The Guangdong Emissions Trading Scheme

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A pilot carbon emissions trading scheme (ETS) has been launched for three years in the Guangdong (GD) Province in China, with the power industry contributing nearly 66% of the covered CO_2 emissions. This article reviews the policy design of the power sector in the GD ETS, and finds that the percentage of paid allowance is the primary factor reflected in the carbon cost for generators with an average efficiency. The ways the GD ETS influences the costs and profits of power plants are our primary focus.

The impacts of carbon cost on the overall cost of 300 MW, 600 MW and 1,000 MW plants are analyzed. The results indicate that the ratio of carbon cost to total cost is about 0.5% for the power plants in the GD ETS. This small percentage has little influence on plant operations. The impacts of the carbon cost on the cash flow of the three sizes of plants are assessed by their internal rates of return. A critical curve is developed and shows the benefit scope for the plants at a specific paid allowance and carbon price. This can be used by governments to improve policy design and by the enterprises to manage their carbon assets.

INTRODUCTION

With China's rapid economic development, energy consumption and carbon dioxide emissions have grown rapidly. To alleviate being the world's largest greenhouse gas emitter [1], a number of policies have been introduced to reduce emissions in China. Given that administrative measures are effective but not efficient, China is harnessing market forces to reduce its greenhouse gas emissions. Emission trading systems (ETS) are effective tools, and emitters have incentive to reduce emissions when they are well-designed. Designing and operating emissions trading schemes has become one of the main policies adopted to reduce CO_2 emissions globally. Examples include the European Union's ETS, and those in the U. S. including the Regional Greenhouse Gas Initiative (RGGI) and the Western Climate Initiative (WCI) [2].

In October 2011, China's National Development and Reform Commission (NDRC) approved carbon ETS pilot programs in seven regions, including two provinces (Guangdong and Hubei) and five municipalities (Beijing, Tianjin, Shanghai, Chongqing and Shenzhen) [3]. Duan provided an overview of the status of these seven ETS pilots [4]. The Hubei ETS pilot [5], Shanghai ETS pilot [6], and Shenzhen ETS pilot [7] were detailed including their coverage sectors, allowance allocation, monitoring, reporting, verification, compliance and related mechanisms.

As one of the pilot provinces designated by Chinese government for a carbon ETS, Guangdong (GD) ranks highest in total emissions among the seven pilot regions [8,9]. The emissions reduction targets of GD include lowering the energy intensity per unit of GDP by 18% and the carbon intensity by 19.5% from 2011 to 2015 [10]. After its pilot phase (2013-2015), the GD ETS added power, cement, steel and petrochemical sectors in 2016. It now covers approximately 56% of the total CO_2 emissions of Guangdong Province. The power sector is by far the biggest CO_2 emitter within this emissions scheme, accounting for 230 million metric tons of CO_2 emissions of the total 350 million metric tons [11]. The power-generating facilities, especially the conventional ones, are in the sector most seriously affected by the GD ETS.

There have been no similar studies on the power plants in the GD ETS and only a few in China that considered electricity sectors in the ETS. Cong and Wei adopted the agent-based model to study the potential impact of an assumed ETS on China's power sector and found that an ETS would internalize the external environmental cost of carbon, influencing the relative costs of different power generation technologies through pricing [12]. Zhao et al. applied the DEA-Malmquist Index to empirically analyze the impact of various environmental regulations on the efficiency and CO_2 emissions of power plants in China, and concluded that market-based regulations (namely a possible ETS) have an irreplaceable role in promoting green development among power plants [13]. Both papers focus on predicting possible results by building some models. Teng et al. provided an analysis of institutional barriers in China's electricity pricing and dispatching systems that may affect the performance of a presumed ETS and discussed several options to reconcile the ETS and electricity market [14].

In contrast to these previous studies, ours investigates the actual power plants covered in an operating ETS pilot and adopted a basic and classic parameter—the internal rate of return (IRR) to analyze whether the power plants can operate profitably. As the IRR is widely used in the actual investment and management of businesses, the result can be easily understood and then adopted by governments and power generators to improve ETS rule structures and manage carbon as an enterprise asset. The characteristics of policy design for the power sector in the GD ETS are also considered. Next, we compare and analyze the overall cost of coal-fired power plants in the GD ETS and determine the critical point of the impact of carbon cost on the profit of the plants. Finally, we offer conclusions and policy suggestions to improve the GD ETS.

POWER SECTOR POLICY DESIGN IN THE GUANGDONG ETS

The greenhouse gas (GHG) emissions in the power system can be divided into two parts: 1) direct emissions from the production; and 2) indirect emissions from consumption.

Greenhouse Gas Emission Sources from the Power Sector in the GD ETS

In the EU ETS, RGGI, and WCI, the installations which emit GHG directly are included in the schemes by the principle that "those who produce, take responsibility." The direct emissions or the production from the power sector are covered in the ETS, as appears in Scenario 1 (see Figure 1). Power plant owners may argue that the power generation process is simply an energy transition from fossil fuel to electricity. In their opinion, the facilities which consume electricity should be included in the schemes by the principle that "those who consume, take responsibility."

The indirect emissions or consumption including the plant service power are covered in the ETS, as appears in Scenario 2 (see Figure 1). In Scenario 1, industrial facilities, like cement and steel companies, make little effort to reduce emissions as their emissions (excluding electricity consumption) are comparatively trivial and not covered by the ETS, or their complied emissions are ignored when covered by an ETS. Owners of industrial facilities often fail to notice the increased cost passed by the power suppliers because of the Chinese government's strict control of the fixed feed-in and retail electricity prices. Industrial enterprises could be inclined to change from fossil fuels to electricity consumption in order to reduce their recorded emissions. A large amount of electricity consumed in GD is imported from other regions such as Guangxi and Yunnan Provinces.

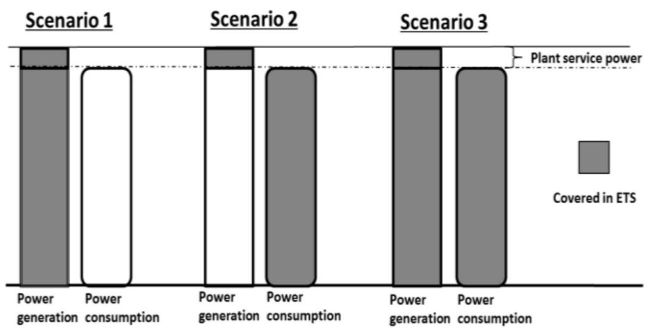

Figure 1. Scenario analysis of power system covered in ETS.

In Scenario 2, since electricity used by the power plant itself (plant service power) usually accounts for about 5% of the total electricity it produces, most of the emissions from the power sector should be controlled by the thousands of electricity consumption entities. This is more difficult than regulating only the power plants. Since only a small percentage of electricity is used by the power plants, regulating points of consumption fails to motivate the power plants to reduce emissions.

For the GD ETS, the emissions from both power generation and consumption are covered in Scenario 3 (see Figure 1). This scenario uses the "double counting" principle. It offers regulation at both the source of production and point of consumption, alleviating pollution transfer. For electric generation, the power plants must improve generator efficiency or transfer to cleaner fuels to reduce emissions. For electric consumption, enterprises such as cement, steel or construction companies must adopt advanced technology to decrease the electricity used. With more emissions counted, more allowances are needed, which may incentivize the carbon market to a greater extent. The double accounting of emissions can be alleviated by baselining. Many enterprises are experienced with measuring and controlling electricity consumption to meet energy-saving targets. Using historical energy consumption data, the emissions accounting and allowance allocations can be calculated by the enterprises in the GD ETS, rather than by specific installations as in the EU ETS.

Allowance Allocations in the GD ETS Power Sector

The indirect emissions from consumption are counted according to the consumed electricity quantities multiplied by the emissions coefficient of the South Power Grid. These are published by the NDRC, and the allowance allocation of indirect emissions vary based on each industry's production processes. This assessment focuses on the direct emissions from power generation.

Benchmarks are used to allocate allowances for the pure-power plants in the GD ETS. Benchmarking avoids penalizing enterprises that have previously taken action to reduce emissions. This also provides for inefficient and smaller power production facilities. Many smaller generation facilities are essential for mountainous and remote regions to ensure stable working and living conditions. It may be difficult for them to improve their efficiency to the level of larger producers. Different benchmark values can be set for the various types of generation using different fuels (see Table 1).

Table 1. Benchmark values for power units in 2013 [11].

Unit type	*Coal fired generator*				*Gas fired generator*	
	1000MW	600MW	300MW	Under 300MW	390MW	Under 390MW
Benchmark value (gCO_2/kWh)	770	815	865	930	415	482

Based on the Notice of the First Allowance Allocation Plan in the Guangdong ETS [10], the allowance allocation of the pure-power unit can be calculated as the equation follows:

$$EA = \sum_{i=1}^{n} (HP_i \text{ X } BM_i) \text{ X } CF \text{ X } (1 - PA) \quad (1)$$

Emissions allowance, *EA*, is the free allowance of one power plant which may include *n* generator units. Historical production, HP_i, is the unit *i* average power generation, in years for the period from 2010 to 2012, excluding those when the unit was not operated continually for at least six months. BM_i is the benchmark value of the unit *i* shown in Table 1, or the average of a similar unit covered by the GD ETS. The compliance factor, *CF*, is used for coordinating the results of setting emission caps and allowance allocations (typically 1). The percentage of the paid allowance, *PA*, reflects allowance shortages compared to historical emissions when power unit efficiency is at mean output and generation is steady. The *PA* was 3% in 2013.

After operating for the compliance period, the GD ETS exposed some problems. With an economic downturn and more inflows of electricity from other provinces in 2013, the power generated by plants in Guangdong Province was far less than that in the previous three years, which led to a large surplus of allowances. To avoid productive volatility, ex-post adjustments were applied in the second compliance period of the GD ETS. The allowance allocation equation of the pure-power unit was changed to:

$$EA = \sum\nolimits^{n}_{i=1} (CP_i \text{ X } BM_i) \text{ X } CF \text{ X } (1 - PA) \qquad (2)$$

The *HP* in Equation (1) was changed to *CP*, current production, the plant's actual power generation in the compliance year. As emissions verification in 2013 was more accurate and detailed than the emissions inventory for previous years, the *BM* and unit type are updated for Table 2. To balance the surplus allowance from 2013 and maintain the constraints of the ETS, the *PA* was increased to 5% in 2014.

As output uncertainties are eliminated by ex-post adjustments, the percentage of paid allowance is the only variable of carbon cost for a generating unit with an average efficiency. We next focus on how the different percentages of paid allowances impact the costs and profits of

Table 2. Benchmark values for power units in 2014 and 2015 [15,16].

Unit type			*Benchmark value (gCO_2/kWh)*
Coal-fired generator	1,000MW		825
	600MW	Ultra-supercritical	850
		Supercritical	865
		Subcritical	880
	300MW	Non-circulating fluidized bed	905
		Circulating fluidized bed	927
	Under 300MW	Non-circulating fluidized bed	965
		Circulating fluidized bed	988
Gas fired generator	390MW		390
	Under 390MW		440

coal-fired thermal power plants since they will continue to be dominate in the future [17].

ANALYSIS OF COAL-FIRED THERMAL PLANTS

There are four types of coal-fired generators in Guangdong ETS categorized by their size—under 300 MW, 300 MW, 600 MW and 1,000 MW. The number of 300 MW generators is greatest in Guangdong Province which also has the largest total installed capacity of 600 MW generators. The number of generators and the total installed capacity of the 1,000 MW generators are increasing while the number of generators rated below 300 MW are decreasing.

Coal-fired power plants with generators sized 300 MW, 600 MW and 1,000 MW are chosen as reference power plants. Coal-fired plants usually have at least two identical generators to achieve the maximal efficiency, so each reference power plant is assumed to have two generators.

Cost of the Standard Reference Power Plants

According to the investigation on the coal-fired power plants in Guangdong Province and the reference cost index on the design limitations of thermal power engineering [18], the basic financial parameters for 2014 are as follows:

- Coal price 800 yuan/tce
- Limestone price is 100 yuan/t
- Equipment operates 4,500 hours for 20 years
- Loan percent of total static investment 80%
- Loan term is 15 years
- Interest rate for the loan is 6.55%
- Depreciation period is 15 years
- Residual value is 5%
- Insurance premium rate is 0.25% of total investment
- Repair costs are 2% of total investment
- Staff salaries total 50,000 yuan annually plus 60% for welfare

The feed-in tariff is pegged at 0.502 yuan/kWh including tax [19]. Coal cost can be derived from the benchmark value. The average low calorific value of standard coal is 29,307 MJ/tce with a carbon content of

26.37 gC/MJ [20].

The parameters of coal-fired power plants with two 300 MW generators (300 MW plant) are as follows: investment of 4,394 yuan/kW, staff of 234, material fee is 6 yuan/kWh, other costs of 12 yuan/kWh, limestone consumption 8 tons/hour (2% sulphur content), discharge fees including SO_2, NO_x and fume emissions are 1,430, 1,620 and 80,000 yuan/coiler/year respectively. The total cost of a 300 MW plant is 1,094,210 thousand yuan.

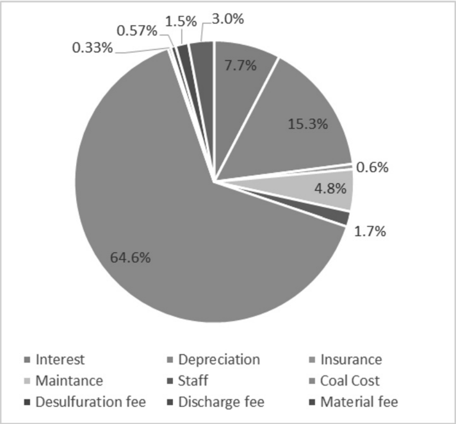

Figure 2. The overall costs of the 300 MW plant.

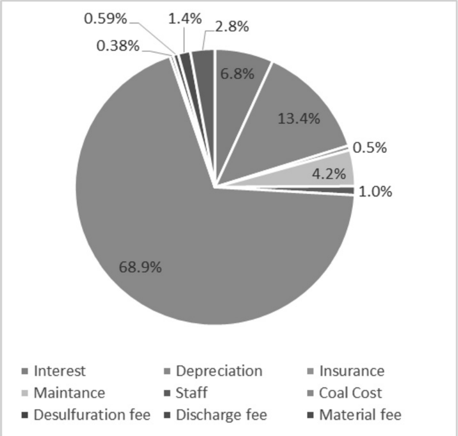

Figure 3. The overall costs of the 600 MW plant.

The parameters of coal-fired power plants with two 600 MW generators (600 MW plant) are as follows: investment of 3,367 yuan/kW, staff of 247, material fee 5 yuan/kWh, other cost 10 yuan/kWh, limestone consumption 16 tons/hour (2% sulphur content), discharge fees including SO_2, NO_x and fume emissions are 2,600, 2,930 and 150,000 yuan/coiler/year respectively. The total cost of a 600 MW plant is 1,913,100 thousand yuan.

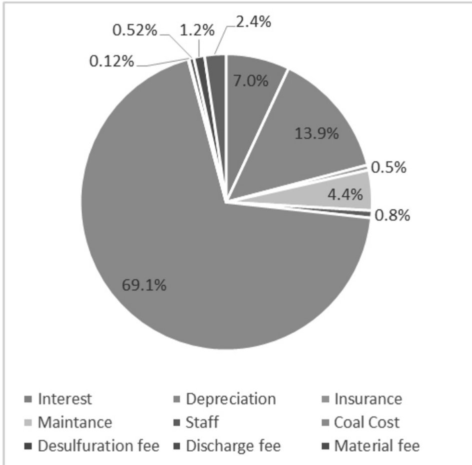

Figure 4. The overall costs of the 1,000 MW plant.

The parameters of coal-fired power plants with two 1,000 MW generators (1,000 MW plant) are as follows: investment of 3,334 yuan/kW, staff of 300, material fee is 4 yuan/kWh, other cost is 8 yuan/kWh, limestone consumption 8 tons/hour (0.9% sulphur content), discharge fees including SO_2, NO_x and fume emissions are 3,600, 4,100 and 240,000 yuan/coiler/year respectively. The total cost of a 1,000 MW plant is 3,032,550 thousand yuan.

The costs of the three kinds of plants are shown respectively in Figures 2, 3 and 4.

As shown in Figures 2, 3, and 4, the main costs of the plants include coal, depreciation, interest, maintenance and other costs, which account for over 95% of the total cost. The cost of coal is two thirds of the total cost. Any fluctuation in the coal cost may determine whether the enterprise is profitable. With capacity increases, the proportion of human cost, material cost, and management cost decrease. Using higher quality coal with lower sulfur content, the proportional cost of desulfurization is lower for the 1,000 MW plants than for the smaller plants.

Impact of ETS on the Cost of Coal-fired Power Plants

As an external environmental management regulation, ETS influences plants covered in ETS in both the short and long terms. The plants may benefit from carbon trading, or suffer from additional expenses.

For the short term, the plants need to increase the corresponding manpower and resources in carbon asset management. If the carbon emissions of the plants are more than the free quota, extra credits must be purchased for compliance. If excess allowance is validated by an emission reduction action, the plants profit by selling the surplus allowance, offsetting the cost of the emission reduction activity. The various allowance allocation schemes have different carbon costs. When the allowance is available at no cost and the benchmark value is set as the average efficiency in the industry, plants with the average efficiency are hardly influenced by the carbon cost. With more stringent carbon limits, carbon emission caps will be gradually tightened. With the total allowance in the ETS tightened, the free allowance would be reduced on the basis of the constant benchmark value. In such cases, the enterprises must purchase more allowances from the government or market, increasing their production cost.

For the different scenarios with different carbon prices and *PA*, the impacts of ETS on the coal-fired thermal power plants can be calculated and analyzed. According to the carbon allowance allocation scheme in Guangdong Province and the sampled generating plants, the hypotheses of this study are as follows:

1) The carbon cost in this study only involves the expense that the enterprise needs to purchase for allowances, regardless of the hidden costs such as the resources that the enterprise invests in carbon asset management or carbon trading.

2) The efficiency of the standard reference power plants is the average of the unit type, so the total enterprise allowances are equal to its carbon emissions when the allowance allocation benchmarks are the average of the energy consumption for specific type of generator.

3) When free quotas issued by the government are less than the carbon emissions of an enterprise, purchasing allowances in the carbon market or taking measures to reduce carbon emissions should be adopted to achieve carbon management goals. The enterprise bears the cost. Various technical mitigation actions are possible and calculating carbon reduction costs are complex. Therefore, the cost from taking carbon reduction actions is estimated to be equal to purchasing equivalent allowances.

4) The *PA* is set as 3%, 5%, 10% and 100%. According to Trial Management Measures on Carbon Emissions in Guangdong Province, "the allowance is partly free, and the free quota proportion will be gradually reduced." The free allowance proportion of the power industry is 97% in 2013 and 95% in 2014 [11,15]. The allowances of the power industry in second and third phase of the EU-ETS and in the U.S. RGGI carbon market are almost all auctioned.

5) The carbon prices are set as 5 yuan/tCO_2, 60 yuan/tCO_2 and 120 yuan/tCO_2. The allowance auction price was set as 60 yuan/tCO_2 in Guangdong Province in 2013. The carbon price in China varies in the various carbon market pilot programs with the highest price being 120 yuan/tCO_2 in Shenzhen and the lowest of 5 yuan/tCO_2 in Shanghai.

According to the research hypothesis and the characteristics of the electric power industry, the calculation formula of carbon cost is:

Carbon cost = Installed capacity X Operational hours X
Quota allocation benchmark X *PA* X Carbon price

The carbon costs of the three types of plants were calculated and analyzed based on this formula.

As shown in Figures 5, 6, and 7, when the carbon price is low (5 yuan/tCO_2), the ratio of carbon cost to total cost is small, and is only about 1% even when the *PA* is 100%. The carbon cost has little influence on the enterprise cost. When the carbon price is high (120 yuan/tCO_2), the proportion of carbon cost to total cost increases, accounting for 1% at the *PA* of 3% and 35% at the *PA* of 100%, which is second in magnitude to the cost of coal. In this case, the carbon cost has a significant effect on the enterprises. The impact of the ETS is closely related to the carbon price and *PA*. When carbon emissions are stable and the *PA* increases, the more allowance the plants must purchase and the carbon price becomes key to quota expenditures. As the carbon price rises, the carbon cost has increasing influence on enterprise cost. When both the carbon price and *PA* are high, the carbon cost rises quickly and may have disruptive effects on production decisions.

With the *PA* of coal-fired thermal power plants in the GD ETS equal to 3% in 2013 and 5% in 2014, and the carbon price at 60 yuan/tCO_2, the ratio of carbon cost to total cost is only 0.5%. This is roughly equal to the ratio of gas pollutant discharge costs.

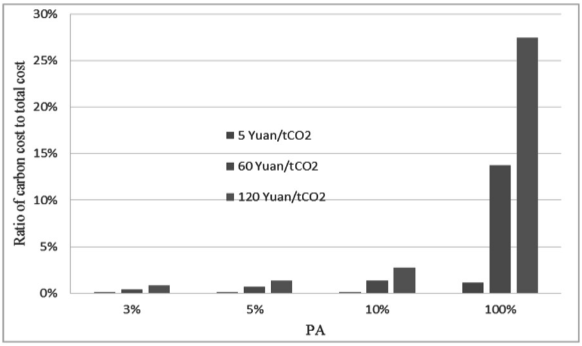

Figure 5. The ratio of carbon cost to total cost for the 300 MW plant.

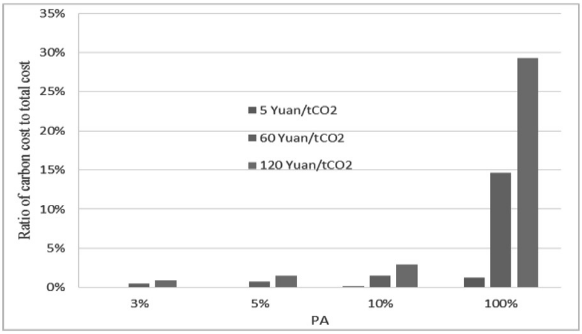

Figure 6. The ratio of carbon cost to total cost for the 600 MW plant.

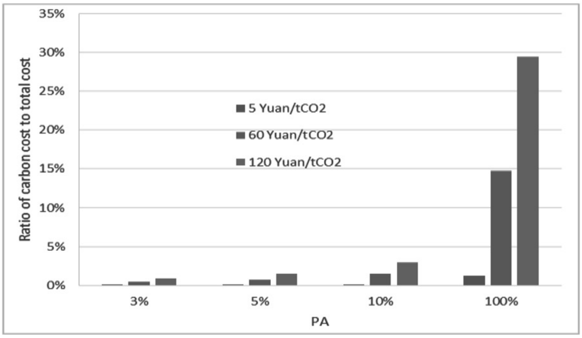

Figure 7. The ratio of carbon cost to total cost for the 1,000 MW plant.

The power industry may be more sensitive to the carbon cost because of its large carbon emissions and higher *PA* relative to other industries in the GD ETS. Presently, the impact of the ETS is limited as carbon cost accounts for only a small portion of the total cost.

IMPACT OF THE GD ETS ON THE PROFITS OF THERMAL PLANTS

To further analyze the dynamic impacts of carbon cost on enterprise production cycles, the internal rate of return (IRR) was used to measure and compare the profitability of the three types of power plants (300 MW, 600 MW and 1,000 MW) in hypotheses 1-3. Hypotheses 4 and 5 were designed to study the effect of different carbon emission constraints. The *PA* values were set as 3%, 5%, 10%, 20%, 30%, 50%, and 100%, and the carbon price was from 5 yuan to 300 yuan, with 36 increments with 5 yuan intervals below 60 yuan, and 10 yuan intervals above 60 yuan.

Impact of Carbon Cost on the Cash Flow of Thermal Power Plants

The IRR is used in capital budgeting to measure the profitability of potential investments or projects and is an indicator of the efficiency or yield of an investment. Investors should only undertake projects or investments with IRRs that exceed the cost of capital. The higher a project's IRR, the more appealing the investment becomes. The IRR of an investment or project is the annualized effective compounded return rate. The greater the projected rate of return from a particular investment after incorporating all cash flows (both positive and negative), the greater the likelihood that investors will risk their funds. Given the (period, cash flow) pairs (n, C_n) where n is a positive integer, the total number of periods N, we find in the equation for the net present value (NPV) the IRR represented by the variable r:

$$\text{NPV} = \sum\nolimits^{n}_{i=1} [C_n/(1 + r)^n] = 0 \quad (3)$$

The IRR can be calculated using software. The results indicate that the IRR of the 300 MW plant, 600 MW plant and 1,000 MW plant are 8.7%, 15.6% and 17.7% respectively without ETS. According to the Electric Power Planning and Engineering Institute [18], the baseline IRR is

8%, meaning that the power plant can operate economically only when the IRR of the power plant is greater than 8%. Without a carbon cost, all three types of thermal power plants can retain their investment value within the assumed parameters. With the added carbon cost, whether the plants can retain their investment value depends on how much their IRR declines due to the increased cash outflows.

IRRs for the standard reference power plants were calculated for the different carbon cost scenarios using *PA* and carbon prices for the IRRs of 300 MW, 600 MW and 1,000 MW (see Figures 8, 9 and 10).

As shown in the Figures 8, 9, and 10, the IRRs decline as the carbon cost increases. When *PA* is 3% and the carbon price is below 150 yuan/t, the IRR's curve is a straight line and begins to tilt when the carbon price exceeds 150 yuan/t. When *PA* is 5% and the carbon price is below 100 yuan/t, there is a slight lean to the IRR's curve, which is more pronounced when carbon prices exceed 100 Yuan/t. When *PA* is greater than 10%, the slope of the IRR curve changes as the carbon price increases.

The influence of ETS on the IRR is dependent on the generation unit size. The results show that as the installed capacity of the generator increases, the slope of the IRR curve is less, the initial IRR (without carbon cost) is higher, and more carbon cost can be absorbed.

For the 300 MW plant, the IRRs are below 8% with *PA* = 3% and the

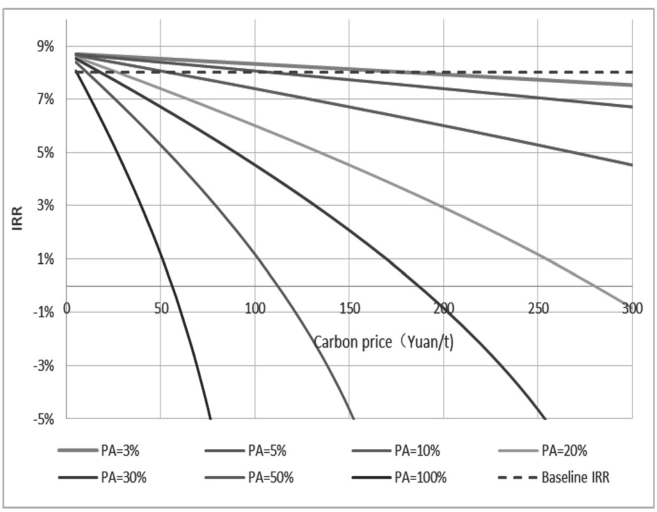

Figure 8. Impact of carbon cost on the IRR of the 300 MW plant.

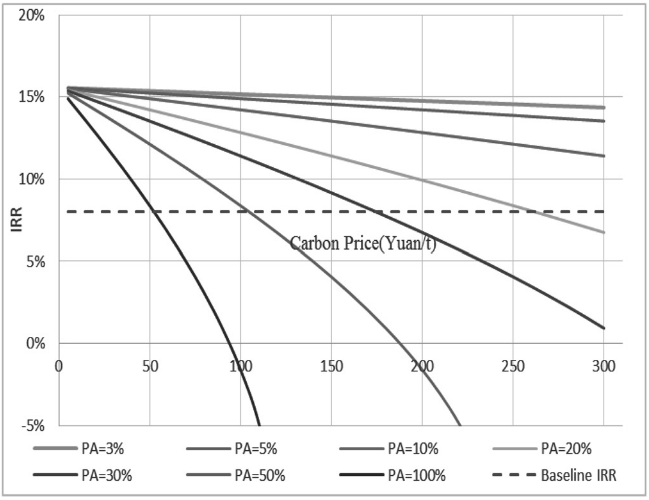

Figure 9. Impact of carbon cost on the IRR of the 600 MW plant.

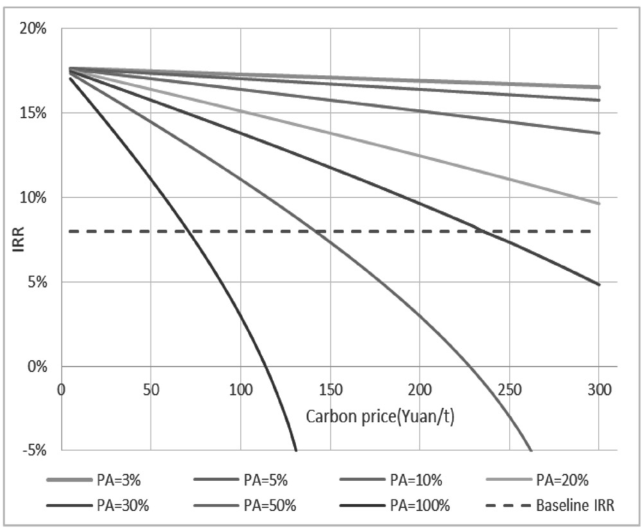

Figure 10. Impact of carbon cost on the IRR of the 1,000 MW plant.

carbon price is above 180 yuan/t, or when *PA* = 5% and the carbon price is above 110 yuan/t, or if the *PA* = 10% and the carbon price is above 55 yuan/t. For these *PA* percentages, the IRRs of the 600 MW and 1,000 MW plants are over 8% if the carbon price is less than 300 yuan/t.

When *PA* is 20% and the carbon price is 263 yuan/t, the 600 MW plant can't operate profitably but the 1,000 MW plant remains feasible. If the *PA* were to reach 100%, the 300 MW, 600 MW and 1,000 MW plants are unable to retain their investment values when carbon prices are higher than 5.5 yuan/t, 52 yuan/t and 71 yuan/t respectively.

Critical Point of the Impact of Carbon Cost on the Profit of Power Plants

Given the paid allowances and carbon prices, the IRR of the three units is such that they can operate economically (IRR=8%). The critical impact points of carbon cost on the profits of the power plants are indicated in Figure 11.

The combinations of *PA* and carbon price where the IRR of the 300 MW plant is 8% are: 3% (80 yuan), 5% (110 yuan), 10% (55 yuan), 20% (27 yuan), 30% (18 yuan), 50% (11 yuan) and 100% (5.5 yuan). These can be used to construct the critical curve of the impact of carbon cost on the profits of the 300 MW plant. Each point in the critical curve represents that the plant can afford the maximum *PA* at some carbon price, ensuring that the IRR is equal to or greater than 8%. The points in the lower left area of the curve are the combinations of *PA* and carbon price satisfying an IRR greater than 8%, while the points in the upper right area of the curve are the combinations with the IRR less than 8%.

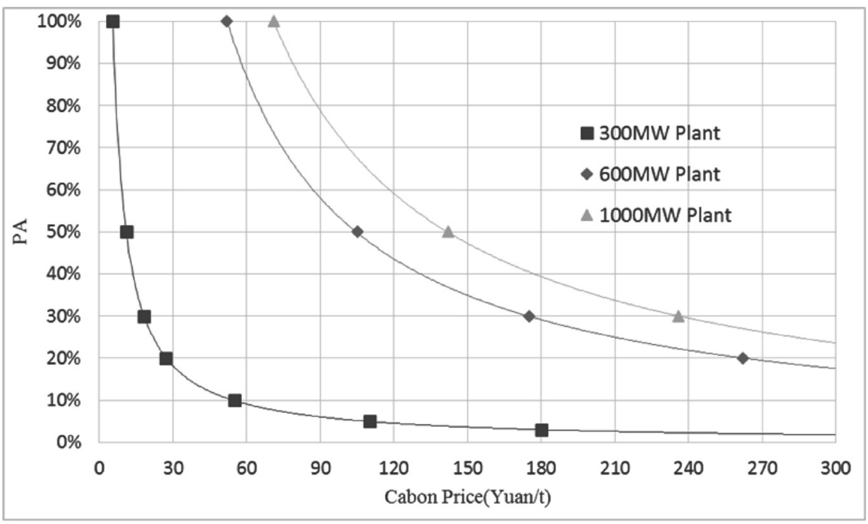

Figure 11. Critical impact curve of carbon cost on the profit of the three types of the plants.

The combinations of *PA* and carbon price when the IRR of the 600 MW plant is 8% are: 20% (262 yuan), 30% (175 yuan), 50% (105 yuan) and 100% (52 yuan). The combinations of *PA* and carbon price when the IRR of the 1,000 MW plant is 8% are: 0% (236 yuan), 50% (142 yuan) and 100% (71 yuan). The critical curve for 600 MW and 1,000 MW plants can be constructed in a similar manner.

From Figure 11, the carbon cost tolerance of the various units with various combinations of *PA* and carbon prices can be compared. For example, to maintain an IRR above 8% when the carbon price is 90 yuan/tCO_2, the 300 MW plant can purchase at most 7% of its total allowance, the 600 MW plant 58% of its allowance, and the 1,000 MW plant can afford 79% of its allowance. If the power plants must purchase 30% of their total allowances to maintain their normal profits, the 300 MW, 600 MW and 1,000 MW plants can afford the carbon price of 20 yuan, 175 yuan and 238 yuan respectively.

The smaller the installed capacity of the generation unit, the lower its efficiency, and the less it's owners can pay for carbon if profit levels are to be maintained. For installed capacities from 300 MW to 1,000 MW, the generator efficiency increases, the critical curves deviate more from the axis, the profits are larger, and the ability to pay higher prices for carbon increases. If carbon prices are below 60 yuan/t, the *PA* should be less than 10% to ensure that all generating units operate profitably. As carbon prices increase, the *PA* should be reduced accordingly.

The higher the plant's operations cost, the greater the cash outflows, and the less a plant can afford to pay for carbon emissions. Since acquiring coal is the plant's largest operational cost, the price of coal impacts the cost of operation. If the coal price increases from 800 yuan/tce to 1,000 yuan/tce, the critical curve of 1,000 MW plant will move lower and to the left, as shown in the Figure 12.

In the U.S., RGGI distributes nearly all CO_2 allowances through quarterly, regional auctions, which is similar to distributing 100% of the *PA* for the GD ETS. In RGGI, the volume-weighted average auction clearing price of CO_2 allowance per ton was \$1.86, \$1.89, \$1.93, \$2.92, \$4.72 and \$6.10 respectively from 2010 to 2015 [21]. In the GD ETS, the ceiling carbon price is 5.5 yuan/t, 52 yuan/t and 71yuan/t for the IRR for the 300 MW, 600 MW, and 1,000 MW plants above 8% when the *PA* is 100%. This means that the ceiling carbon price for the 300 MW generator unit is roughly equal to the average auction clearing price in the early phases of RGGI. The average carbon auction clearing price avail-

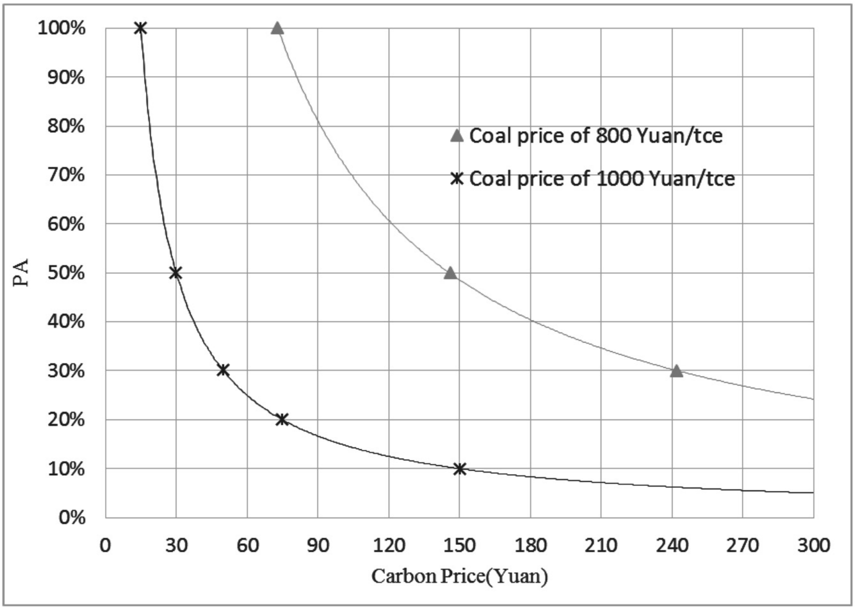

Figure 12. Influence of coal prices on the critical curve of the 1,000 MW plant.

able from RGGI from 2013 to 2015 approached the ceiling price of our example 600 MW generator. As generator efficiency improves from 300 MW to 600 MW, and the energy efficiency improves, the CO_2 emissions rate for RGGI electric generation sources declines by almost 20%. The evidence indicates that the threshold values of carbon prices that thermal power plants can afford to pay appear reasonable.

CONCLUSIONS AND POLICY IMPLICATIONS

The emissions from both power generation and consumption are covered in the GD ETS, which control the emissions in two ways and alleviate pollution transfer. Based on the allowance allocation method of the power plants in the GD ETS, the paid allowance is the only carbon cost factor for generators with average efficiency, as the output uncertainty is eliminated by ex-post adjustment.

The paid allowance of 5% was adopted by the GD ETS in 2014 and 2015. The carbon prices varied from 60 yuan/t in 2013 to 20 yuan/t in 2015. The carbon cost represents a small proportion of the total cost and is acceptable for the thermal power plants in Guangdong Province.

In our study, the threshold values of carbon cost that the three types of coal-fired thermal power plants can afford in terms of *PA* and carbon price have been calculated using the IRR. We determined that the values are reasonable compared with the volume-weighted average auction clearing price of CO_2 allowances in RGGI. We also identified the conditions under which thermal power plants can economically operate.

Considering the impact of carbon cost on the profit of the power plants, the regional governments should notice that different generators can afford various combinations of allocations and carbon price. This improves the allowance allocation and justifies the allowance distribution when coal prices or on-grid tariffs fluctuate.

Several policy recommendations should be considered. First, it is possible to set different *PA*s for different units when carbon prices are too high, as different units can afford different *PA*s at specific carbon prices. All units can operate economically with the paid allowance of 5% when the carbon price is about 20 yuan/t. When the carbon price exceeds 100 yuan/t as in the Shenzhen ETS in 2013, the 300 MW units will not operate economically. A solution might be to reduce the *PA* for 300 MW units to 3% and not change the *PA* for the other units. Secondly, a linkage mechanism between *PA* and coal prices or on-grid tariffs might mitigate the cost burden. The generating plant's affordability of *PA* weakens when the coal prices increase from 800 yuan/tce to 1,000 yuan/tce for the 1,000 MW units when the on-grid tariff is invariant (see Figure 12). It is likely necessary to justify the *PA* according to coal prices or on-grid tariffs. To enable plant owners to budget costs, future year *PA*s should be published in advance. Finally, the complex trading strategies that include carbon derivatives should be encouraged, to allow the enterprises to hedge their carbon emission procurement strategies.

Enterprises are fully capable of managing their carbon assets and controlling carbon market risk. For this assessment, the main parameters of the three types of coal-fired thermal power plants were averaged and standardized for reference. There are variable cash flows for different operational schedules of the generating plants which are impacted by interest and depreciation. Each enterprise should apply the parameters according to their actual situation.

The power plants may facilitate other measures to help achieve their carbon management goals. These might include improving efficiency, developing renewables, fuel substitution, purchasing certified emission reduction certificates or developing infrastructure for carbon capture and storage.

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