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A Case Study of China's Iron and Steel Industry

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Abstract

Outdated capacity and substantial potential for energy conservation are the two main features of energy-intensive sectors in developing countries. Such countries also seek to implement market-based options to further control domestic carbon emissions as well as to promote the withdrawal of outdated capacity and upgrade production levels. This paper presents a quantitative assessment of an emission trading scheme (ETS) for China's iron and steel industry. The diverse array of normal and outdated capacities are modeled in a two-country, three-good partial equilibrium model. The energy-saving benefits that result from emission abatement were captured through a technology-based marginal abatement cost (MAC) curve. Simulation results show that the abatement potential can be underestimated if the energy-saving benefits that result from emission abatement are not considered. In the scenario analysis, we demonstrate that the free allocation of allowances can cause a competitiveness distortion among normal and outdated domestic capacities, and such a distortion cannot be corrected by implementing supplementary measures such as border carbon adjustments. Given the government's intention to promote outdated capacity withdrawal and production-level upgrading, an output-based allocation approach is strongly suggested for China's iron and steel sector.

Key Words: emission trading scheme, iron and steel sector, energy saving, competitiveness, output-based allocation

JEL Codes: C63, Q48, Q52, Q59

Contents

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1. Introduction

Aside from the energy sector itself, energy-intensive sectors (iron and steel, cement, chemical, and nonferrous metals) are arguably the sectors most sensitive to CO_2 emission abatement actions. This is because the production costs in these sectors can be affected very significantly by energy price changes. Focusing on industry competitiveness and carbon leakage, a series of studies have presented quantitative assessments of the impact of unilateral emission abatement policies (emission trading, carbon tax, border carbon adjustment, and output-based rebating and allocation) on energy-intensive sectors (Grubb and Wilde 2004; Demailly and Quirion 2008; Dissou 2006; Monjon and Quirion 2010; Fischer and Fox 2012; Böhringer et al. 2011). Most of the emphasis has been placed on developed countries, especially the sectors covered by the European Union Emission Trading Scheme (EU-ETS), while less attention has been paid to developing countries.

In developing countries, there are two related features that exist in energy-intensive sectors: 1) diverse levels of technology among firms within the sector, with some outdated capacity and 2) on average, higher energy consumption per unit of output than the international advanced level. A typical example is China's iron and steel sector. The rapid economic growth in the last few years has boosted the demand for iron and steel products, which resulted in the expansion of domestic production capacity. While China is the world's largest steel producer, with its crude steel production accounting for 44% of total global production in 2010, the technological efficiency varies greatly among firms. Meanwhile, the sector consumes 17% of total domestic energy consumption, which leads to large amounts of greenhouse gas emissions.

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An important issue related to production level diversity is outdated capacity.[1] There are more than 500 iron and steel enterprises in China. The limited capital budgets and short-sighted investment behavior have made most small and medium enterprises adopt out-of-date technologies in their production. Compared with advanced production technologies, these outdated technologies consume more energy when producing equal units of output, and they produce more CO_2 emissions and air pollution. In 2010, the share of outdated capacity accounted for more than 25% of total domestic production capacity in the iron and steel sector (Jiang 2013).

To address the above-mentioned issues, two command and control measures were launched by the government during the 11th Five Year Plan (11th FYP, from 2006 to 2010).[2] The marginal effects of such command and control measures weakened in the 12th FYP (from 2011 to 2015) after one period of implementation in the 11th FYP. After 2010, the government proposed the application of market-based instruments (e.g., ETS) to further control domestic carbon emissions and energy consumption in energy-intensive sectors as well as to promote withdrawal of outdated capacity and upgrading of production (MIIT 2011; State Council 2012). Currently, seven CO_2 pilot regions for emission trading have been established, and a national CO_2 emission trading scheme (ETS) has also been prepared.[3]

For the iron and steel sector, accelerating the withdrawal of outdated capacity is one of the synergistic effects that the Chinese government wishes to generate through the implementation of an ETS. An ETS would result in a change in the relative competitiveness[4]

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[1] According to Lv (2010), the definition of outdated capacity is mainly based on two considerations 1) the technological level of production capacity, i.e., production equipment that is below the industry average level, and 2) the consequences of production, such as greater pollution and emissions generated by the production process, or higher consumption of water and energy resources than the industry average level. It should be mentioned here that the evaluation of outdated capacity will change over time due to technological progress in the industry.

[2] During the 11th FYP, the two measures that the government launched in the iron and steel industry were 1) energy efficiency improvements and emission reduction, where the government set a goal for the comprehensive energy consumption per ton of steel to be reduced to 730 kgce (kg standard coal equivalent) in 2010, compared to 760 kgce in 2005, and 2) outdated capacity withdrawal, in which a total of 100 million tons of iron smelting outdated capacity and 55 million tons of steel outdated capacity were forced to withdraw from the market by the end of 2010.

[3] In 2011, the NDRC (National Development and Reform Commission) issued a document stating that the carbon emission trading scheme (ETS) will be piloted in seven regions (Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, and Shenzhen). In 2014, the state council announced the establishment of a national unified CO_2 emission trading market in its "2014-2015 Energy Saving, Emission Reduction, and Low-Carbon Development Action Plan."

[4] Industrial competitiveness usually refers to the ability to offer products and services that meet the quality standards of local and world markets at prices that are competitive and provide adequate returns on the resources employed or consumed in producing them, among the firms within the sector.

among firms with normal and outdated capacities. Referring to Demailly and Qurion (2008), two of the most intuitive indexes for measuring competitiveness changes are loss in production and loss in profits.[5] A proper ETS design will encourage the withdrawal of outdated capacity if the scheme leads to reduced output and profit by firms using outdated capacity; conversely, if the scheme leads to an increase in the output or profit of firms with outdated capacity, competition will be distorted between firms with normal and outdated capacity. Such distortion is possible because the efficiency of the ETS would be affected under the imperfect competition in the output market.

In previous studies analyzing the impact of an ETS on the competitiveness of the affected sectors, the choice of approach to allowance allocation (grandfathering, auction, or output-based allocation) plays an important role in affecting the sector's competitiveness (Fischer and Fox 2004; 2010; Peterson and Schleich 2007; Demailly and Quirion 2008; Takeda et al. 2014; Meunier et al. 2014). The questions worth studying for China's iron and steel sector are whether an ETS can promote outdated capacity withdrawal and how different allocation approaches affect competitiveness changes among firms with normal and outdated capacities.

A number of quantitative studies have been conducted on energy use and CO_2 emissions in China's iron and steel industry, including the performance measure of energy efficiency and CO_2 emissions (Ma et al. 2002; Movshuk 2004; Wei et al. 2007), assessment of energy saving and CO_2 emission reduction potential (Wang et al. 2007; Ali et al. 2013; Wen 2014; Zhang et al. 2013), and energy or CO_2 emissions embodied in China's exports (Kahrl and Roland-Holst 2008; Yan and Yang 2010; Liu et al. 2010; Cui et al. 2015). Additionally, the impacts of carbon policies and national emissions intensity reduction targets on the iron and steel sector have been investigated with the adoption of national/regional CGE models (Zhang 2000; Liang et al. 2007; Zhang et al. 2013). Although the issues of outdated capacity and diversity of technological levels have been noted in most of the above-mentioned studies, the impact of emission reduction policies on normal and outdated capacities within the sector was not addressed because the sector was treated as a whole in these studies.

With the establishment of a two-country, three-good partial equilibrium model, this paper proposes an analytical framework for studying the impact of CO_2 emission trading on China's iron and steel sector. Our study adds to the existing literature in the following ways:

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[5] According to Demailly and Qurion (2008), the changes in production and profit can affect industrial relocation, domestic employment, carbon leakage, and the stock value of domestic firms, so they are the most intuitive indexes to measure the competitiveness change.

1) With the consideration of outdated capacity, we establish a market structure with mixed output competition (between two goods in the domestic market) and price competition (between domestic and foreign goods) to describe the competitive situation of China's iron and steel industry. In view of the large diversity of production levels among domestic iron and steel enterprises, it is not enough to view the sector as a whole. Thus, we divide total domestic iron and steel production into two groups – production from normal capacity and production from outdated capacity – to investigate the interaction between these two products under ETS.

2) Given that the main option for reducing CO_2 emissions in the iron and steel sector is to continuously improve energy efficiency, the energy saving gain should also be taken into consideration when assessing the impact of ETS. We adopt a technology-based abatement cost curve and take into consideration the benefits of the energy saving resulting from emission abatement. Currently, China's energy consumption per ton of crude steel is approximately 15% higher than the international advanced level. This indicates that the use of energy-saving technologies is still below what is possible. In the previous studies, the marginal abatement cost (MAC) curves derived from the integrated assessment models (IAM) or the computable general equilibrium models (CGE) were not able to clearly define the co-benefits that result from emission abatement.

3) We comprehensively evaluate the price pass-through effects of the iron and steel sector's up and down streams. The ETS is designed to cover multiple sectors in a given region, and the changes of the output price due to the carbon price in one sector will obviously affect its downstream sectors. Energy-intensive sectors' production costs are sensitive to output price changes in the energy sectors. In the model, we have taken the price pass-through rates from the upstream sectors into consideration, not only in measuring the changes in the sector's production costs but also in valuing the energy saving benefits. Furthermore, by applying the price multiplier matrix, the impact of the output price change in the iron and steel sector on other sectors has also been estimated in the model's welfare calculation.

The rest of the paper is organized as follows: Section 2 introduces the theoretical model applied in this study; Section 3 presents the case study on China's iron and steel sector in the context of the ETS; Section 4 analyzes the sensitivity of the calculation results to key parameters; and Section 5 provides conclusions.

2. Theoretical Model

China is considered to be the domestic region, and its production is divided into two parts: production from normal capacity (good N) and production from outdated capacity (good

B), each of which is produced by a representative firm. The rest of the world is considered to be the foreign region, which produces good F.

2.1 Market Structure and Demand for Each Good

Each entity consumes a certain quantity of the three goods, assuming that China's two domestic goods are homogeneous with respect to each other but are heterogeneous compared to the foreign good. In China's iron and steel sector, the products from the normal and outdated capacities have, to a great extent, the same product portfolios (screw thread steel, hot/cold rolled coil, hot/cold rolled strip, and so forth), which means that the majority of their products satisfy the same purposes. Although the products from normal and outdated capacities could be different because of their technological levels and qualities, such diversity is mainly reflected in production costs, energy consumption, and water consumption, but not in their market prices.[6] By contrast, most of China's iron and steel imports are special steel products (heat-resistant steel, dual-phase steel, super austenitic steel, and so forth) as well as ordinary steel products with complex production processes. Domestic enterprises are unable to produce certain of these products. Based on the 2010 data, the average import price is nearly 100% higher compared to domestic products (the price data can be found in Appendix A2). Therefore, the price diversity between normal and outdated products is relatively small compared to the price diversity between domestic and imported products. Referring to the actual market structure, domestic goods N and B are assumed to be perfect substitutes for each other, while domestic goods N and B (taken together), and foreign good F are assumed to be imperfect substitutes.

For the domestic firms producing homogeneous goods, we adopt Cournot's oligopoly model with a linear demand curve to describe the output competition between the two representative firms in the domestic market. The goods consumed in domestic market are N_d and B_d, and the total domestic demand is

$$\begin{aligned} P_D &= \alpha - \beta D \\ D &= N_d + B_d \end{aligned} \tag{1}$$

[6] Taking construction steel (steel bars) as an example, the product from normal capacity production is a HRB400 bar and that from outdated capacity product is a HRB335 bar. The price for a HRB400 bar is usually 5-10% higher than that of HRB335.

in which α and β are the constant term and coefficient of the inverse demand curve, P_D is the unified price level (in Yuan/t crude steel) for N_d and B_d in the domestic market and D is the total domestic demand for N and B.

According to Fischer and Fox (2012), the consumer demand for good F is a simple function of the prices of the heterogeneous competing goods in the region of consumption. With the assumption of constant elasticity of demand functions, we have

$$\begin{aligned} F_m(P_D, P_F) &= \alpha_m P_F^{\eta_{mm}} P_D^{\eta_{md}} \\ F_w(P_D, P_F) &= \alpha_w P_F^{\eta_{ww}} P_D^{\eta_{wx}} \end{aligned} \tag{2}$$

in which F_m is the import of good F, F_w is the foreign consumption, P_F is the price for good F (in Yuan/t crude steel), α_m and α_w are the constant scale parameters for the demand functions of F_m and F_w, and η_{mm}, η_{md}, η_{ww}, η_{wx} are the own-price and cross-price elasticities for demand for F_m and F_w.

To distinguish the consumer demand for N and B in the two markets, we refer to the work conducted by Demailly and Quirion (2008), who defined the price for EU steel consumers as the weighted sum of EU and non-EU prices. The total EU demand for all products (domestic and import) can be determined by the weighted price, while the domestic consumption for EU production can be obtained by the total EU demand minus the imports. In our model, the domestic consumption for N_d and B_d can be determined using Cournot's oligopoly model. By defining the export of N and B to the foreign market, and with domestic price P_D adopted for the export, we can obtain the total consumption of N and B in both the domestic and foreign markets. To simplify this, we have adopted a simple function to describe the foreign demand of N and B

$$\begin{aligned} N_x(P_D, P_F) &= \alpha_N P_D^{\eta_{xx}} P_F^{\eta_{xw}} \\ B_x(P_D, P_F) &= \alpha_B P_D^{\eta_{xx}} P_F^{\eta_{xw}} \end{aligned} \tag{3}$$

in which N_x and B_x are the exports of N and B, α_N and α_B are the constant scale parameters for demand functions of N_x and B_x, and η_{xx} and η_{xw} are the own-price and cross-price elasticities for demand for N_x and B_x.

For N_x, B_x, F_m, and F_w, let us assume that their own-price elasticities are negative while their cross-price elasticities are positive (Fischer and Fox 2011). The total consumption of the three goods is $N_d + B_d$ and F_m in the domestic market and $N_x + B_x$ and F_w in the foreign market. In the market equilibrium,

$$
\begin{aligned}
N &= N_d\left(P_D\right) + N_x\left(P_D, P_F\right) \\
B &= B_d\left(P_D\right) + B_x\left(P_D, P_F\right) \\
F &= F_m\left(P_D, P_F\right) + F_w\left(P_D, P_F\right)
\end{aligned} \tag{4}
$$

Thus far, a market structure with mixed price competition (between domestic and foreign goods) and output competition (between two goods in the domestic market) has been established to describe the competitive situation in China's iron and steel industry. Therefore, with this imperfect market structure, each domestic representative firm (with either normal or outdated capacity) would be faced with domestic and foreign markets at the same time. Each domestic representative firm's output decision will be introduced in Section 2.4. In addition, the consumption of N , B, and F are all converted to the unified unit of crude steel.

2.2 Changes in Costs with the Implementation of ETS

The ETS has been introduced to address the emissions in domestic firm production. We assume that the per unit production costs of domestic goods N and B are c_N and c_B , respectively. As we mentioned in Footnote 1, the definition of outdated capacity is mainly based on the technology level of production capacity and the consequences of production. The energy consumption and environmental pollution per unit of output caused by outdated capacity are higher than the average industry level, and these factors are strongly related to the technical level as well as the production equipment. In China's previous policy, outdated capacity was defined mainly by the volume of production that was possible with given equipment.[7] This definition has caused serious controversy. In the 12th FYP, the definition was adjusted to account more for the consequences resulting from production.[8]

Our definition of outdated capacity also considers the consequences resulting from production, and thus the differences between normal and outdated capacity will be reflected in

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[7] In the 11th FYP, the government set a goal to shut down blast furnaces with a capacity of less than 300 cubic meters, as well as steelmaking converters with a capacity of less than 30 tons.

[8] In the 12th FYP, from the perspective of the energy consumption per unit of output, the normal capacity should satisfy the comprehensive energy consumption standard of less than 620 kgce per ton of steel, as well as the water consumption standard of less than 5 tons of water per ton of steel. Additionally, from the perspective of environmental pollution, the normal capacity should satisfy the standard of smoke emission per ton of steel of less than 1.0 ton and CO_2 emissions of less than 1.8 ton.

their unit production cost, energy consumption, and CO_2 emissions. We have divided production cost into four parts: fuel cost, electricity cost, abatement cost, and other costs (the costs for raw materials, operation and maintenance (O&M) and so forth). After the ETS is implemented with the CO_2 price P_C (in Yuan/tCO_2), production cost can be expressed as

$$
\begin{aligned}
c_N = c_{NOther} &+ (P_{Elec} + \delta_{Elec} \cdot P_C \cdot e_{Elec}) \cdot \left(Ec_{NElec0} - Es_{NElec}(r_N) \right) \\
&+ (P_{Fuel} + \delta_{Fuel} \cdot P_C \cdot e_{Fuel}) \cdot \left(Ec_{NFuel0} - Es_{NFuel}(r_N) \right) + c_{NAC}(r_N)
\end{aligned}
\tag{5}
$$

$$
\begin{aligned}
c_B = c_{BOther} &+ (P_{Elec} + \delta_{Elec} \cdot P_C \cdot e_{Elec}) \cdot \left(Ec_{BElec0} - Es_{BElec}(r_B) \right) \\
&+ (P_{Fuel} + \delta_{Fuel} \cdot P_C \cdot e_{Fuel}) \cdot \left(Ec_{BFuel0} - Es_{BFuel}(r_B) \right) + c_{BAC}(r_B)
\end{aligned}
\tag{6}
$$

In Equations (5) and (6), c_{NOther} and c_{BOther} are the other costs for N and B; $c_{NAC}(r_N)$ and $c_{BAC}(r_B)$ are the abatement costs with the emission reductions r_N and r_B per unit of output; $\partial c_{AC}(r) / \partial r = c_{MAC}(r)$; P_{Elec} and P_{Fuel} are the electricity and fuel prices before the ETS implementation (in units of Yuan/kWh and Yuan/t fuel); e_{Elec} and e_{Fuel} are their emission factors (here, e_{Fuel} is not the emission factor for the fuel combustion process but the emission factor during the fuel production process, in units of tCO2/kWh and tCO2/t of fuel); δ_{Elec} and δ_{Fuel} are the price pass-through rates of electricity and fuel; Ec_{NElec0}, Ec_{NFuel0}, Ec_{BElec0}, and Ec_{BFuel0} are the electricity and fuel inputs in producing one unit of N and B before ETS implementation; and $Es_{NElec}(r_N)$, $Es_{NFuel}(r_N)$, $Es_{BElec}(r_B)$, and $Es_{BFuel}(r_B)$ are the saved electricity and fuel inputs associated with the emission abatement r_N and r_B. In general, the goods produced by the outdated capacity have higher energy consumption and CO_2 emissions compared with those of normal capacity. The costs data calibration among normal and outdated capacities will be presented in Section 3.1 and Appendix A4.

Comparing our cost accounting with previous studies, we add two items: the production cost without the carbon price and the abatement cost with the carbon price. By separating electricity and fuel costs, we can take into account the price pass-through effects and energy saving benefits in the energy sector that result from the implementation of ETS. These effects depend on the carbon price level and the firms' emissions abatement. Moreover, the traditional carbon price determined by the emission abatement level ($P_C = c_{MAC}(r)$) has to be revised into a combination of carbon price, price pass-through effects, energy saving benefits, and MACs.

In addition, the good F produced abroad is set at a per-unit cost c_F for simplicity. In our studies, c_F is set as a constant and is equal to that of its price P_F. Additionally, foreign goods are assumed to have a constant emission intensity e_F.

2.3 Technology-Based MAC Curve

Based on the literature review conducted by Grubb et al. (1993), the methodologies for emission reduction cost analysis can be roughly classified into two categories: top-down and bottom-up modeling, corresponding to analysis at the macro and micro levels. The marginal abatement costs (MACs) derived from CGE or IAM models belong to the top-down methodology or macro level, where the cost is always expressed as the impact of emission control (or achieving a given emission reduction target) on country/regional economics (e.g., losses to GDP, sectoral output, domestic consumption, and social welfare). At the micro level, the GHG emission reduction cost estimation is based on the total cost of abatement technologies that need to be input, and these technologies are ranked based on their cost effectiveness. The bottom-up modeling approach assigns great importance to technology costs and effectiveness, including engineering computing, dynamic energy optimization, and energy system simulation models.

In this study, to adopt a conservation supply curve (CSC)-based MAC curve, we use a bottom-up approach due to the following advantages:

1) Avoiding the double-accounting issue. The macro level MAC curve derived from the IAM or CGE models includes the effects of sectoral output/price adjustment and pass-through effects inside and across sectors under a given climate policy, and the cost is a combination of abatement technology input/investment, changes in output/price, and pass-through effects from up and down stream. In our partial equilibrium analysis, such effects will result from the model calculation, so a double accounting issue would have arisen if the macro level MAC curve had been adopted.

2) Supporting firm-level decision-making. Two representative firms are defined here to describe the production from normal and outdated capacities in the iron and steel sector. The enterprises within the sector are more concerned about the cost effectiveness of different abatement technologies, rather than considering macro costs in their abatement decision-making. Hence, such costs contained in the MAC curve derived from the macro level may be too rough to be applied to firm-level technology adoption.

3) Ensuring transparency and flexibility. It is difficult to define the energy savings that result from emission abatement in a macro-level estimated MAC curve, even if they are reflected better in the portfolio adjustment of sectoral energy inputs and the substitution of energy for other input factors. The emission abatement potential and its associated energy savings are clear in each technology in the micro-level MAC curve. This curve can provide a transparent view when measuring the co-benefits of energy savings resulting from emission abatement.

Furthermore, a set of sectoral total abatement technologies provides us with enough flexibility to distinguish the normal capacity from the outdated capacity by adjusting the technology sets among the two categories. By contrast, it would not be easy to distinguish the curves for normal and outdated capacities with an estimated macro MAC curve for one given sector.

We introduce a curve ranking based on the cost of conserved energy (CCE) of multiple energy-saving technologies in China's iron and steel industry (referring to Li and Zhu 2014). Per unit of output, technology j has four attributes: abatement cost tc_j (in Yuan/tCO_2 by converting the cost of conserved energy to the cost of emission reduction), potential for emission reduction r_j, potential for electricity savings $s_{Elec\,j}$, and potential for fuel savings $s_{Fuel\,j}$. The MAC curves adopted here are a set of technologies St, which are composed of { j, tc_j, r_j, $s_{Elec\,j}$, $s_{Fuel\,j}$ }. If the adoption cost of technology is considered alone, the order of technologies in the set is ranked by the rule of $tc_{j-1} < tc_j$. Similarly, if we take the price pass-through effects and energy-saving benefits into consideration, the rank will be as follows:

$$\begin{pmatrix} tc_{j-1} - \left(P_{Elec} + \delta_{Elec} \cdot P_C \cdot e_{Elec}\right) \cdot s_{Elec\,j-1} \\ -\left(P_{Fuel} + \delta_{Fuel} \cdot P_C \cdot e_{Fuel}\right) \cdot s_{Fuel\,j-1} \end{pmatrix} < \begin{pmatrix} tc_{j} - \left(P_{Elec} + \delta_{Elec} \cdot P_C \cdot e_{Elec}\right) \cdot s_{Elec\,j} \\ -\left(P_{Fuel} + \delta_{Fuel} \cdot P_C \cdot e_{Fuel}\right) \cdot s_{Fuel\,j} \end{pmatrix}.$$

Given a certain amount of emission reduction r, if n technologies need to be adopted, then we have $r = \sum_{j=1}^{n} r_j$, $c_{AC} = \sum_{j=1}^{n} tc_j \cdot r_j$, $Es_{Elec} = \sum_{j=1}^{n} s_{Elec\,j}$, $Es_{Fuel} = \sum_{j=1}^{n} s_{Fuel\,j}$.

For N and B, there are two sets of technologies: St_N and St_B. Given the diversity of production technology levels among N and B, St_N and St_B will not be the same. This will be discussed in Section 3.1.

2.4 Effects of the Implementation of ETS on Domestic Production

2.4.1 Free Allocation + Auction

Both representative firms with normal and outdated capacity will be included in the ETS, and they can trade allowances in the market; the trading is not only between the two representative firms but among all the sectors covered in the ETS. With the implementation of ETS, given the allocation method as a combination of grandfathering and auction ('Free Allocation + Auction'), the profits of two domestic representative firms (π_N and π_B) will be

$$\pi_N = P_D \cdot (N_d + N_x) - c_N \cdot (N_d + N_x) - P_C \left((N_d + N_x) \cdot (e_N^0 - r_N) - FA_N \right) \quad (7)$$

$$\pi_B = P_D \cdot (B_d + B_x) - c_B \cdot (B_d + B_x) - P_C \left((B_d + B_x) \cdot (e_B^0 - r_B) - FA_B \right) \quad (8)$$

in which e_N^0 and e_B^0 are the initial emission intensities for N and B, and FA_N and FA_B are their lump-sum free allocations. If $FA_N + FA_B$ is equal to the total emission cap, then the allocation involves pure "grandfathering." If $FA_N = FA_B = 0$, then the allocation is fully "auction."

Given $N_x = \alpha_N P_D^{\eta_{xx}} P_F^{\eta_{xw}}$ and $B_x = \alpha_B P_D^{\eta_{xx}} P_F^{\eta_{xw}}$, profit maximization leads to the first-order conditions:

$$\frac{\partial \pi_N}{\partial N_d} = \begin{pmatrix} P_D + \frac{\partial P_D}{\partial N_d} \cdot N_d + P_D \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} + \frac{\partial P_D}{\partial N_d} \cdot N_x - c_N - c_N \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} \\ -P_C (e_N^0 - r_N) - P_C (e_N^0 - r_N) \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} \end{pmatrix} = 0 \quad (9)$$

$$P_C = \frac{\partial c_N}{\partial r_N}$$

$$\frac{\partial \pi_B}{\partial B_d} = \begin{pmatrix} P_D + \frac{\partial P_D}{\partial B_d} \cdot B_d + P_D \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} + \frac{\partial P_D}{\partial B_d} \cdot B_x - c_B - c_B \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} \\ -P_C (e_B^0 - r_B) - P_C (e_B^0 - r_B) \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} \end{pmatrix} = 0 \quad (10)$$

$$P_C = \frac{\partial c_N}{\partial r_B}$$

The first order conditions of ${\partial \pi_N}/{\partial N_d}$ and ${\partial \pi_B}/{\partial B_d}$ contain the output competition, not only in the domestic market but also in relation to the exports (with P_D determined by N_d and B_d, and P_D also taken as the export price). Hence, each representative firm's decision will take both the domestic and foreign market into consideration, and the profit maximization will result in competitive equilibrium in both domestic and foreign markets.

Given that P_C is exogenous,[9] expanding Equation (9) to obtain r, we obtain

$$P_C = \frac{c_{NMAC}(r_N) - P_{Elec} \cdot \frac{\partial Es_{NElec}(r_N)}{\partial r_N} - P_{Fuel} \cdot \frac{\partial Es_{NFuel}(r_N)}{\partial r_N}}{1 + \delta_{Elec} \cdot e_{Elec} \cdot \frac{\partial Es_{NElec}(r_N)}{\partial r_N} + \delta_{Fuel} \cdot e_{Fuel} \cdot \frac{\partial Es_{NFuel}(r_N)}{\partial r_N}} \tag{11}$$

Because the MAC curve adopted in our model is a set of technologies St, $\partial Es_{NElec}(r_N) / \partial r_N \geq 0$ and $\partial Es_{NFuel}(r_N) / \partial r_N \geq 0$.[10] Given the same abatement technology set but only considering abatement cost, we have the carbon price-determined emission abatement level, $P_C = c_{MAC}(r)$. The following relationship can be derived between r and r_N:

$$c_{NMAC}(r_N) = c_{NMAC}(r)\begin{pmatrix} 1 + \frac{\partial Es_{NElec}(r_N)}{\partial r_N} \cdot \delta_{Elec} \cdot e_{Elec} \\ + \frac{\partial Es_{NFuel}(r_N)}{\partial r_N} \cdot \delta_{Fuel} \cdot e_{Fuel} \end{pmatrix} + \begin{pmatrix} \frac{\partial Es_{NElec}(r_N)}{\partial r_N} P_{Elec} \\ + \frac{\partial Es_{NFuel}(r_N)}{\partial r_N} P_{Fuel} \end{pmatrix} \tag{12}$$

Because $\partial Es_{NElec}(r_N) / \partial r_N \geq 0$ and $\partial Es_{NFuel}(r_N) / \partial r_N \geq 0$, then $c_{NMAC}(r_N) \geq c_{NMAC}(r)$, which means that $r_N \geq r$. With the consideration of the combined effects of price pass-through and energy-saving benefits, the firms will reduce more emissions than otherwise.

Given P_C, based on the demand function $P(D)$ and the first order conditions (9) and (10), a relationship between N_d and B_d can be established. Hence, P_D, N_d, and B_d can be solved by non-linear programming, after which N_x, B_x, F_m, and F_w can be calculated based on Equations (2) and (3). The solution to the model is presented in Appendix A1, which also proves the existence of a unique solution.

After the implementation of ETS, with the production-based emission accounting approach, the domestic total emissions are

[9] In China, the iron and steel sector amounts about 15% of total domestic CO_2 emissions, so it may have the market power to affect the price of CO_2. However, it is not easy to model the market power in a single sector-specific analysis, as the discussion of market power may relate to the emission abatement actions among other sectors. Therefore, we assume here that the CO_2 price is exogenous, which implies that the iron and steel sector is a price taker in China.

[10] The following case exists: if technology j only saves one kind of energy, then its marginal contribution to the savings of other kinds of energy is zero.

$$E = N \cdot (e_N^0 - r_N) + B \cdot (e_B^0 - r_B) \tag{13}$$

The consumption-based domestic emissions are

$$E_c = N_d \cdot (e_N^0 - r_N) + B_d \cdot (e_B^0 - r_B) + F_m \cdot e_F \tag{14}$$

Here, carbon leakage is difficult to measure because it is not possible to estimate F_w. An approximate measurement is adopted here by defining the net carbon-embodied export ($E_n = E - E_c$). Regarding F_w as a constant, E_n can reflect the leakage after the ETS is implemented in the domestic market.

2.4.2 Free Allocation + Border Carbon Adjustment

To address competitiveness loss and carbon leakage, some developed countries (e.g., France) have called for border adjustment measures such as levying taxes (e.g., carbon tariffs) on the carbon content of imports from countries with less ambitious climate policies. Notably, Fisher and Fox (2012) have conceptually and empirically explored the effectiveness of four border carbon adjustment polices: a border charge on imports (carbon tariff), a border rebate for exports, a full border adjustment, and a domestic output-based rebate (tying the allocation of allowances in an emissions trading scheme to output, which will be discussed in Section 2.4.3). Border carbon adjustment is an active topic in developed countries, but it is seldom discussed in developing countries, as most have not introduced quantitative measures to control their domestic CO_2 emissions. We assume that China has implemented the ETS in domestic industries and thus simulate the impact of a border carbon adjustment on the domestic iron and steel industry.

The export rebate and full border adjustment have been introduced into our model. The allocation method is the same as that in Section 2.4.1. Referring to Fischer and Fox (2012), the export rebate value is the emissions embodied in the exports of N and B after the implementation of ETS (for N and B, they are $P_C \cdot (e_N^0 - r_N)$ and $P_C \cdot (e_B^0 - r_B)$). The expression of the profits of two domestic representative firms (π_N and π_B) is the same as that in Section 2.4.1 but for $N_x = \alpha_N (P_D - P_C \cdot (e_N^0 - r_N))^{\eta_{xx}} P_F^{\eta_{xw}}$ and $B_x = \alpha_B (P_D - P_C \cdot (e_B^0 - r_B))^{\eta_{xx}} P_F^{\eta_{xw}}$.

With the full border adjustment, in addition to the export rebate, the imports are charged an emission tax at a rate equal to the carbon price P_C. Considering the emission intensity of foreign goods e_F as a constant, the price of $P_C \cdot e_F$ will be added to the embodied emissions per unit of the imports. The demand for imports is then revised as $F_m(P_D, P_F) = \alpha_m \left(P_F + P_C \cdot e_F\right)^{\eta_{mm}} P_D^{\eta_{md}}$. The rest of the model is the same as that in Section 2.4.1.

2.4.3 Free Allocation + Differential Electricity Price

To channel investment and capacity expansion in energy-intensive sectors in the direction of technological efficiency, the Chinese government has proposed a differential electricity price policy in such sectors. Under this policy, a higher electricity price will be implemented for enterprises with outdated capacity. This policy aims to accelerate the withdrawal of outdated capacity from the market. In our model, the policy is introduced in the case where P_{Elec} is multiplied by coefficient d_e for B. After the implementation of ETS, c_B is revised as

$$\begin{aligned} c_B &= c_{BOther} + d_e \cdot (P_{Elec} + \delta_{Elec} \cdot P_C \cdot e_{Elec}) \cdot \left(Ec_{BElec0} - Es_{BElec}(r_B)\right) \\ &\quad + (P_{Fuel} + \delta_{Fuel} \cdot P_C \cdot e_{Fuel}) \cdot \left(Ec_{BFuel0} - Es_{BFuel}(r_B)\right) + c_{BAC}(r_B) \end{aligned} \tag{15}$$

The rest of the model is the same as that in Section 2.4.1.

2.4.4 Output-Based Allocation (OBA)

After the implementation of ETS, an alternative to the border carbon adjustment to compensate for the competitiveness loss is to offer rebates to domestic production. This policy can be implemented using rate-based mechanisms for emissions allowance allocation, which has already been implemented in New Zealand and California (Fischer and Fox 2012; Meunier et al. 2014). In this paper, output-based allocation (OBA) has been introduced among domestic firms. This is a unified rate of subsidy as compensation for both types of firms (normal and outdated). Because the allocation of allowances is attached to output, firms receive a given number of allowances (ob) per unit of output. With OBA, the profit function can be rewritten as

$$\begin{aligned} \pi_N &= P_D \cdot (N_d + N_x) - c_N \cdot (N_d + N_x) \\ &\quad - P_C \left((N_d + N_x) \cdot (e_N^0 - r_N) - (N_d + N_x) \cdot ob\right) \end{aligned} \tag{16}$$

$$\begin{aligned} \pi_B &= P_D \cdot B_d + (P_D - P_C \cdot (e_B^0 - r_B)) \cdot B_x - c_N \cdot (B_d + B_x) \\ &\quad - P_C \left((B_d + B_x) \cdot (e_B^0 - r_B) - (B_d + B_x) \cdot ob\right) \end{aligned} \tag{17}$$

In such a case, the first-order conditions of π_N and π_B are

$$\frac{\partial \pi_N}{\partial N_d} = \begin{pmatrix} P_D + \frac{\partial P_D}{\partial N_d} \cdot N_d + P_D \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} + \frac{\partial P_D}{\partial N_d} \cdot N_x - c_N - c_N \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} \\ -P_C (e_N^0 - r_N) - P_C (e_N^0 - r_N) \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} \\ +P_C \cdot ob + P_C \cdot ob \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} \end{pmatrix} = 0 \quad (18)$$

$$P_C = \frac{\partial c_N}{\partial r_N}$$

$$\frac{\partial \pi_B}{\partial B_d} = \begin{pmatrix} P_D + \frac{\partial P_D}{\partial B_d} \cdot B_d + P_D \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} + \frac{\partial P_D}{\partial B_d} \cdot B_x - c_B - c_B \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} \\ -P_C (e_B^0 - r_B) - P_C (e_B^0 - r_B) \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} \\ +P_C \cdot ob + P_C \cdot ob \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} \end{pmatrix} = 0 \quad (19)$$

$$P_C = \frac{\partial c_N}{\partial r_B}$$

2.5 Welfare Measure and Feasible OBA Rate

There is always a trade-off between emission reduction and sectoral competitiveness loss. OBA, acting as an important option to compensate for sectoral competitiveness loss, could provide continuous abatement incentives to firms; for consumers, this could result in excessive consumption of products that benefit from the scheme (Meunier et al. 2014). The introduction of a social welfare function can provide a measurement to determine a feasible rebate rate. In previous studies (Fowlie et al. 2012; Lecuyer and Quirion 2013; Meunier et al. 2014), welfare is defined as the difference between gross consumer surplus and the sum of production cost and environmental damage. Such a definition limits the measurement of welfare in a sectoral-specific analysis, as it only accounts for welfare effects in the sector itself and does not consider the impact on downstream sectors. In our model, however, the impact of changes of output price on the downstream sectors' output has been considered. By adopting a sectoral price multiplier matrix, assume that there are K sectors downstream from the iron and steel sector, $k \in K$. The price multiplier (Pm_k) from the iron and steel sector to sector k is converted to the change in k's output level. This implies an assumption that a price change in the iron and steel sector will affect its downstream sectors' output and the sector's output price P_k will remain unchanged. Welfare is then measured as

$$\begin{aligned} Wl &= U(N_d, B_d) + U(F_m) - N\cdot c_N - B\cdot c_B - P_F F_m + P_D(N_x + B_x) \\ &- P_C\left(N\cdot(e_N^0 - r_N) + B\cdot(e_B^0 - r_B) + F_m\cdot e_F\right) \\ &+ \sum_{k=1}^{K} P_k\cdot Q_k\cdot Pm_k\cdot\left(1-\left(\frac{P_D(N_d+B_d)+P_F F_m}{N_d+B_d+F_m}\Big/\frac{P_{D0}(N_{d0}+B_{d0})+P_F F_{m0}}{N_{d0}+B_{d0}+F_{m0}}\right)\right) \end{aligned} \tag{20}$$

where $U(N_d, B_d)$ is the domestic gross consumer surplus; $U(F_m)$ is the utility of consumer goods F; Q_k is the downstream sector k's output, which is also assumed to be constant in relation to P_k; and $P_k\cdot Q_k$ can be viewed as the sectoral output value. It should be acknowledged here that the last item in Equation (20) is an approximation, if we consider that the fact that other sectors may also be covered by the ETS and that these sectors will adjust their output due to the level of the carbon price. On the other hand, our approximation can make sense if, disregarding the changes caused by ETS in other sectors, we measure only the impact of the change in price level from one sector to other sectors.

Furthermore, for the quantitative assessment, we set $\partial U/\partial N_d = \partial U/\partial B_d = P_D$, and $\partial U/\partial F_x = P_F$.

In the partial equilibrium analysis, the optimal rebate rate is determined by maximizing welfare if P_C is endogenous.[11] In our paper, given that P_C is an exogenous factor, it can be inferred that a higher ob rate will result in a greater welfare level. Therefore, with additional conditions added, a trigger or threshold of the ob rate can be calculated. We define such conditions as "feasible conditions."

Apart from curbing emissions, two forms of feasible conditions have been introduced:

1) Setting the welfare change equal to zero ($\Delta Wl = 0$), which means that the implementation of OBA can at least prevent domestic welfare from deteriorating. Here, the OBA rate is defined as ob^{**}.

2) Setting the domestic total output change equal to zero ($\Delta(N+B)=0$), which means that the implementation of OBA can maintain the competitiveness of the whole sector. Here, the OBA rate is defined as ob^{*}.

[11] In a social welfare function, assuming that an endogenous carbon price level is equal to marginal climate damage, we can derive a balance between output and emission reduction. Hence, an optimal rebate rate can be determined (Meunier et al. 2014).

The first feasible condition is based in part on Fischer and Fox (2004). The second feasible condition is designed to solve the issue of overcapacity in China's energy-intensive sectors. It is certain that the OBA will not result in another round of capacity expansion in the iron and steel sector. We also give a range for changes in ob, $0 \le ob \le \left(N_0 \cdot e_N^0 + B_0 \cdot e_B^0\right) / \left(N_0 + B_0\right)$.

The determination process of ob^{**} and ob^{*} under two feasible conditions is presented in Appendix A1. Given the constraints on feasible conditions, a feasible ob may not exist in all levels of P_C, which will be discussed in the numerical simulations.

3. Case Study on China's Iron and Steel Sector

3.1 Parameters and Model Calibration

The model is applied to China' iron and steel sector and the base year is set as 2010. The parameters can be categorized into three groups: 1) Parameters from the actual data in 2010; 2) Parameters that are estimated based on the historical data from 2005-2010; 3) Parameters that are calibrated by our model, which are mainly for showing the difference between N and B.

For the first group of parameters, the production, consumption, and price data were taken mainly from the China Statistical Yearbook 2010 (NBS 2011) and the Steel Statistical Yearbook 2011 (WSA 2011). Coking coal was used as the representative fuel consumed in the iron and steel sector. The average energy consumption per unit output, energy prices, and emission factors were taken from the Annual Report of Electricity Regulation (SERC 2011), China Energy Statistical Yearbook 2011 (NBS 2011), and Li and Zhu (2014). In addition, the price pass-through rates of electricity and coking coal were all set to 0.9.[12] The carbon price and free allocation were set at 50 Yuan/tCO_2 and 90% of initial emissions. The detailed parameter values are shown in Appendix A2. To guarantee the calculation accuracy of our policy shock analysis,

[12] It should be pointed out that the domestic electricity price is currently strictly regulated by the government. The electricity price pass-through rate applied here implies that the domestic electricity market is, to a great extent, market based. We applied this assumption because, with the further development of the domestic power system reform, the ongoing plant on-grid competitive price bidding, and separation of electricity transmission and distribution, thermal power plant owners may have more flexibility to pass extra emission costs to their downstream consumers. For the EU's iron and steel sector, the electricity pass-through rate is set at 0.75 in Demailly and Quirion (2008). In our model, we increased the rate to 0.9 based on the results of the market-based power generation simulation in Chen et al (2013). The impact of different pass-through rates on the calculation results has been examined in a sensitivity analysis.

we calibrated an initial equilibrium in which domestic consumption, export and import, and total domestic emission are calculated based on the estimated parameters in Appendix A3, instead of applying the real ones.

For the parameters in the demand functions, historical data from 2005 to 2010 have been used in the estimation. These were obtained mainly from the China Statistical Yearbooks (NBS 2006; 2007; 2008; 2009; 2010; 2011) and Steel Statistical Yearbooks (WSA, 2006; 2007; 2008; 2009; 2010; 2011). The price data applied in the estimation have been adjusted to the base year 2010, excluding the consumer price index (CPI) and exchange rate effects. The estimation results are shown in Appendix A3. Here we do not estimate the parameters based on longer historical data as our model provides a static analysis. Years 2005 to 2010 were also the period when China's energy intensive sectors experienced rapid expansion of production capacity and the issue of overcapacity became more serious (the estimated values of α and β also show a "weak" demand situation in the domestic iron and steel industry).

To ensure the initial equilibrium status, the domestic price P_{D0} is calculated by the domestic demand function with the estimated parameters in Appendix A3. Export and import are also calculated by Equations (2) and (3) with the parameters estimated in Appendix A3 and P_{D0}. The total domestic production ($N_0 + B_0$) and emissions from the production ($E_0 = e^0_{N+B} \cdot (N_0 + B_0)$) can then be derived. The detailed calibration results are given in Appendix A4.

The most critical part is to distinguish N and B, as there is a limited amount of data on capacity for the two groups. We calibrate the data for N and B in several steps. The details of the calibration steps and results for N and B are shown in Appendix A4.

3.2 Technology Sets and Sectoral Price Multiplier

For the MAC curves adopted in this paper, the technologies refer to the collection and collation conducted by Li and Zhu (2014). A total of 35 energy-saving technologies have been included in our technology set. The detailed technology set is shown in Appendix A4.

First, to describe the diversity of MACs for N and B, the technologies contained in each set are different. For St_N, the technologies with market shares larger than 70% have been removed because we assume that such technologies have already been adopted by firm N. Apart from this, we also removed some technologies that have market shares larger than 50% to adapt to the difference in emission intensity between N and B. Consequently, St_N and St_B contain 24 and 35 energy-saving technologies, respectively.

Second, the adoption share (sh_j) of each technology based on the year 2010 has been investigated by Li and Zhu (2014). The technology's emission abatement potential is set as $r_j \cdot \left(1-sh_j\right)$.

Third, with the consideration of the discontinuation of the technology-based MACs, given P_C, if $P_C > tc_{n-1}$, and $P_C < tc_n$, the calculation of r and c_{AC} would be

$$r = \sum_{j=1}^{n-1} r_j \cdot \left(1-sh_j\right) + r_n \cdot \left(1-sh_n\right) \cdot \frac{P_C}{ct_n} \quad (21)$$

$$c_{AC} = \sum_{j=1}^{n-1} tc_j \cdot r_j \left(1-sh_j\right) + P_C \cdot r_n \cdot \left(1-sh_n\right) \quad (22)$$

The same rule also applies to Es_{Elec} and Es_{Fuel}. It should be mentioned that the parameters of technologies adopted here use constant values. The technology progress or spillover effects have not been considered, as our model is based on a static partial equilibrium analysis. Such effects should be considered if the study is extended to middle- and long-term dynamic analysis.

For the sectoral Price Multiplier matrix adopted in the welfare measure, the calculation is presented in Appendix A5. According to the value of the sectoral Price Multipliers, five sectors (Manufacture of Metal Products, Manufacture of Electrical Machinery and Apparatus, Manufacture of General and Special Purpose Machinery, Manufacture of Transport Equipment, and Construction) have been assumed as downstream of the iron and steel sector.

3.3 Numerical Simulations

Considering the potential negative impact of ETS on the industry's competitiveness, most of the pilot regions allocate allowances based on grandfathering. In addition, some regions propose the introduction of a partial auction (Shenzhen) or benchmarking to specific sectors (e.g., energy-intensive firms in Guangdong). In our analysis, given the emission cap of 90% of initial emissions, the carbon prices ranged from 50 Yuan/tCO_2 to 250 Yuan/tCO_2. We mainly simulated four scenarios:

S1: Free Allocation (FA) + Auction, where the FA share changes from 90% (totally free allocation) to 0% (fully auctioned);

S2: Free Allocation + Border Carbon Adjustment (Export Rebate and Full Border Adjustment);

S3: Free Allocation + Differential Electricity Price;

S4: Output-Based Allocation. In S4, we did not simulate the impact of the different *ob* levels but calculated the optimal *ob* rates given the two forms of “feasible condition” definitions in the welfare description.

Before presenting the simulation results, we would like to investigate the impact of the different cost definitions for the evaluation results in the iron and steel sector. Given P_C=50 Yuan/tCO_2 and FA=90%, the production costs are defined as follows:

In Case 1, $c = c_{Other} + P_{Elec} \cdot Ec_{Elec0} + P_{Fuel} \cdot Ec_{Fuel0} + c_{AC}(r)$. Neither the energy saving (ES) benefits nor the price pass-through (PP) effects have been taken into account;

In Case 2, $$c = c_{Other} + (P_{Elec} + \delta_{Elec} \cdot P_C \cdot e_{Elec}) \cdot Ec_{Elec0} + (P_{Fuel} + \delta_{Fuel} \cdot P_C \cdot e_{Fuel}) \cdot Ec_{Fuel0} + c_{AC}(r)$$. Only the price pass-through effects have been taken into account;

In Case 3, the costs follow Equations (6) and (7). Both the energy-saving (ES) benefits and price pass-through effects have been taken into account.

The same technology sets have been applied in N and B, but the rankings are based on different principles of technology cost accounting. In Cases 1 and 2, the ranking is based on the technology abatement cost tc_j. In Case 3, the ranking is based on the combined cost as

$$tc_j - \left(P_{Elec} + \delta_{Elec} \cdot P_C \cdot e_{Elec}\right) \cdot s_{Elec\,j} + \left(P_{Fuel} + \delta_{Fuel} \cdot P_C \cdot e_{Fuel}\right) \cdot s_{Fuel\,j}$$.

The comparison index in the iron and steel industry has been categorized in terms of industrial competitiveness, emission control, firms’ performance, and domestic consumption and welfare. The calculation results are shown in Table 1.

Table 1: Results Comparison among Different Cost Definitions

Cap=90% of E_0 P_C=50 Yuan/tCO_2 FA=90% of E_0		Case 1 No ES Benefits & No PP Effects	Case 2 No ES Benefits & With PP Effects	Case 3 With ES Benefits & With PP Effects
Industrial Competitiveness	△N	-1.61%	-1.87%	0.10%
	△B	-5.04%	-6.30%	0.88%
	△(N+B)	-2.64%	-3.20%	0.34%
	△(N_x+B_x)	-0.64%	-0.78%	0.08%
	△P_D	1.84%	2.23%	-0.23%
Emission Control	ΔE_N	-0.60%	-0.87%	-16.54%
	ΔE_B	-3.01%	-4.30%	-18.46%
	ΔE	-7.94%	-8.53%	-17.24%
	ΔE_{con}	-7.77%	-8.35%	-16.74%
	Δ(E- E_{con})	-12.19%	-12.87%	-29.51%
Firms' Performance	Market Share of N	70.74%	70.96%	69.82%
	Market Share of B	29.26%	29.04%	30.18%
	Δ$Profit_N$	1.82%	1.31%	5.25%
	Δ$Profit_B$	2.88%	0.45%	14.73%
Domestic Consumption and Welfare	Δ(N_d+B_d)	-2.78%	-3.37%	0.35%
	ΔF_m	3.09%	3.75%	-0.39%
	ΔWl	-16.16%	-17.15%	6.51%

If we do not consider the energy-saving benefits, the implementation of ETS can cause negative impacts on China's iron and steel industry. Such negative impacts become larger if we take the effects of the energy price pass-through into account. Emissions have been reduced by 7.94% and 8.53% in Cases 1 and 2, respectively. Given an emission cap of 90% (which means a 10% emission-reduction target compared with the base year), the iron and steel sector would be a net buyer of allowances in the emission trading market.

Both *N* and *B* will experience a loss in production in Cases 1 and 2. Firm *N* demonstrates better performance than firm *B* when we compare the index of production, market share, and profit. Thus, it can be seen that, although the ETS will decrease the whole sector's output, it can promote an outdated capacity withdrawal and production-level upgrading to some extent, even in a situation with low carbon price and totally free allocation.

It is another story if we consider the energy-saving benefits in Case 3. In Case 3, both firms *N* and *B* experience an increase in their production and profits. The industry would be a net seller of allowances, as emissions have been reduced by 16.54%. Furthermore, if we look into the changes in *N* and *B*, a competitiveness distortion has occurred inside the industry. Given a larger energy-saving potential, firm *B* has better performance than firm *N* does; meanwhile, the market share of *B* also increases. Hence, it seems that the ETS will lead the sector in an opposite direction and will not conform to the original intentions of the government (in the promotion of the outdated capacity withdrawal and production-level upgrading).

Some empirical evidence from the EU-ETS supports the results in Case 3. In Phase I of the EU-ETS, due to concern about the competitiveness loss in EU energy-intensive industries, grandfathering-based free allocation was implemented. In the impact analysis performed by the European Commission, the energy-saving benefits that resulted from emission abatement in energy-intensive sectors were, to a great extent, neglected, which caused an underestimation of such sectors' abatement potential. Such underestimation has resulted in excess permits in the market and the carbon price being lower than expected, as well as energy intensive sectors being unaffected by the ETS (Anger and Oberndorfer 2008).

3.3.1 Results in Scenario 1: FA + Auction

In S1, given that FA=90% of E_0, the carbon prices will increase from 50 Yuan/tCO_2 to 250 Yuan/tCO_2. The results are summarized in Table 2.

Table 2: Simulation Results in S1

Cap=90% of E_0 FA=90% of E_0		P_C=50 Yuan/tCO_2	P_C=100 Yuan/tCO_2	P_C=150 Yuan/tCO_2	P_C=200 Yuan/tCO_2	P_C=250 Yuan/tCO_2
Industrial Competitiveness	$\triangle N$	0.10%	-0.91%	-1.94%	-2.77%	-3.65%
	$\triangle B$	0.88%	-3.76%	-8.09%	-12.72%	-17.07%
	$\triangle(N+B)$	0.34%	-1.76%	-3.78%	-5.76%	-7.67%
	$\triangle(N_x+B_x)$	0.08%	-0.43%	-0.92%	-1.38%	-1.83%
	$\triangle P_D$	-0.23%	1.23%	2.63%	4.01%	5.34%
Emission Control	ΔE_N	-16.54%	-21.70%	-27.12%	-28.25%	-29.40%
	ΔE_B	-18.46%	-25.71%	-31.58%	-36.65%	-40.36%
	ΔE	-17.24%	-23.03%	-28.52%	-30.96%	-32.93%
	ΔE_{con}	-16.74%	-22.40%	-27.75%	-30.14%	-32.07%
	$\Delta(E- E_{con})$	-29.51%	-38.75%	-47.68%	-51.42%	-54.38%
Firms' Performance	Market Share of N	69.84%	70.61%	71.34%	72.22%	73.05%
	Market Share of B	30.16%	29.39%	28.66%	27.78%	26.95%
	$\Delta Profit_N$	5.25%	6.82%	8.36%	10.31%	12.19%
	$\Delta Profit_B$	14.73%	16.02%	18.37%	20.53%	23.63%
Domestic Consumption and Welfare	$\Delta(N_d+B_d)$	0.81%	-1.09%	-2.93%	-4.74%	-6.51%
	ΔF_m	-0.39%	2.06%	4.44%	6.78%	9.08%
	ΔWl	6.51%	-6.57%	-19.80%	-33.37%	-34.78%

With the carbon price higher than 100 Yuan/tCO_2, the industry will experience a loss in competitiveness, and more losses are contributed by the production decrease of *B* rather than that of *N* (see Figure 1a and 1b). Because of the larger market share of *N* in terms of total production, the total emission reduction contribution by *N* is always larger than that of *B*. However, with the increase of the carbon price level, the share of abatement from *B* has increased (see Figure 1c). For *N*, most of its abatement is the result of the emission intensity improvement among all carbon price levels. For *B*, with the increase of the carbon price, the share of emission abatement contributed by the output decrease will become larger (see Figures 1d and 1e).

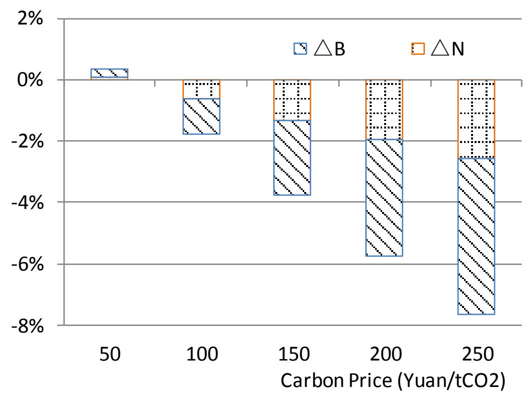

Figure 1a: Percentage Change in Domestic Production and Contributions by ΔN and ΔB

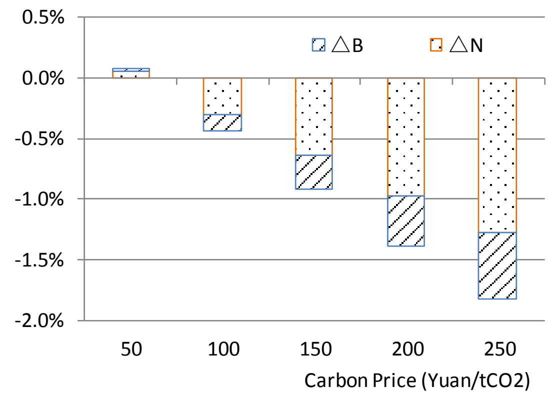

Figure 1b: Percentage Change in Total Export and Contributions by ΔN and ΔB

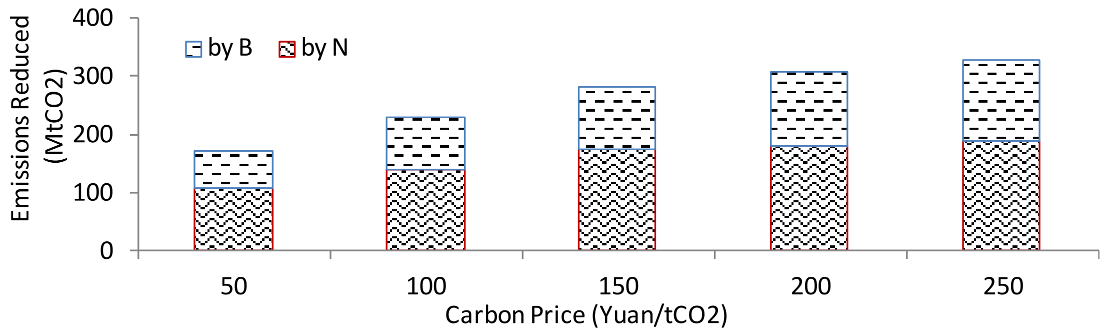

Figure 1c: Emission Abatement and Contributions by *N* and *B*

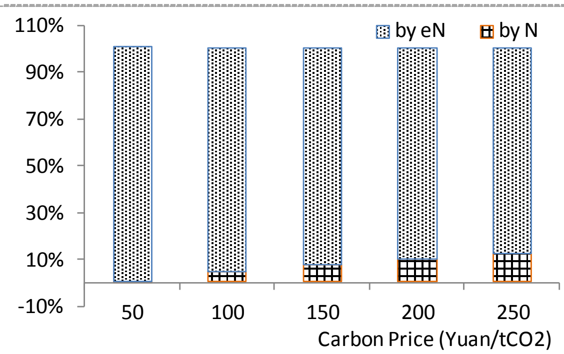

Figure 1d: *N*'s Emission Abatement Contributions from Emission Improvement and Production Change

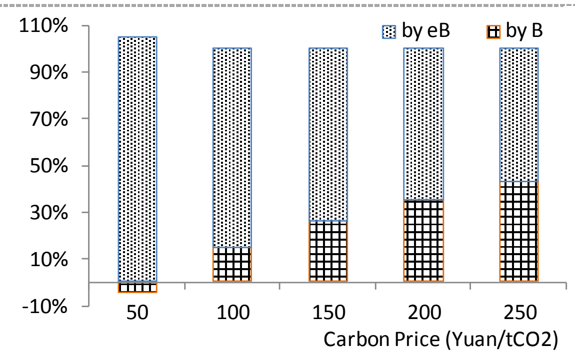

Figure 1e: *B*'s Emission Abatement Contributions from Emission Improvement and Production Change

Although the domestic (per unit) output price continues to increase with the increase in carbon price, if we look into the actual cost changes of *N* and *B* (Figures 2a and 2b), their actual costs both show the trends of decrease along with the increase of carbon price levels. The increased abatement cost contributes to the increase in production cost, while the energy-saving benefits can, to a great extent, offset such effects, even with the presence of upstream price pass-through effects. We have noticed that the contribution of the energy cost change showed a U-shaped trend in both *N* and *B*, along with an increase in carbon price. This is mainly because of the mixed effects caused by both price pass-through and energy saving.

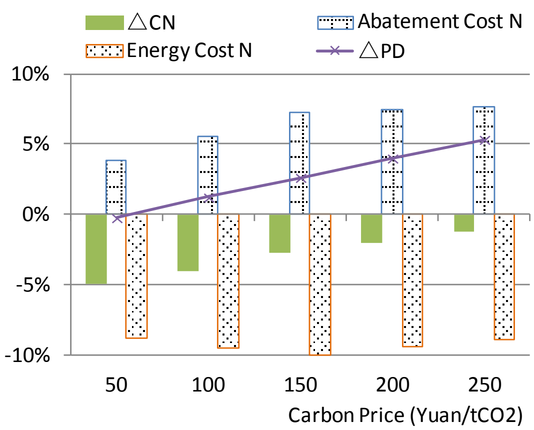

Figure 2a: Change in Per Unit Cost of *N* (ΔC_N) and Contributions from Abatement and Energy Costs

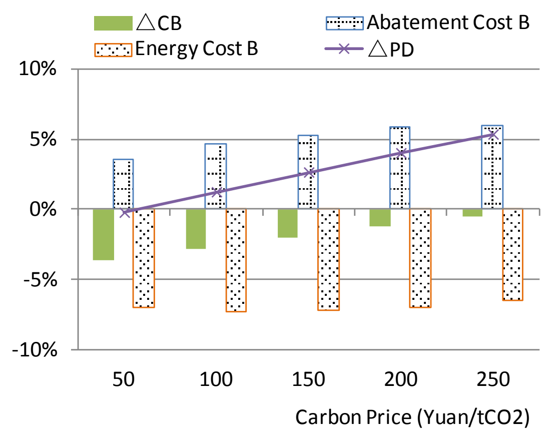

Figure 2b: Change in Per Unit Cost of *B* (ΔC_B) and Contributions from Abatement and Energy Costs

The profits of both *N* and *B* increase with the carbon price. On the other hand, welfare shows a decreasing trend (see Table 2). Referring to the above discussions, it seems that, apart from the distortion effect that occurs when the carbon price is 50 Yuan/tCO_2, by paying the price for loss in domestic production and welfare, the ETS with free allocation can promote outdated capacity withdrawal in the iron and steel industry if the carbon price is high (more than 100 Yuan/tCO_2). Essentially, when we look at the profits of *N* and *B*, the distortion effect still exists. Although *B* loses more production and market share under the higher carbon price level, its profit continues to increase and is always higher than that of *N*. Such capacities cannot be considered abandoned under the condition of increasing profit. The main reason behind the distortion effect in profits is the free allocated allowances. Our simulated results are in accordance with empirical findings about windfall profits in the electricity and cement sectors in Phase I of EU-ETS (Smale et al. 2006; Veith et al. 2009; Kim et al. 2009; Oberndorfer 2009).

Next, we change the FA share from 90% (totally freely allocated) to 0% (fully auctioned) to investigate the impact of FA sharing on the firms' profits. Details of the results are shown in Figure 5. As has been discussed, to promote outdated capacity withdrawal and production-level upgrading, it is necessary to weaken the competitiveness of outdated capacity. The best way to do this is to reduce the production and profit of the outdated capacity and at the same time maintain total domestic output (it is also a feasible condition defined in Section 2.5). Following this rule, and by adjusting the carbon price level, we try to find whether such a condition exists among different shares of free allocation. The changes in the profits of *N* and *B*, as well as their corresponding changes in total domestic output, have been mapped in Figure 3.

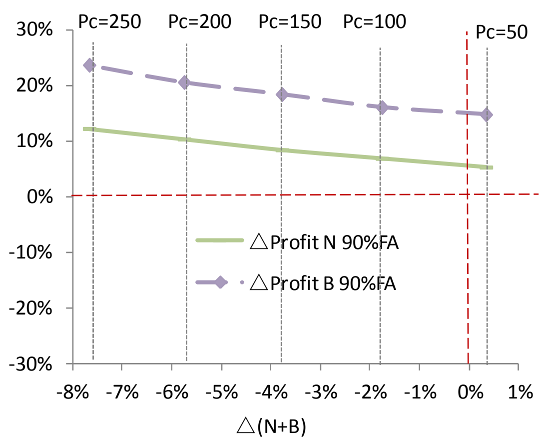

Figure 3a: Changes in Domestic Production and Profits of *N* and *B* (90%FA)

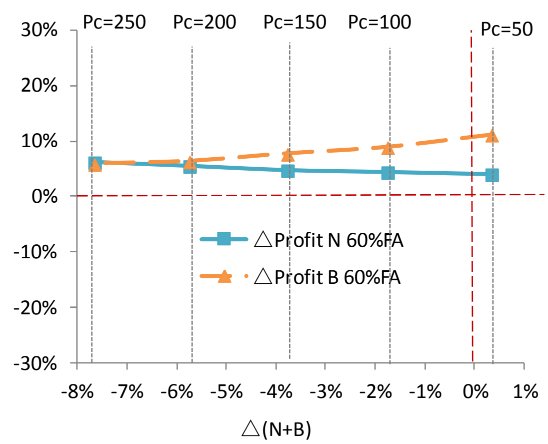

Figure 3b: Changes in Domestic Production and Profits of *N* and *B* (60%FA)

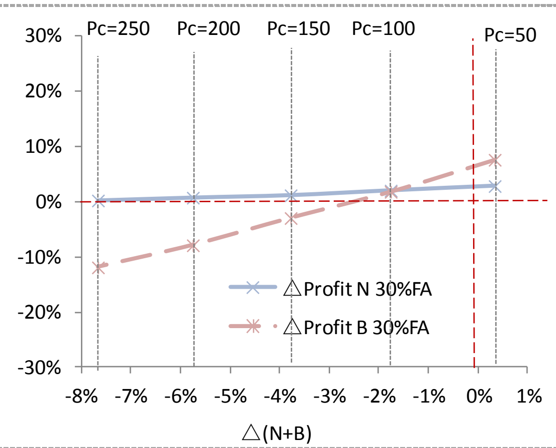

Figure 3c: Changes in Domestic Production and Profits of *N* and *B* (30%FA)

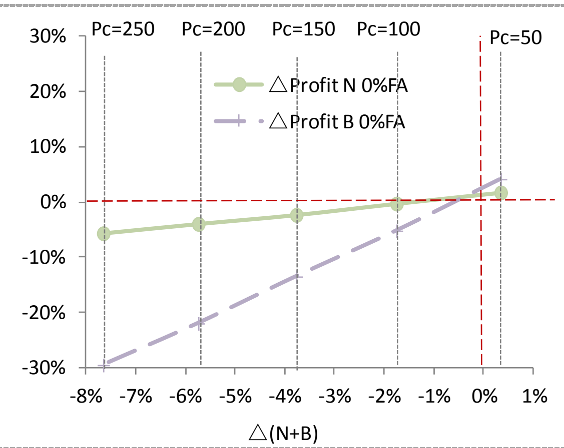

Figure 3d: Changes in Domestic Production and Profits of *N* and *B* (0%FA)

The distortion effect on the firms' profits is offset to a great extent by the decrease in the share of free allocation, especially for the profits of *B*. In Figures 3a and 3b, the feasible condition may not occur, as the changes in both of the firms' profits are higher than 0 given 90% FA and 60% FA, respectively. In Figure 3c, although the changes in the profits of *B* are negative — given that the carbon price level is higher than 100 Yuan/tCO_2 — its profit change is still higher than 0 at the point where $\triangle(N+B)=0$. Therefore, given 30% FA, the feasible condition does not exist either. In Figure 3d, on the left-hand side close to the point of $\triangle(N+B)=0$, the change in firm *N*'s profit is positive while the change in firm *B*'s profit is negative; hence, it can be inferred that the feasible condition may exist in the full auctioning situation.

3.3.2 Results in Scenario 2: FA + BCA

Given the free allocation as 90% (90%FA), the results of the export rebate (ER) and full border adjustment (FBA) are shown in Figure 4. It should be noted that we do not present the changes of the indexes compared to the base year but instead compare them to those in S1 (the comparison is between the two scenarios with or without the border carbon adjustment, e.g., the result of *N* presented in Figure 4 is calculated as $\triangle N_{ER}/\triangle N_{S1}$-1).

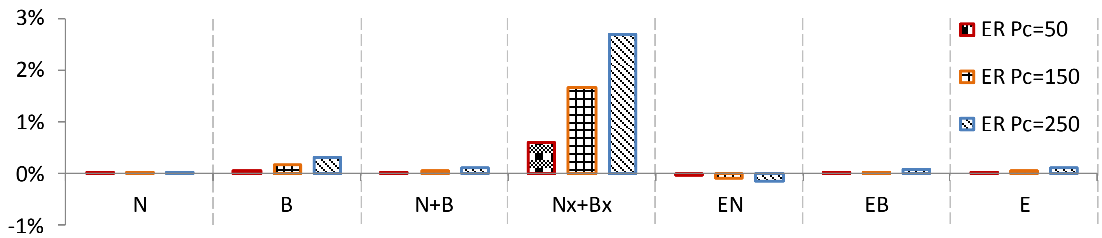

Figure 4a: Change in Industrial Competitiveness and Domestic Emission in ER Compared with that in S1

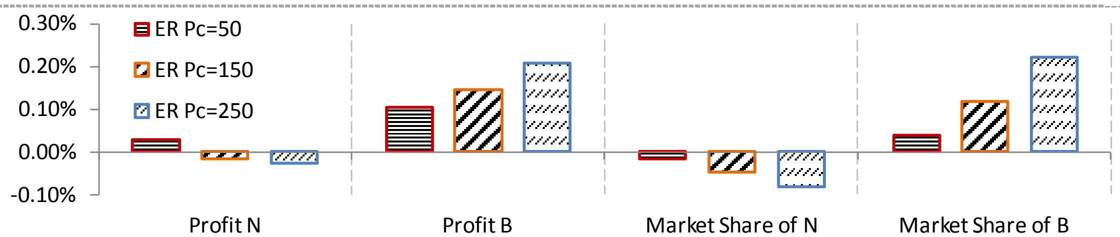

Figure 4b: Change in Firms' Performance in ER Compared with that in S1

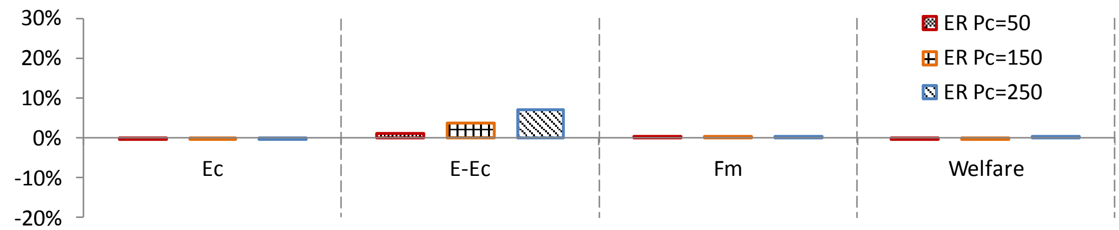

Figure 4c: Change in Net Carbon Embodied Export, Imports, and Welfare in ER Compared with that in S1

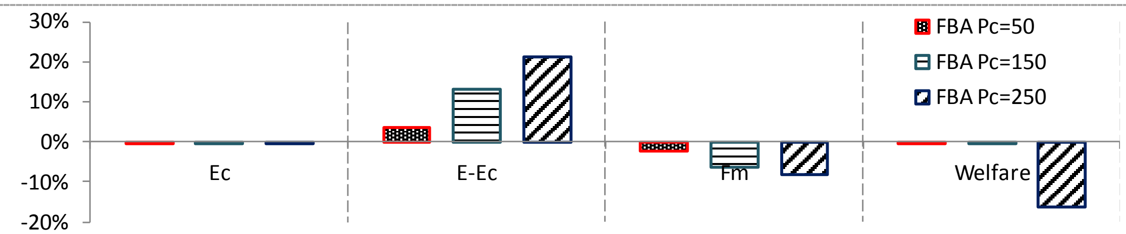

Figure 4d: Change in Net Carbon Embodied Export, Imports, and Welfare in FBA Compared with that in S1

From the perspective of competitiveness, with ER, the domestic total production and export show trends of positive increase compared with Scenario 1, especially for export. If we look into the production change between *N* and *B*, first, among all carbon price levels, the magnitude of the output increase in *B* is larger than that in *N*. Second, there is a decrease in the profit of *N* compared to the case of S1, with carbon price levels higher than 150 Yuan/tCO_2, and the profit of *B* always increases for all carbon price levels. Third, compared to S1, the market share of *N* shows a decreasing trend while that of *B* is increasing. With the introduction of the export rebate, the outdated capacity rather than the normal capacity will be compensated for the competitiveness loss in production.

In our model, because there is a Cournot competition for domestic firms in the domestic market, the implementation of the carbon tariff will not affect the output of domestic firms but will affect the import, welfare, and most significantly, the net carbon embodied export (E-E_c). From the perspective of emissions and leakage, domestic production-based emissions (E) show an increasing trend compared to that in S1, while there is a decrease in consumption-based emission (E_c). Such trends result in a reverse effect that deviates from the original design of border carbon adjustment. There is a potential increase in the net carbon-embodied export (E-E_c) compared to that in S1, and this trend is more significant with the full border adjustment (as the import F_m is affected by the carbon tariff).

In developed countries, the border carbon adjustment has been viewed as an option for addressing industrial competitiveness loss and emission leakage after implementing emission-reduction measures. In developing countries, given the diversity in domestic production technology levels and the higher emission intensity compared to foreign goods, the border carbon adjustment measures may diverge from their original purpose. The emission leakage could be worse compared with ETS alone because the export rebate can stimulate domestic export. Furthermore, with the implementation of such measures, the outdated capacity can be compensated more than the normal capacity, which makes the distortion between *N* and *B* worse, not only with respect to their profits but also their outputs.

3.3.3 Results in Scenario 3: FA + Differential Electricity Price

Two levels of differential electricity prices have been introduced to outdated capacity: low level, d_e=1.1, with the results denoted as S3.1; and high level, d_e=1.2, with the results denoted as S3.2. Given the free allocation as 90% (90%FA), the results are shown in Figure 5.

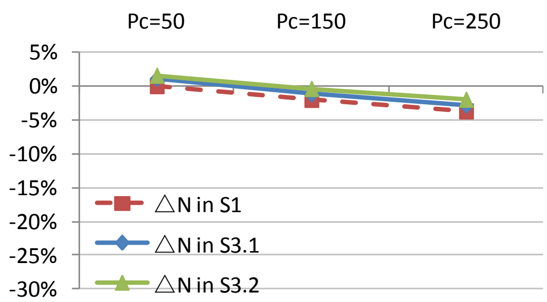

Figure 5a: Changes in Outputs of *N*

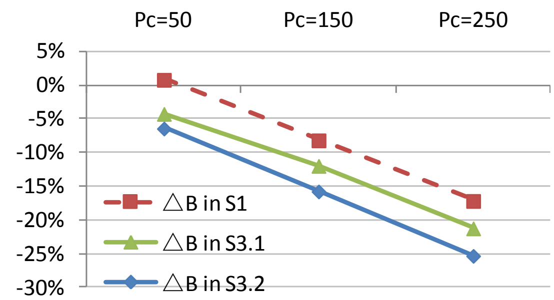

Figure 5b: Changes in Outputs of *B*

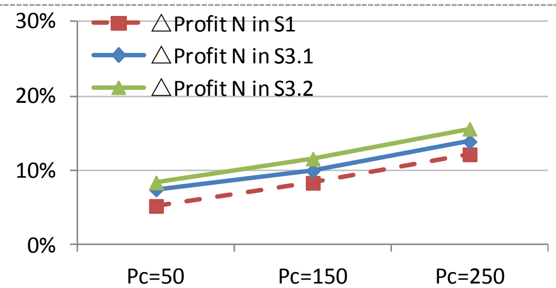

Figure 5c: Changes in Profits of *N*

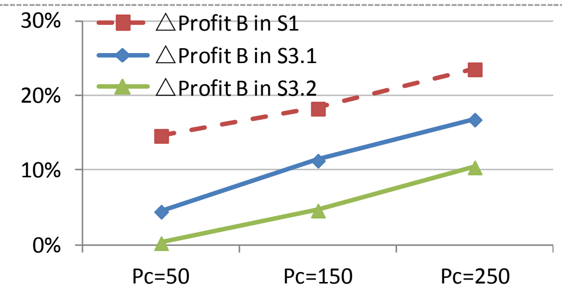

Figure 5d: Changes in Profits of *B*

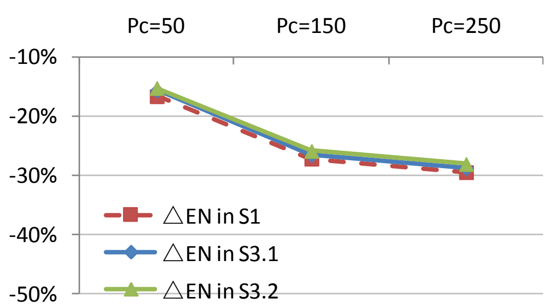

Figure 5e: Changes in Emissions of *N*

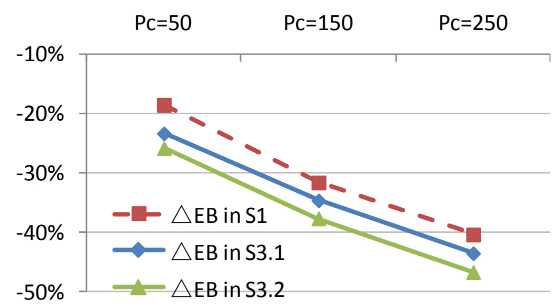

Figure 5f: Changes in Emissions of *B*

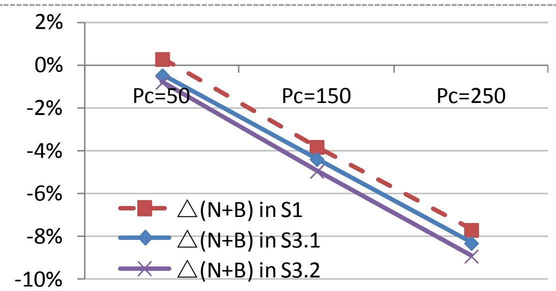

Figure 5g: Changes in Total Domestic Outputs

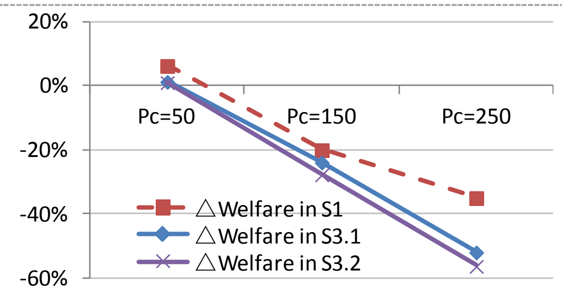

Figure 5h: Changes in Welfare

It can be seen that a higher electricity price than the price in S1 essentially increases the production cost for *B* and reduces its output, emissions, and profits. At the same time, *N* also experiences a slight increase in output, emissions, and profits. In particular, if the carbon price is low (50 Yuan/tCO_2) with a higher electricity price for *B*, the output distortion of *N* and *B* can be addressed. Given the situation of a higher carbon price level (higher than 100 Yuan/tCO_2), although the output from the outdated capacity could be reduced compared to the output in S1, the policy cannot generate enough incentives to increase the output from the normal capacity, resulting in more losses in total domestic output, as well as in welfare.

3.3.4 Results in Scenario 4: OBA

In S4, the OBA has been discussed. The calculation for feasible *ob* starts from P_C=50 Yuan/tCO_2. Given the two forms of feasible conditions defined in Section 2.5, S4.1 is the feasible condition in which the domestic total output change is equal to zero ($\triangle(N+B)=0$, *ob**) and S4.2 is the feasible condition that welfare change is equal to zero ($\triangle Wl=0$, *ob***). From the results summarized in Tables 3 and 4, we can see that either set $\triangle(N+B)=0$ or $\triangle Wl=0$, and the feasible conditions do not exist given that the carbon price is equal to 50 Yuan/tCO_2.

Table 3: Simulation Results in S4.1

Cap=90% of E_0 △(N+B)=0		P_C=50 Yuan/tCO_2 +ob*	P_C=100 Yuan/tCO_2 +ob*	P_C=150 Yuan/tCO_2 +ob*	P_C=200 Yuan/tCO_2 +ob*	P_C=250 Yuan/tCO_2 +ob*
Feasible ob* Rate (tCO2/t crude steel)		0	0.79	1.13	1.30	1.39
ob*/e^0_{N+B}		0%	43.99%	62.98%	71.98%	76.98%
ob*/e^0_N		0%	47.59%	68.14%	77.87%	83.28%
ob*/e^0_B		0%	37.39%	53.53%	61.18%	65.43%
Industrial Competitiveness	△N	0.10%	0.36%	0.77%	1.36%	1.87%
	△B	0.88%	-0.87%	-1.88%	-3.26%	-4.42%
	△(N+B)	0.34%	0.00%	0.00%	0.00%	0.00%
	△(N_x+B_x)	0.08%	0.00%	0.00%	0.00%	0.00%
	△P_D	-0.23%	0.00%	0.00%	0.00%	0.00%
Emission Control	ΔE_N	-16.54%	-20.65%	-25.01%	-25.05%	-25.16%
	ΔE_B	-18.46%	-23.34%	-26.65%	-29.30%	-30.59%
	ΔE	-17.24%	-21.60%	-25.58%	-26.54%	-27.06%
	ΔE_{con}	-16.74%	-20.99%	-24.86%	-25.80%	-26.31%
	Δ(E- E_{con})	-29.51%	-36.73%	-43.41%	-44.94%	-45.72%
Firms' Performance	Market Share of N	69.84%	70.26%	70.56%	70.97%	71.32%
	Market Share of B	30.16%	29.74%	29.44%	29.03%	28.68%
	Δ$Profit_N$	5.25%	2.19%	3.04%	4.24%	5.30%
	Δ$Profit_B$	14.73%	0.48%	-1.54%	-4.30%	-6.57%
Domestic Consumption and Welfare	Δ(N_d+B_d)	0.81%	0.00%	0.00%	0.00%	0.00%
	ΔF_m	-0.39%	0.00%	0.00%	0.00%	0.00%
	ΔWl	6.51%	4.58%	4.88%	5.42%	6.09%

Table 4: Simulation Results in S4.2

Cap=90% of E_0 ∆Wl=0		P_C=50 Yuan/tCO_2 +ob**	P_C=100 Yuan/tCO_2 +ob**	P_C=150 Yuan/tCO_2 +ob**	P_C=200 Yuan/tCO_2 +ob**	P_C=250 Yuan/tCO_2 +ob**
Feasible ob Rate (tCO2/t crude steel)**		0	0.47	0.92	1.12	1.22
ob**/e^0_{N+B}		0%	25.99%	50.98%	61.98%	67.98%
ob**/e^0_N		0%	28.12%	55.16%	67.05%	73.54%
ob**/e^0_B		0%	22.09%	43.33%	52.68%	57.78%
Industrial Competitiveness	△N	0.10%	-0.16%	0.26%	0.78%	1.23%
	△B	0.88%	-2.05%	-3.06%	-4.57%	-5.89%
	△(N+B)	0.34%	-0.73%	-0.74%	-0.82%	-0.91%
	△(N_x+B_x)	0.08%	-0.18%	-0.18%	-0.20%	-0.22%
	△P_D	-0.23%	0.51%	0.51%	0.57%	0.63%
Emission Control	∆E_N	-16.54%	-21.08%	-25.41%	-25.50%	-25.66%
	∆E_B	-18.46%	-24.31%	-27.59%	-30.32%	-31.73%
	∆E	-17.24%	-22.19%	-26.14%	-27.15%	-27.75%
	∆E_{con}	-16.74%	-21.57%	-25.41%	-26.40%	-26.98%
	∆(E- E_{con})	-29.51%	-37.56%	-44.22%	-45.83%	-46.73%
Firms' Performance	Market Share of N	69.84%	70.40%	70.70%	71.13%	71.51%
	Market Share of B	30.16%	29.60%	29.30%	28.87%	28.49%
	∆$Profit_N$	5.25%	1.15%	1.99%	3.07%	3.98%
	∆$Profit_B$	14.73%	-1.90%	-3.90%	-6.88%	-9.44%
Domestic Consumption and Welfare	∆(N_d+B_d)	0.81%	-0.77%	-0.78%	-0.87%	-0.96%
	∆F_m	-0.39%	0.85%	0.86%	0.96%	1.06%
	∆Wl	6.51%	0.00%	0.00%	0.00%	0.00%

Comparing ob/e0N and ob/e0B, the OBA can be viewed as a diversified refund mechanism, which can provide incentives to increase the production and profit in N while decreasing the production and profit in B. In Figure 6, with different levels of carbon prices, the changes in the profits of N and B and their corresponding changes in output in S1, S2, and S4 have been mapped. The distortion effect occurring in S1 and S2 can, to a great extent, be corrected under the ob* and ob** conditions.

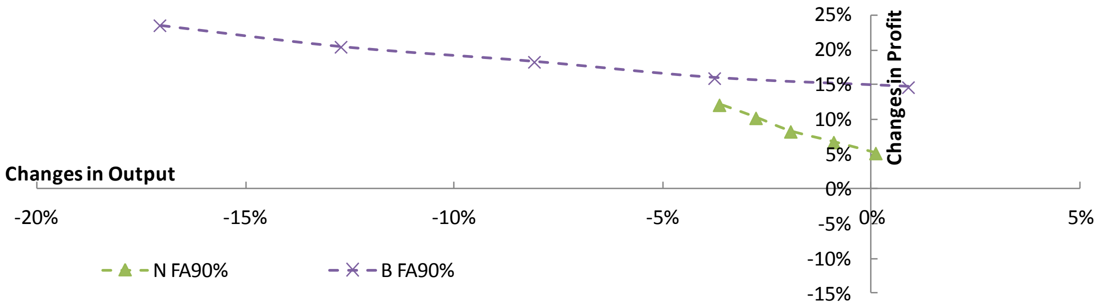

Figure 6a: Change in Profits of *N* and *B* with the Change in Carbon Price in S1

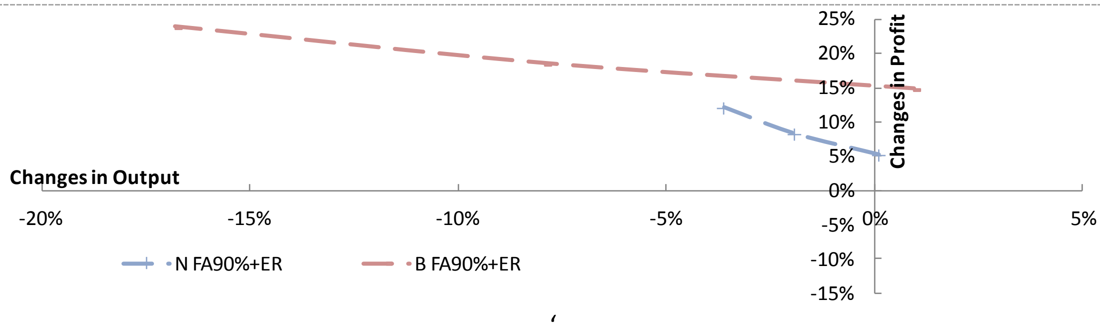

Figure 6b: Change in Profits of *N* and *B* with the Change in Carbon Price in S2

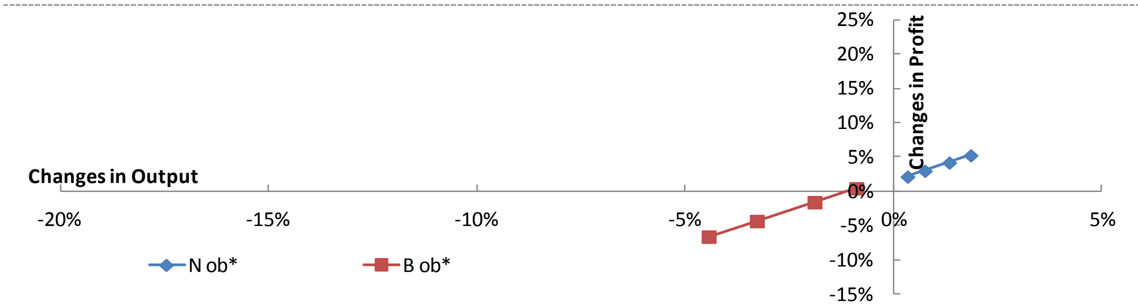

Figure 6c: Change in Profits of *N* and *B* with the Change in Carbon Price in S4.1 (△(N+B)=0)

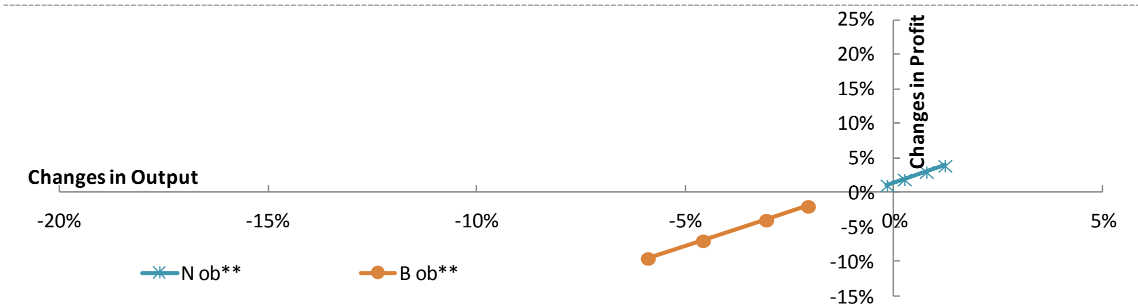

Figure 6d: Change in Profits of *N* and *B* with the Change in Carbon Price in S4.2 (△Wl=0)

In Figure 7a, with the increase in carbon prices, more rebates (increases in the level of *ob** and *ob***) need to be provided to keep the industry's output (social welfare) unchanged and at the same time promote the withdrawal of outdated capacity. In addition, in Figure 7b, by comparing the losses in welfare in terms of the per-unit emissions abated in S1, S2, and S4 (which equals $\triangle Wl/\triangle E$), it can even generate gains in welfare (with emission reduction in S4.1).

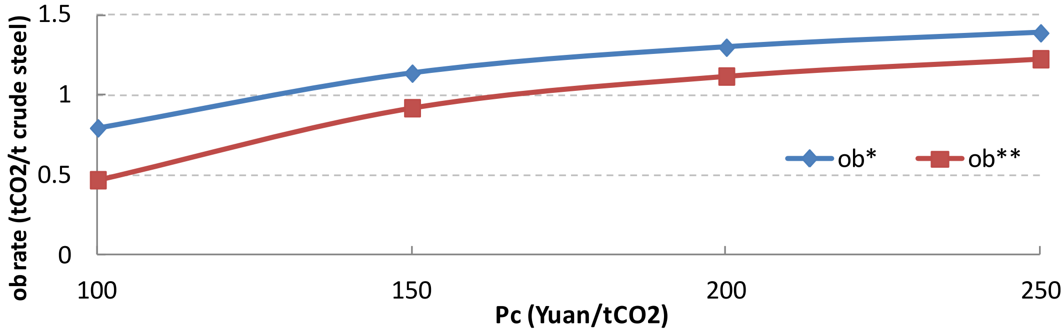

Figure 7a: Feasible ob Rate in S4

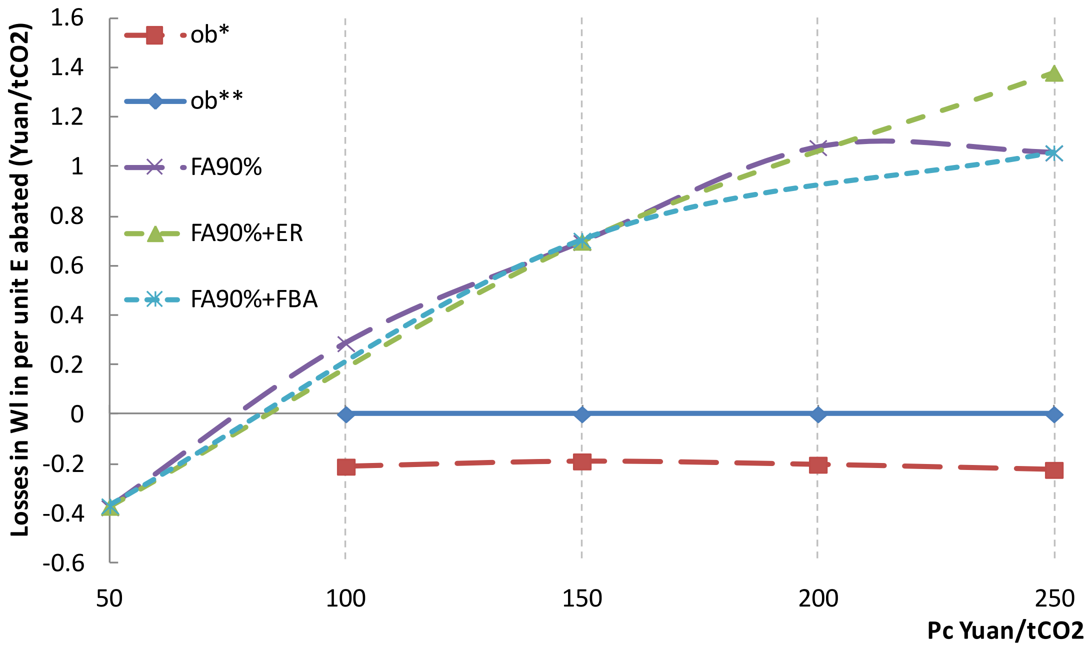

Figure 7b: Cross-Scenarios Comparison in Losses in Welfare Per Unit of Emission Abated

The changes of *ob** and *ob*** in the carbon price level have shown a trend of marginal decreases with the increase in the carbon price level, and the gap between *ob** and *ob*** has also been narrowed. With the feasible condition of ΔWl=0, the *ob* rate is lower than that in the condition of $\Delta(N+B)$=0, and the domestic total output will experience a slight decrease, in which $\Delta(N+B)$ is less than -1% with the carbon price change from 100 Yuan/tCO_2 to 250 Yuan/tCO_2. By defining these two forms of feasible conditions, a feasible *ob* range (between *ob** and *ob***) is proposed with the carbon price higher than 100 Yuan/tCO_2. Given the *ob* rate in this range, it can, to a great extent, maintain the competitiveness of the domestic iron and steel sector, avoid welfare loss, and effectively accelerate the withdrawal of outdated capacity from the market.

In addition, Meunier et al. (2014) calculated the value of the optimal OBA in the EU cement sector. In their study, given the price of carbon as 20 Euro/tCO_2, the OBA* accounts for 37.08% of the benchmark for EU free allocation (which is calculated on the basis of the average specific emissions of the 10% most CO_2-efficient clinker kilns in the EU). For *ob** and *ob*** calculated in our model, given P_C=100 Yuan/tCO_2, the feasible *ob* range is from 25.99% to 43.99% (calculated by ob/e^0_{N+B}), or 28.12% to 47.59% (calculated by ob/e^0_N). OBA* just about falls into the feasible *ob* range proposed in our paper. Although there is a difference in the modeling approaches used in specific sectors, our results are in accordance with those of Meunier et al. (2014).

4. Sensitivity Analysis

Among all the parameters used in this paper, the electricity price pass-through rate (PP) and the abatement potential of the outdated capacity (AP) have been chosen for the sensitivity analysis. They are also the most critical parameters in our analysis. The sensitivity analysis is conducted for the calculation of 90%FA with a carbon price of 50 Yuan/tCO2 in S1. The results are presented in Figure 8. Following the comparison in S2, we compare the changes of the indexes directly to S1.

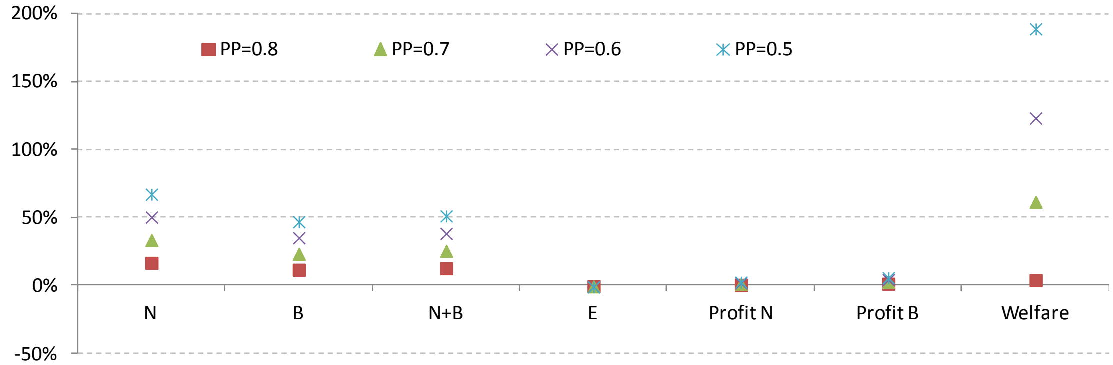

Figure 8a: Sensitivity Analysis of Electricity Price Pass-through Rate Compared with that in S1

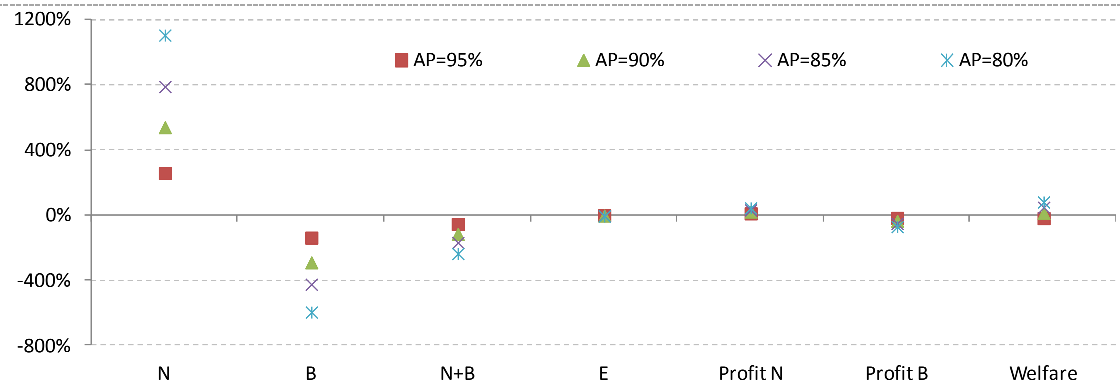

Figure 8b: Sensitivity Analysis of the Abatement Potential of *B* (as a percentage of that of *N*) Compared with that in S1

In our simulation, the electricity price pass-through rate, δ_{Elec}, is set as 0.9, which implies that the domestic electricity market is market-based. Considering the strictly regulated electricity price set by the Chinese government, we gradually reduce the price pass-through rate from 0.9 to 0.5. In Figure 8a, with a lower electricity price pass-through rate, fewer upstream emission costs are passed to the iron and steel sector, and an extensive increase in domestic output (both *N* and *B*) occurs, as well as an increase in welfare. The profits of *N* and *B* also increase, and the magnitude of the profit increase in *B* is larger than that in *N*. Although the decrease in the electricity price pass-through rate would affect the calculation results for domestic production, it will not change the competitiveness distortion in S1.

Another critical concern is the abatement potential of outdated capacity (AP). With the technology-based MAC adopted in our model, for each single technology, we assume that its abatement potential is the same for normal and outdated capacities (the difference is the number of technologies in the sets *N* and *B*). It should be noted that, given the lower productivity level in the outdated capacity, even with the adoption of the same technology, the abatement potential in the outdated capacity may not match that in the normal capacity. Therefore, we gradually reduce the emission reduction potential of the technologies (r_j) in set *B* to a certain percentage of that of set *N* (from 95% to 80%). In Figure 8b, with less emission abatement potential for *B*, its output is reduced to a large extent, while the output in *N* experiences a large increase. It seems that the competitiveness distortion does not appear in S1, given the possibility that the emission abatement potential is limited for the outdated capacity. Actually, the distortion effect still exists in the profits of *N* and *B*. With the decrease of emission abatement potential in *B*, although the profits show a decreasing trend compared to S1, the value of profits is still positive. Furthermore, we only discussed the possibility of less emission abatement potential for the outdated capacity, and it can be inferred that such a distortion effect will be even worse if there is a possibility that the emission abatement potential of *B* is larger than that of *N*.

5. Conclusions

This paper provides an analytical framework to study the impact of an Emissions Trading Scheme (ETS) on the withdrawal of outdated capacity in the energy-intensive sectors of developing countries. The production from normal and outdated capacity is separately modeled in a two-country, three-good partial equilibrium model, and the energy-saving benefits generated from the abatement technology adoption are captured by using micro-level MAC curves. Furthermore, the price pass-through effects from the iron and steel sector's up and down streams are also taken into account.

Based on the results of case studies performed in China's iron and steel sector, the free allocation of allowances can cause an increase in the profit of outdated capacity. In fact, both output and production will increase under a carbon price level of 50 yuan/tCO_2. Such a competitiveness distortion can be corrected by the adoption of an output-based allocation among the normal and outdated capacities, with the feasible range of the OBA rate determined in our numerical simulations. Given the government's intention to promote the withdrawal of outdated capacity and the upgrading of the technological level of production, an OBA approach is strongly suggested for energy-intensive sectors.

We discussed whether the competitiveness distortion among normal and outdated capacities caused by the free allocation of allowance can be corrected with supplementary measures. One viable option will not be a border carbon adjustment, but rather a differential electricity pricing mechanism. Given that the emission intensity is higher than that of developed countries, export rebates or full border adjustments would only exacerbate the competitiveness distortion in output and profit between *N* and *B*. Compared with OBA, although the free allocation of allowances plus the differential electricity pricing mechanism can reduce the output and profit of outdated capacity, it cannot generate enough incentives to increase the output from normal capacity, in which case the result will be losses in total domestic output.

Our model can be applied to other energy-intensive sectors with the same features as those in China's iron and steel sector if the micro-level MAC curve can be obtained (e.g., the cement or chemistry sector in China). It should be noted that the technology-based MACs adopted here are not able to fully reflect the actual relationship between normal and outdated capacity. Given the controversies about the abatement potential in firms with normal and outdated capacities, a substantial on-site investigation among different enterprises needs to be conducted to derive more accurate, technology-based MACs.

The analytical framework proposed in this paper can also be extended to multiple sectors (e.g., by including several energy-intensive sectors). The most critical part of the multi-sector extension is how to address the interlinkage among the different sectors. The sectoral price multiplier matrix adopted here can only provide an approximate measure of the effects of change in output prices on downstream sectors. One can argue that the macro-level MAC has already taken such effects into account, but its adoption may result in a double accounting issue related to the output/price adjustment and pass-through effects inside and across sectors. A rigorous treatment of this issue lies beyond the reach of this paper.

Finally, in this paper, we did not address the issue of carbon leakage. This is because our simulation shows that the implementation of ETS can result in a negative carbon leakage rate in China's iron and steel industry. The evidence is based on the calculation of the net carbon-embodied export in S1 and S4, because most of China's imports of iron and steel products are from the EU and the US, which have lower emission intensity per unit of output; an increase in imports would indeed reduce net carbon-embodied exports in the domestic sector. Another situation that may occur but is not discussed in the paper is that the implementation of the ETS may also cause domestic firms (especially small and medium-sized firms with outdated capacities) to move their plants to other developing countries close to China, and then export the product to the domestic market, which would obviously cause leakage. A better understanding of such a mixed effect of leakage would be helpful in designing better regulatory policies for developing countries. However, the limitations of our model in describing the foreign market have prevented us from further investigating this point. This is one direction for future study.

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Appendix

Appendix A1: Model Solving

A1.1 Solution to Free Allocation + Auction

With the demand functions for N_d, N_x, B_d, and B_x (Equations (1), (2), and (3)), we have:

$$\begin{cases} \dfrac{\partial N_x}{\partial P_D} = \alpha_N \cdot \eta_{xx} P_D^{\eta_{xx}-1} P_F^{\eta_{xw}}, & \dfrac{\partial P_D}{\partial N_d} = -\beta \\ \dfrac{\partial B_x}{\partial P_D} = \alpha_B \cdot \eta_{xx} P_D^{\eta_{xx}-1} P_F^{\eta_{xw}}, & \dfrac{\partial P_D}{\partial B_d} = -\beta \end{cases} \quad \text{(A1.1)}$$

The first-order conditions of profit maximization for N and B (Equations (9) and (10)) can become:

$$\begin{bmatrix} \alpha - \beta(N_d + B_d) - c_N - P_C(e_N^0 - r_N) - \\ \beta \cdot N_d - \beta \cdot \alpha_N \left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}} P_F^{\eta_{xw}} \\ +\alpha_N \cdot \eta_{xx} \left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}-1} P_F^{\eta_{xw}} \cdot (-\beta) \begin{pmatrix} \alpha - \beta(N_d + B_d) \\ -c_N - P_C(e_N^0 - r_N) \end{pmatrix} \end{bmatrix} = 0 \quad \text{(A1.2)}$$

$$\begin{bmatrix} \alpha - \beta(N_d + B_d) - c_B - P_C(e_B^0 - r_B) \\ -\beta \cdot B_d - \beta \cdot \alpha_B \left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}} P_F^{\eta_{xw}} \\ +\alpha_B \cdot \eta_{xx} \left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}-1} P_F^{\eta_{xw}} \cdot (-\beta) \begin{pmatrix} \alpha - \beta(N_d + B_d) \\ -c_B - P_C(e_B^0 - r_B) \end{pmatrix} \end{bmatrix} = 0 \quad \text{(A1.3)}$$

For Equation (A1.2), here define: $\overline{A} = \alpha - c_N - P_C(e_N^0 - r_N)$, $\overline{B} = \beta \cdot \alpha_N P_F^{\eta_{xw}} + \alpha_N \cdot \eta_{xx} \beta P_F^{\eta_{xw}}$, and $\overline{C} = \alpha_N \cdot \eta_{xx} \beta P_F^{\eta_{xw}} (c_N + P_C(e_N^0 - r_N))$, hence Equation (A1.2) becomes:

$$\overline{A} - \beta B_d - 2\beta \cdot N_d - \overline{B}\left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}} + \overline{C}\left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}-1} = 0 \quad \text{(A1.4)}$$

Then by denoting: $\alpha - \beta(N_d + B_d) = x$, $\beta N_d = y$, $\beta B_d = \alpha - x - y$ and letting $\overline{D} = \overline{A} - \alpha$, we can obtain:

$$x - y - \overline{B}x^{\eta_{xx}} + \overline{C}x^{\eta_{xx}-1} + \overline{D} = 0 \quad \text{(A1.5)}$$

Similarly, for Equation (A1.3), define the following variable: $A = \alpha - c_B - P_C(e_B^0 - r_B)$, $B = (\beta \cdot \alpha_B P_F^{\eta_{xw}} + \beta\alpha_B \cdot \eta_{xx} P_F^{\eta_{xw}})$, and $C = \beta\alpha_B \cdot \eta_{xx} P_F^{\eta_{xw}}(c_B + P_C(e_B^0 - r_B))$, we can obtain:

$$A - \beta N_d - 2\beta \cdot B_d - B\left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}} + C\left(\alpha - \beta(N_d + B_d)\right)^{\eta_{xx}-1} = 0 \qquad \text{(A1.6)}$$

Considering the substitution that: $\alpha - \beta(N_d + B_d) = x$, $\beta N_d = y$, $\beta B_d = \alpha - x - y$, and letting $D = A - 2\alpha$, we have:

$$2x + y - Bx^{\eta_{xx}} + Cx^{\eta_{xx}-1} + D = 0 \qquad \text{(A1.7)}$$

Thus, by solving the equation system (A1.5 and A 1.7) simultaneously, and by defining $b = B + \bar{B}$, $c = C + \bar{C}$, and $d = D + \bar{D}$, we have:

$$3x - bx^{\eta_{xx}} + cx^{\eta_{xx}-1} + d = 0 \qquad \text{(A1.8)}$$

x can be numerically determined by solving a nonlinear equation in Matlab with the parameter values given. The same approach can be adapted to the calculation of other policy shocks in FA + BCA and FA + Differential Electricity Price, as well as in the determination of a feasible OBA rate.

A1.2 Proof of the Existence of a Unique Solution

For x in Equation (A1.8), we will prove that Equation (A1.8) has one and only one root in the interval $(0, \infty)$.

Consider the following function:

$$f(x) = bx^{\eta} - cx^{\eta-1} - 3x - d = 0 \qquad \text{(A1.9)}$$

According to the value of the parameters presented in Section 3, it can be inferred that: $b > 0$, and $c, d, \eta_{xx} < 0$. Taking the derivatives of the function, we have:

$$\begin{cases} f'(x) = b\eta_{xx}x^{\eta-1} - c(\eta_{xx} - 1)x^{\eta-2} - 3 \\ f''(x) = (\eta_{xx} - 1) \cdot b\eta_{xx} \cdot x^{\eta_{xx}-3}\left(x - \dfrac{c(\eta_{xx} - 2)}{b\eta_{xx}}\right) \end{cases} \qquad \text{(A1.10)}$$

Hence, the $f''(x)$ has root $x = \dfrac{c(\eta_{xx} - 2)}{b\eta_{xx}} < 0$ and $x = 0$, and $f''(x) > 0$ on $(0, \infty)$. Then, we consider $\lim_{x \to 0} f'(x)$ and $\lim_{x \to \infty} f'(x)$:

$$\begin{cases} \lim_{x\to\infty} f'(x) = \lim_{x\to\infty}(b\eta_{xx}x^{\eta_{xx}-1} - c(\eta_{xx}-1)x^{\eta_{xx}-2} - 3) = -3 \\ \lim_{x\to 0} f'(x) = \lim_{x\to 0} x^{\eta_{xx}-2}(b\eta_{xx}x - c(\eta_{xx}-1)) - 3 = -\infty \end{cases} \tag{A1.11}$$

Namely, $f'(x)$ is increasing from $-\infty$ to -3 on $(0,\infty)$. So $f'(x) < 0$, always on $(0,\infty)$.

Then, considering $f(x)$ on $(0,\infty)$, with $\eta_{xx} < 0$, and $c < 0$, we have:

$$\begin{cases} \lim_{x\to\infty} f(x) = \lim_{x\to\infty}(bx^{\eta_{xx}} - cx^{\eta_{xx}-1} - 3x - d) = -\infty \\ \lim_{x\to 0} f(x) = \lim_{x\to 0}(x^{\eta_{xx}-1}(bx - c) - 3x - d) = +\infty \end{cases} \tag{A1.12}$$

Hence, $f(x)$ has one and only one root in the interval $(0,\infty)$.

A1.3 Determination of Feasible OBA Rate

The determination of ob^* and ob^{**} is as follows:

1) Given an explicit formulation for $U(N_d, B_d)$ and $U(F_m)$ as:

$$\begin{cases} U(N_d, B_d, F_m) = \alpha \cdot (N_d + B_d) - \tfrac{1}{2} \cdot \beta \cdot (N_d + B_d)^2 \\ P_F \cdot F_m \end{cases} \tag{A1.13}$$

2) With the first order conditions of π_N and π_B in Section 2.4.4, change ob from 0 to $\left(N_0 \cdot e_N^0 + B_0 \cdot e_B^0\right) / \left(N_0 + B_0\right)$. Let $ob(i) = i \cdot \frac{\left(N_0 \cdot e_N^0 + B_0 \cdot e_B^0\right)/\left(N_0 + B_0\right)}{n}$, $i = 1, 2, ..., n$, and $n = 1000$.

3) Based on the solution method proposed in Appendix 1.1, taking $ob(i)$ into the model and calculating the results from $i = 1, 2, ..., n$.

4) With Feasible Condition 1 ($\Delta Wl = 0$), searching the calculation results to find the $ob(i)$ which satisfy that $\min\left(wl_i / wl_0 - 1\right)^2$, here $ob(i) = ob^{**}$.

5) With Feasible Condition 2 ($\Delta(N + B) = 0$), searching the calculation results to find the $ob(i)$ which satisfy that $\min\left(\left(N_i + B_i\right)/\left(N_0 + B_0\right) - 1\right)^2$, here $ob(i) = ob^*$.

Appendix A2: Model Parameters (From Actual Data)

Parameters	**Value**
Domestic consumption of production $N_{d0}+B_{d0}$	547.83 Mt crude steel
Foreign price P_{F0}	8202.85 Yuan/t crude steel
Electricity price P_{Elec}	0.85 Yuan/kWh
Fuel price P_{Fuel}	900 Yuan/t coking coal
Average electricity consumption in per unit output Ec_{Elec0}	10.44 kWh/t crude steel
Average fuel consumption in per unit output Ec_{Fuel0}	8.20 GJ/t crude steel
Fuel calorific value	28.44 GJ/t coking coal
Average emission intensity in per unit output e_{N+B}^{0}	1.80 tCO_2/t crude steel
Elec Emission Factor e_{Elec}	0.0008 tCO_2/kWh
Fuel Emission Factor e_{Fuel}	0.0050 tCO_2/t coking coal
Electricity price pass-through rate δ_{Elec}	0.9
Fuel price pass-through rate δ_{Fuel}	0.9
Carbon price P_C	50 Yuan/tCO_2
Free allocation FA	90% of E_0

Note: 1) The production, consumption, and price data were mainly taken from China Statistical Yearbook 2010 (NBS 2011) and Steel Statistical Yearbook 2011 (WSA 2011);

2) Coking coal was used as the representative fuel consumption in China's iron and steel sector. The average energy consumption per unit of output, energy prices, and emission factors data were taken from the Annual Report of Electricity Regulation (SERC 2011), China Energy Statistical Yearbook 2011 (NBS 2011), and Li and Zhu (2014);

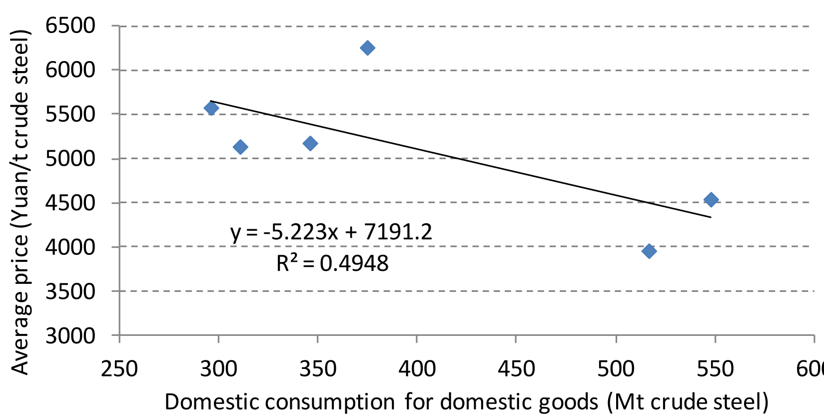
3) To guarantee the accuracy of the calculation, domestic consumption, export and import, and total domestic emission are calculated based on the estimated parameters in Appendix A3, instead of applying the real ones.

Appendix A3: Model Parameters (Estimated Data)

Parameters	Value
α for N_d+B_d	7191.2
β for N_d+B_d	5.223
α_{N+B} for export	8.03E-7
α_{N0} for N_x	5.62E-07
α_{B0} for B_x	2.41E-07
α_m for F_m	64242.40
Own-price elasticity η_{xx} for P_D in export	-0.3547
Cross-price elasticity η_{xw} for P_F in export	2.2923
Own-price elasticity η_{mm} for P_F in import	-2.4526
Cross-price elasticity η_{md} for P_D in import	1.6703

Note: 1) The function of domestic demand for domestic production is estimated based on the historical domestic consumption and average prices from 2005-2010. The estimation result is shown in Figure A3-1. The estimated values of α and β also show a 'weak' demand situation in the domestic iron and steel industry.

Figure A3-1: Estimation Result for Domestic Demand Curve



2) The export and import functions are estimated based on the historical imports and exports and on average import prices from 2005-2010. Here it should be pointed out that, as in our model, P_D is also adopted as the export price, so the export price series are taken from the average domestic price from 2005-2010; they are not the actual average export prices. The estimation results are shown in Table A3-1.

Table A3-1 Estimation Results for Export and Import Functions

	η_{xw}	η_{xx}	$\ln(\alpha_{N+B})$	η_{md}	η_{mm}	$\ln(\alpha_m)$
Value	2.2923	-0.3547	-14.0350	1.6703	-2.4526	11.0704
Standard error	0.8577	0.9812	6.8868	0.9484	1.0621	4.4578
R^2	0.7184			0.6568		
F statistics	5.1015			2.8706		

3) The price data applied in the estimation have been adjusted to the base year 2010 by excluding the consumer price index (CPI) and exchange rate effects.

Appendix A4: Model Parameters (Calibrated Data)

Parameters	**Value**
Domestic production $N_0 + B_0$	586.45 Mt crude steel
Export $N_{x0} + B_{x0}$	38.62 Mt crude steel
Import F_{m0}	19.15 Mt crude steel
Domestic price P_{D0}	4329.88 Yuan/t crude steel
Initial emissions E_0	1055.35 $MtCO_2$
Production of N_0	409.01 Mt crude steel
Production of B_0	175.29 Mt crude steel
Domestic consumption N_{d0}	382.50 Mt crude steel
Domestic consumption B_{d0}	163.93 Mt crude steel
Export N_{m0}	26.51 Mt crude steel
Export B_{m0}	11.36 Mt crude steel
Per unit production cost c_{N0}	2374.07 Yuan/t crude steel
Per unit production cost c_{B0}	3543.23 Yuan/t crude steel
Per unit production cost exclude energy cost $c_{NOther0}$	1589.38 Yuan/t crude steel
Per unit production cost exclude energy cost $c_{BOther0}$	2544.45 Yuan/t crude steel
Emission intensity in per unit output of *N* e_N^0	1.66 tCO_2/t crude steel
Emission intensity in per unit output of *B* e_B^0	2.12 tCO_2/t crude steel
Electricity consumption in per unit output of *N* Ec_{NElec0}	617.77 kWh/t crude steel
Electricity consumption in per unit output of *B* Ec_{BElec0}	786.33 kWh/t crude steel
Fuel consumption in per unit output of *N* Ec_{NFuel0}	8.20 GJ/t crude steel
Fuel consumption in per unit output of *B* Ec_{BFuel0}	10.44 GJ/t crude steel
Abatement technology set of *N* St_N	24 energy saving technologies
Abatement technology set of *B* St_B	35 energy saving technologies

Note: 1) The domestic price P_{D0} is calculated by the domestic demand function (Equation (1)) with estimated parameters in Appendix A3. With P_{D0}, the export ($N_{x0} + B_{x0}$) and import (F_{m0}) can be calculated by Equations (2) and (3) with the estimated parameters in Appendix A3. Then the total domestic production ($N_0 + B_0$), as well as the emissions caused by the production ($E_0 = e_{N+B}^0 \cdot (N_0 + B_0)$), can be derived. Using calibrated data instead of the actual values ensures an initial equilibrium status of our model. Table A4-1 shows the results with the calibrated parameters compared to the actual values.

Table A4-1 Comparison of Calibrated and Actual Values

	Calibrated Value	Actual Value (2010)	Standard Errors
$N_0 + B_0$	586.45 Mt crude steel	592.24 Mt crude steel	0.69%
$N_{x0} + B_{x0}$	38.62 Mt crude steel	44.41 Mt crude steel	9.88%
F_{m0}	19.15 Mt crude steel	17.07 Mt crude steel	8.13%
P_{D0}	4329.88 Yuan/t crude steel	4172.00 Yuan/t crude steel	2.63%
E_0	1055.35 $MtCO_2$	1061.86 $MtCO_2$	0.69%

2) In order to distinguish normal and outdated production, a series of calibrations have been done to clearly separate N and B. Referring to Jiang (2013), the share of domestic iron and steel products produced by the outdated capacity was 25% in 2005. Given that the government tends to speed up industrial upgrading and to control overcapacity, the standards used for distinguishing the normal and outdated capacities will increase over time. So the shares of N_{d0} and B_{d0} are set as 70% to 30%. Such shares are also applied to the export of N and B. Therefore, with the estimated scale parameter α_{N+B} for the total export demand in Appendix A3, we have $\alpha_N = \alpha_{N+B} \cdot 0.7$, and $\alpha_B = \alpha_{N+B} \cdot 0.3$.

3) Given E_0 as known (calculated in Appendix A4), e_N^0 and e_B^0 can be determined by solving the equation: $N_0 \cdot e_N^0 + B_0 \cdot e_B^0 = E_0$, in which, $0 < e_N^0 < e_{N+B}^0$, and $e_B^0 > e_{N+B}^0$. With e_N^0 and e_B^0, assuming that the diversity in per-unit output emission results from energy consumption, we have $Ec_{NElec0} = Ec_{Elec0} \cdot \frac{2 \cdot e_N^0}{e_N^0 + e_B^0}$, $Ec_{BElec0} = Ec_{Elec0} \cdot \frac{2 \cdot e_B^0}{e_N^0 + e_B^0}$, $Ec_{NFuel0} = Ec_{Fuel0} \cdot \frac{2 \cdot e_N^0}{e_N^0 + e_B^0}$, and $Ec_{BFuel0} = Ec_{Fuel0} \cdot \frac{2 \cdot e_B^0}{e_N^0 + e_B^0}$, respectively;

4) There is a lack of data on detailed production costs for c_{N0} and c_{B0}. They are estimated given the initial equilibrium without ETS implementation. In this case, the first order condition for N and B can be expressed as:

$$\begin{cases} \dfrac{\partial \pi_N}{\partial N_d} = \left[P_D + \dfrac{\partial P_D}{\partial N_d} \cdot N_d + P_D \cdot \dfrac{\partial N_x}{\partial P_D} \cdot \dfrac{\partial P_D}{\partial N_d} + \dfrac{\partial P_D}{\partial N_d} \cdot N_x - c_N - c_N \cdot \dfrac{\partial N_x}{\partial P_D} \cdot \dfrac{\partial P_D}{\partial N_d} \right] = 0 \\ \dfrac{\partial \pi_B}{\partial B_d} = \left[P_D + \dfrac{\partial P_D}{\partial B_d} \cdot B_d + P_D \cdot \dfrac{\partial B_x}{\partial P_D} \cdot \dfrac{\partial P_D}{\partial B_d} + \dfrac{\partial P_D}{\partial B_d} \cdot B_x - c_B - c_B \cdot \dfrac{\partial B_x}{\partial P_D} \cdot \dfrac{\partial P_D}{\partial B_d} \right] = 0 \end{cases}$$

Then we have:

$$c_{N0} = \left(P_{D0} + \frac{\partial P_D}{\partial N_d} \cdot N_{d0} + P_{D0} \cdot \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} + \frac{\partial P_D}{\partial N_d} \cdot N_{x0} \right) \Big/ \left(1 + \frac{\partial N_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial N_d} \right)$$

$$c_{B0} = \left(P_{D0} + \frac{\partial P_D}{\partial B_d} \cdot B_{d0} + P_{D0} \cdot \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} + \frac{\partial P_D}{\partial B_d} \cdot B_{x0} \right) \Big/ \left(1 + \frac{\partial B_x}{\partial P_D} \cdot \frac{\partial P_D}{\partial B_d} \right)$$

Given Equations (1) and (3) in Section 2.1, as well as the parameters in Appendix A2, A3, and A4, c_{N0} and c_{B0} can be calculated. Their values also satisfy the initial equilibrium status. Then, c_{NOther} and c_{BOther} can be calculated by removing the energy costs in c_{N0} and c_{B0}, respectively.

Appendix A5: Technology-Based MAC Curve

No.	Energy Saving Technology Options	Fuel Savings (GJ/t)	Electricity Savings (kWh/t)	CO_2 Emission Reductions (tCO_2/t)	Technology Abatement Cost (Yuan/tCO_2)	Share of Adoption	Sets of *N* and *B*
1	Oxy-fuel burners	0.00	41.71	0.0327	2.87	50%	N & B
2	Direct current arc furnaces	0.00	88.99	0.0697	44.36	10%	N & B
3	UHP transformer	0.00	58.40	0.0457	250.63	40%	N & B
4	Automated monitoring and targeting system	0.00	33.37	0.0261	269.33	50%	N & B
5	Cogeneration	0.03	83.43	0.0685	280.98	90%	B
6	Eccentric bottom tapping	0.00	25.03	0.0196	341.20	30%	N & B
7	Energy monitoring and management	0.32	2.78	0.0364	45.51	90%	B
8	Blast furnace control	0.36	0.00	0.0385	92.73	30%	N & B
9	Recuperative burners	0.46	0.00	0.0493	101.83	90%	B
10	Preventative maintenance	0.43	5.56	0.0504	189.44	90%	B
11	Recuperator on the hot blast stove	0.30	0.00	0.0321	162.18	50%	N & B
12	Flue gas waste heat recovery	0.72	0.00	0.0771	162.65	10%	B
13	TRT(dry type)	0.00	25.03	0.0196	1023.59	58%	B
14	Process control in hot strip mill	0.26	0.00	0.0278	244.78	80%	B
15	Twin shell DC arc furnaces	0.00	35.04	0.0274	1103.71	10%	N & B
16	Waste plastic injected into blast furnace	0.11	0.00	0.0118	284.46	3%	N & B

17	Improved process control	0.01	0.00	0.0011	312.28	90%	B
18	Pulverized coal injection	0.62	0.00	0.0664	333.03	60%	B
19	Thin slab casting	1.18	25.03	0.1460	515.98	5%	N & B
20	Hot furnace systematic energy saving	0.49	0.00	0.0525	424.89	5%	N & B
21	Recovery of blast furnace gas	0.06	0.00	0.0064	469.46	80%	B
22	CCPP	0.51	0.00	0.0546	587.82	10%	N & B
23	Continuous annealing	0.38	0.00	0.0407	913.01	5%	N & B
24	Generating of sinter waste heat	0.04	0.00	0.0043	949.34	20%	N & B
25	Heat recovery of BOF gas	0.50	0.00	0.0535	1040.96	10%	N & B
26	Heat recovery on annealing line	0.11	2.78	0.0140	1240.85	50%	N & B
27	Flue gas monitoring and control	0.00	13.90	0.0109	2052.50	50%	N & B
28	Hot rolling Hot charging	0.19	0.00	0.0203	1287.23	50%	N & B
29	Reduced steam use(picking line)	0.11	0.00	0.0118	1527.34	50%	N & B
30	Coke dry quenching	0.36	0.00	0.0385	1609.92	50%	N & B
31	LT-PR of converter gas	0.00	5.56	0.0044	2842.56	20%	N & B
32	Foamy slag practices	0.00	19.47	0.0152	3384.30	30%	N & B
33	Waste heat recovery	0.03	0.00	0.0032	3060.48	80%	B
34	Insulation of furnaces	0.14	0.00	0.0150	6507.28	50%	N & B
35	Coal moisture control	0.06	0.00	0.0064	7971.44	15%	N & B

Note: 1) The technologies described here are based mainly on the work done by Li and Zhu (2014);

2) The technology data are collected mainly from the Ministry of Industry and Information Technology (MIIT 2010a; 2010b; 2010c; 2010d) and Ministry of Science and Technology (MOST 2014), as well as other studies which focus on the techno-economic analysis of given technology adoption in domestic iron and steel enterprises (Zhang et al. 2006; Zhao and Cui 2007; Liu et al. 2007; Tian 2007; Zhang 2007; Chen and Liu 2008; Li et al. 2009; Wang and Wang 2009; Zhang and Zhang 2009; Xiao et al. 2010; Liu et al. 2010; Jiang et al. 2011; Liu and Tong 2011; An 2012; Zhang et al. 2013);

3) We lack cost data on domestic adoption of some technologies (e.g., blast furnace control, UHP transformer, Oxy-fuel burners). We estimate cost data based on Worrell et al. (2001). The value of such costs are converted from US dollars (USD) to Chinese Yuan and adjusted to the base year (2010) in our study;

4) Because it is difficult to find the exact share for each technology, the technology shares are calibrated based on several sources in the literature, as well as expert information. For some critical technologies, their shares are given as follows: (1) Coke dry quenching (CDQ). According to MIIT (2010c), in the iron and steel sector, the share of CDQ adoption in domestic large and medium-sized enterprises was 56.7% in 2008. With consideration of a large number of small enterprises, the technology share is set at 50%. (2) Recovery of blast furnace gas. According to an expert investigation by the Beijing Shougang Group, this technology has been adopted by almost all large and medium enterprises, so the technology share is set at 80%. (3) Energy monitoring and management. Referring to Jiang et.al (2011), almost all the large and medium-sized enterprises, as well as some small enterprises, have adopted the energy monitoring and management system, so the technology share is set at 90%. (4) Waste plastic injected into blast furnace. Based on Zhao and Cui (2007), the authors state that ‘as the use of waste plastic increases in China, a small number of enterprises use it in blast furnaces’, so the technology share is set at 3%.

Appendix A6: The Calculation of the Price Multiplier Matrix

Based on the SAM table drawn up from China’s Input-Output table in 2007, the sector of metal smelting and rolling processing has been taken to represent the Iron and Steel Industry. Then, the upstream and downstream sectors of this sector can be distinguished, and the forward and backward correlation and decomposed price multiplier can be calculated.

Given an average propensity of expenditure matrix:

$$A = \left[a_{ij} \right] = \left[x_{ij} / x_j \right] \qquad \text{(A6.1)}$$

in which a_{ij} is the transfer payments of units of the total expenditures account for endogenous account j from endogenous account i. At the same time, a_{ij} is an average propensity of expenditure coefficient, which reflects the effect of sector i on sector j.

$M = Pm_{ij}$ represents the price multiplier matrix, with Pm_{ij} representing the case when the product price of account i changes, and the ratio of change of the product price of account j. In this paper, account i is metal smelting and rolling processing industry.

We assume that exogenous shocks resulted in change Δv of costs in the metal smelting and rolling processing industry, and also caused change Δp of the product price of other sectors. We can get the balance equation:

$$\sum_{i=1}^{n} P_i \times a_{ij} + v_j = P_j \tag{A6.2}$$

$$\Delta P = \Delta V \times M \tag{A6.3}$$

Based on the definition of the price multiplier matrix, we get:

$$M = (1 - A)^{-1} \tag{A6.4}$$

The price multiplier from sector i to sector j is:

$$Pm_{ij} = \Delta_{ji} / \left| I - A \right| \tag{A6.5}$$

Δ_{ji} represents the co-factor when striking out line i and row j. For more details on these methods of calculation, see Valadkhani et al. (2002), Dietzenbacher et al. (2005), and Wu et al. (2012). The calculation results are shown in Table A6.1.

Table A6.1: Price Multiplier Matrix

From: Metal Smelting and Rolling Processing	Value of Price Multiplier	From: Metal Smelting and Rolling Processing	Value of Price Multiplier
Manufacture of Metal Products	**0.7420**	Composite Technical service	0.1127
Manufacture of Electrical Machinery and Apparatus	**0.6616**	Health, Social Security and Other Services	0.1116
Manufacture of General and Special Purpose Machinery	**0.5745**	Transport and Storage	0.1022
Manufacture of Transport Equipment	**0.4541**	Services to Households and Other Services	0.1022
Construction	**0.4005**	Management of Water Conservation, Environment and Public Facilities	0.0987
Manufacture of Artwork and Other Manufacturing	0.2839	Post	0.0979
Manufacture of Measuring Instruments and Machinery for Cultural Activity and Office Work	0.2654	Information Transmission, Computer Services and Software	0.0948
Manufacture of Communication Equipment, Computers and Other Electronic Equipment	0.2474	Production and Distribution of Water	0.0943
Mining and Washing of Coal	0.2016	Manufacture of Textiles	0.0759
Extraction of Petroleum and Natural Gas	0.1708	Manufacture of Textile Wearing Apparel, Footware, Caps, Leather, Fur, Feather and Related Products	0.0726
Manufacture of Non-metallic Mineral Products	0.1696	Culture, Sports and Entertainment	0.0710
Mining and Processing of Ferrous and Non-ferrous Metal Ores	0.1677	Education	0.0639
Manufacture of Wood and	0.1503	Public Management and Social	0.0610

Furniture		Organizations	
Leasing and Business Services	0.1495	Wholesale and Retail Trades	0.0543
Processing of Petroleum, Coking, Processing of Nuclear Fuel	0.1449	Manufacture of Foods, Beverages and Tobacco	0.0519
Production and Distribution of Electric Power and Heat Power	0.1444	Hotels and Catering Services	0.0486
Gas Production and Supply	0.1443	Agriculture, Forestry, Animal Husbandry and Fishery	0.0367
Mining and Processing of Nonmetal and Other Ores	0.1291	Real Estate	0.0330
Manufacture of Chemical Products	0.1273	Financial Intermediation	0.0308
Printing, Reproduction of Recording Media and Manufacture of Articles for Culture, Education and Sport Activity	0.1273	Recycling and Disposal of Waste	0.0277
Scientific Research and Experimental Development	0.1261		