggestions. Financial support from National Natural Science Foundation of China (NSFC) Grant Nos. 71573214, 71603256, 71673019, 71690245, 71273253 are acknowledged. Also, Dayong Zhang thanks support from 111 project B16040, and Xu Wang thanks support from Jiangsu Planned Projects for Postdoctoral Research Funds (No. 1601086C). In addition, Lei Zhu and Xu Wang have equal contribution to the paper.

REFERENCES

Amundsen, E.S. and L. Bergman (2012). “Green certificates and market power on the Nordic power market.” *The Energy Journal* 33(2): 101–117. https://doi.org/10.5547/01956574.33.2.5.

Betz, R., T. Sanderson, and T. Ancev (2010). “In or out: Efficient inclusion of installations in an emissions trading scheme?” *Journal of Regulatory Economics* 37(2): 162–179. https://doi.org/10.1007/s11149-009-9109-0.

Bohringer, C., B. Dijkstra, and K.E. Rosendahl (2014). “Sectoral and regional expansion of emissions trading.” *Resource and Energy Economics* 37: 201–225. https://doi.org/10.1016/j.reseneeco.2013.12.003.

Bohringer, C. and A. Loschel (2003). “Market power and hot air in international emissions trading: The impacts of US withdrawal from the Kyoto Protocol.” *Applied Economics* 35(6): 651–663. https://doi.org/10.1080/0003684021000035818.

Bohringer, C., U. Moslener, and B. Sturm (2007). “Hot air for sale: A quantitative assessment of Russia’s near-term climate policy options.” *Environmental and Resource Economics* 38(4): 545–572. https://doi.org/10.1007/s10640-007-9089-4.

Bohringer, C. and K.E. Rosendahl (2009). “Strategic partitioning of emission allowances under the EU Emission Trading Scheme.” *Resource and Energy Economics* 31(3): 182–197. https://doi.org/10.1016/j.reseneeco.2009.04.001.

Bueb, J. and S. Schwartz (2011). “Strategic manipulation of a pollution permit market and international trade.” *Journal of Regulatory Economics* 39: 313–331. https://doi.org/10.1007/s11149-011-9150-7.

Burniaux, J.M. (1999). “How important is market power in achieving Kyoto? An assessment based on the GREEN model.” Paper presented at the OECD Workshop on the Economic Modelling of Climate Change.

Carlén, B. (2003). “Market power in international carbon emissions trading: a laboratory test.” *The Energy Journal* 24(3): 1–26. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol24-No3-1.

Coase, R.H. (1960). “The problem of social cost.” *Journal of Law and Economics* 3: 1–44. https://doi.org/10.1086/466560.

Cui, L.B., Y. Fan, L. Zhu and Q.H. Bi (2014). “How will the emissions trading scheme save cost for achieving China’s 2020 carbon intensity reduction target?” *Applied Energy* 136: 1043–1052. https://doi.org/10.1016/j.apenergy.2014.05.021.

Deng, M and W. Zhang (2019). “Recognition and analysis of potential risks in China’s carbon emission trading markets.” *Advances in Climate Change Research* 10: 30–46. https://doi.org/10.1016/j.accre.2019.03.004.

Du, K., H. Lu and K. Yu (2014). “Sources of the potential CO2 emission reduction in China: a nonparametric metafrontier approach.” *Applied Energy* 115: 491–501. https://doi.org/10.1016/j.apenergy.2013.10.046.

Ellerman, D., F. Convery and C. de Perthuis (2010). *Pricing Carbon, the European Union Emissions Trading Scheme*. New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139042765.

Fan, J.H. and N. Todorova (2017). “Dynamics of China’s carbon prices in the pilot trading phase.” *Applied Energy* 208: 1452–1467. https://doi.org/10.1016/j.apenergy.2017.09.007.

Fan, Y. and X. Wang (2014). “Which sectors should be included in the ETS in the context of a unified carbon market in China?” *Energy & Environment* 25(3–4): 613–634. https://doi.org/10.1260/0958-305X.25.3-4.613.

Flåm, S.D. and K. Gramstad (2017). “Reaching Cournot-Walras Equilibrium.” *ESAIM: Proceedings and Surveys* 57: 12–22. https://doi.org/10.1051/proc/201657012.

Flåm, S.D. and A. Jourani (2003). “Strategic behavior and partial cost sharing.” *Games and Economic Behavior* 43(1): 44–56. https://doi.org/10.1016/S0899-8256(02)00547-X.

Flåm, S.D. (2016). “Noncooperative games, coupling constraints, and partial efficiency.” *Economic Theory Bulletin* 4(2): 213–229. https://doi.org/10.1007/s40505-015-0079-3.

Flåm, S.D. and O. Godal (2004). “Greenhouse gases, quota exchange and oligopolistic competition.” In Carraro, C. and W. Fragnelli (Eds), *Game Practice and the Environment*. Edward Elgar, Cheltenham, UK, 212–223. https://doi.org/10.4337/9781845421441.00018.

Frey E.F. (2013). “Technology diffusion and environmental regulation: The adoption of scrubbers by coal-fired power plants.” *The Energy Journal* 34(1):177–205. https://doi.org/10.5547/01956574.34.1.8.

Godal, O. and F. Meland (2010). “Permit markets, seller cartels and the impact of strategic buyers.” *The BE Journal of Economic Analysis & Policy* 10(1): 1–33. https://doi.org/10.2202/1935-1682.2397.

Godal, O. (2005). “Strategic markets in property rights without price-takers.” Working Paper05/05, Department of Economics, University of Bergen.

Godal, O. (2011). "Non cooperative models of permit markets." Working Paper 18/11, Institute for Research in Economics and Business Administration.

Godal, O. and G. Klaassen (2006). "Carbon trading across sources and periods constrained by the Marrakesh accords." *Journal of Environmental Economics and Management* 51: 308–322. https://doi.org/10.1016/j.jeem.2005.07.003.

Goulder L.H., R.D. Morgenstern, C. Munnings and J. Schereifels (2017). "China's national carbon dioxide emission trading system: An introduction." *Economics of Energy & Environmental Policy* 6(2): 1–18. https://doi.org/10.5547/2160-5890.6.2.lgou.

Hagem, C. and H. Westskog (1998). "The design of a dynamic tradable quota system under market imperfections." *Journal of Environmental Economics and Management* 36: 89–107. https://doi.org/10.1006/jeem.1998.1039.

Hahn, R.W. (1984). "Market power and transferable property rights." Quarterly Journal of Economics 99(4): 753–765. https://doi.org/10.2307/1883124.

Hahn R.W. and R.N. Stavins (2011). "The effect of allowance allocations on cap-and-trade system performance". The *Journal of Law and Economics* 54(S4): S267-S294. https://doi.org/10.1086/661942.

Helm, C. (2002). "International emissions trading with endogenous allowance choices." *Journal of Public Economics* 87(12): 2737–2747. https://doi.org/10.1016/S0047-2727(02)00138-X .

Holland S.P., J.E. Hughes, C.R. Knittel and N.C. Parker (2015). "Unintended Consequences of Carbon Policies: Transportation Fuels, Land-Use, Emissions, and Innovation." *The Energy Journal* 36(3): 35–74. https://doi.org/10.5547/01956574.36.3.shol.

Hu, Y.J., X.Y. L, and B.J. Tang (2017). "Assessing the operational performance and maturity of the carbon trading pilot program: The case study of Beijing's carbon market." *Journal of Cleaner Production* 161: 1263–1274. https://doi.org/10.1016/j.jclepro.2017.03.205.

Hyman, R.C., J.M. Reilly, M.H. Babiker, A. de Masin, and H.D. Jacoby (2003). "Modeling non-CO_2 greenhouse gas abatement." *Environmental Modeling & Assessment* 8(3): 175–186. https://doi.org/10.1023/A:1025576926029.

Intergovernmental Panel on Climate Change (IPCC) (2006). IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Kamiyamaguchi Hayama, Japan.

Karplus V.J. and X. Zhang (2017). "Incentivizing firm compliance with Chinas national emissions trading system." *Economics of Energy & Environmental Policy* 6(2):73–86 https://doi.org/10.5547/2160-5890.6.1.vkar.

Klepper G. and S. Peterson (2005). "Trading hot-air. The influence of permit allocation rules, market power and the US withdrawal from the Kyoto Protocol." *Environmental and Resource Economics* 32: 205–227. https://doi.org/10.1007/s10640-005-3362-1.

Limpaitoon T., Y. Chen, and S. Oren (2014). "The impact of imperfect competition in emission permits trading on oligopolistic electricity markets." *The Energy Journal* 35(3): 145–166. https://doi.org/10.5547/01956574.35.3.7.

Linn J. (2008). "Technological modifications in the nitrogen oxides tradable permit program." *The Energy Journal* 29(3): 153–176. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol29-No3-8.

Liski, M. and J.P. Montero (2010). "Market power in an exhaustible resource market: the case of storable pollution permits." *Economic Journal* 121: 116–144. https://doi.org/10.1111/j.1468-0297.2010.02366.x.

Ma C. and A. Hailu (2016). "The Marginal Abatement Cost of Carbon Emissions in China." *The Energy Journal* 37(China Special Issue): 111–127. https://doi.org/10.5547/01956574.37.SI1.cma.

Malueg, D.A. and A.J. Yates (2009). "Bilateral oligopoly, private information, and pollution permit markets." *Environmental and Resource Economics* 43(4): 553–572. https://doi.org/10.1007/s10640-008-9249-1.

Misiolek, W.S. and H.W. Elder (1989). "Exclusionary manipulation of markets for pollution rights." *Journal of Environmental Economics and Management* 16(2): 156–166. https://doi.org/10.1016/0095-0696(89)90006-5.

Montero, J. P. (2009). "Market power in pollution permit markets." *The Energy Journal* 30(SI2): 115–142. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol30-NoSI2-6.

Montgomery, W.D. (1972). "Markets in licenses and efficient pollution control programs." *Journal of Economic Theory* 5(3): 395–418. https://doi.org/10.1016/0022-0531(72)90049-X.

Muller R.A. and S. Mestelman (1994). "Emission trading with shares and coupons: A laboratory experiment." *The Energy Journal* 15(2): 185–211. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol15-No2-10.

Nordhaus, W.D. (1991). "The cost of slowing climate change: a survey." *The Energy Journal* 12(1): 37–65. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol12-No1-4.

Pahle M., K. Lessmann, O. Edenhofer and N. Bauer (2013). "Investments in imperfect power markets under carbon pricing: a case study based analysis." *The Energy Journal* 34(4): 199–227. https://doi.org/10.5547/01956574.34.4.10.

Sartzetakis, E.S. (1997). "Raising rivals' costs strategies via emission permits markets." *Review of Industrial Organization* 12(5–6): 751–765. https://doi.org/10.1023/A:1007763019487.

Sengupta, A. (2012). "Investment in cleaner technology and signaling distortions in a market with green consumers." *Journal of Environmental Economics and Management* 64(3): 468–480. https://doi.org/10.1016/j.jeem.2012.04.001.

Springer, U. (2003). "The market for tradable GHG permits under the Kyoto Protocol: a survey of model studies." *Energy Economics* 25(5): 527–551. https://doi.org/10.1016/S0140-9883(02)00103-2.

Wang X., X.B. Zhang and L. Zhu (2019). "Imperfect market, emissions trading scheme, and technology adoption: A case study of an energy-intensive sector." *Energy Economics* 81: 142–158. https://doi.org/10.1016/j.eneco.2019.03.014.

Wang X., L. Zhu and Y. Fan (2018). "Transaction costs, market structure and efficient coverage of emissions trading scheme: A microlevel study from the pilots in China." *Applied Energy* 220: 657–671. https://doi.org/10.1016/j.apenergy.2018.03.080.

Westskog, H. (1996). "Market power in a system of tradeable CO2 quotas." *The Energy Journal* 17(3): 85–103. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol17-No3-6.

Wu, L., H. Qian and J.L (2014). "Advancing the experiment to reality: Perspectives on Shanghai pilot carbon emissions trading scheme." *Energy Policy* 75: 22–30. https://doi.org/10.1016/j.enpol.2014.04.022.

Zhang J., Z. Wang and X. Du (2017). "Lessons learned from China's regional carbon market pilots." *Economics of Energy & Environment*al Policy 6(2): 19–38. https://doi.org/10.5547/2160-5890.6.2.jzha.

Zhang Y.J., A.D. Wang, and W. Tan (2015). "The impact of China's carbon allowance allocation rules on the product prices and emission reduction behaviors of ETS-covered enterprises." *Energy Policy* 86: 176–185. https://doi.org/10.1016/j.enpol.2015.07.004.