Appendix

Appendix A

Table A.1. Detailed parameters and their sources in the benchmarking

Benchmark line	Categories	Installed capacity (MW)	The benchmark value (tCO_2/MWh)
1	Coal-fired power unit	(0,100]	1.0177
2	Coal-fired power unit	(100,300]	0.9266
3	Coal-fired power unit	(300,600]	0.8748
4	Coal-fired power unit	$(600,+\infty)$	0.8066
5	Integrated Gasification Combined Cycle unit	(0,300]	0.9565
6	Integrated Gasification Combined Cycle unit	$(300,+\infty)$	1.1597
7	Gas-fired power unit	(0,200]	0.5192
8	Gas-fired power unit	$(200,+\infty)$	0.3795

Table A. 2. Technology set for the power industry

Technology	Description	Investment cost (yuan/KW)	Annual change in O&M cost (yuan/KW)	Annual energy savings (tce/MW)	Annual CO_2 emission reductions (t/MW)
A1	Modernized retrofit of flow passage of steam turbine	10.06	0	19	51
A2	Transformation of seal system of steam turbine	2	-0.1	11	29
A3	Control technology of energy-saving and efficiency of electrostatic precipitation	7.83	0	5	12
A4	Transformation of pure condensing steam unit to CHP	2.77	0	35	92
A5	Contacting sealing technology of rotary air pre heater	6	0	12	32
A6	intelligent optimization and online coking early warning system of utility boiler	58	0.5	1	3
A7	Steam heating startup technology of utility boiler from neighboring unit	164.18	0	1	3
A8	Flue gas waste heat recovery and fan operation optimization technology of FGD	625	0	15	38
A9	Integrated technology of improved performance of steam turbine in power plant	3.91	0	30	79
A10	Integrated optimization system of flue gas and advanced heat recovery technology	1	-0.7	13	34

A11	Vacuum maintenance and energy-saving technology of power plants' condensers	40	0.39	10	26
A12	Draft fan and steam-driven technology of SC and USC unit	8.2	0	3	8
A13	Efficient centrifugal spray device in cooling tower	12.9	0	6	16
A14	Double backpressure dual rotor swap cycle-water heating technology	21.85	13.06	180	952
A15	Energy-saving seal technology for rotary air preheater	30	0	4	11
A16	High parameter and large capacity technology for brown coal powder boilers	16.67	0	220	582
A17	Gas-steam combined cycle technology using low-heat value blast furnace gas	30	0	83	218
A18	Pilot fuel gas alternative technology for gas turbine	100	0	98	259
A19	High efficiency combined evaporative condenser	343.33	0	24	64
A20	Boiler combustion temperature monitor and performance optimization system	9	0	7	18
A21	Thermoelectric synergy district heating technology	435.19	0	140.5	743
A22	energy-saving technology of small-middle steam turbine	166.67	0	689	1805
A23	Coordinated control technology of USC unit based on load adjustment of condensate	51.41	0.06	6	16
A24	Stable combustion and oil-saving technology of oxygen-enriched ignition	175	0	19	51
A25	Energy-saving technology of electric precipitation with quasi stable DC power	32.17	0	10	21
A26	generalized regeneration technology for 1000 MW USC unit	1.8	0	55	150
A27	CHP	24	0	80	217
A28	Scaling apparatus of spiral strips for condenser	20.94	0	20	54
A29	Efficient utilization of CFB boiler firing ultra-low heat value gangue	128.1	0	18	46

Source: Chen et.al (2017).

Appendix B

(1) Datang group with market power

Table B.1 shows the simulation results when Datang group with market power and other power plants are price-takers. Compared with the scenario that all power plants are price-takers, the following conclusions can be drawn. First, ETS with different carbon permits allocation schemes will bring about a downturn in carbon price and the average cost-saving effect. Second, the total abatement cost of Datang group changes quite distinctly as the carbon allowance allocation policy changes. For instance, in Scenario S0, Datang group with market power increases its total abatement cost by 0.39% because of a great increase in emission reductions, but significantly reduces trading cost by 16.66% due to the fact that the decrease of carbon price as well as the amount of purchasing carbon permits. However, in Scenarios A1 and A2, Datang group reduces its total abatement cost in a certain extent. Third, more than 75% of price-taking power plants increase their total abatement costs in all three Scenarios S0, A1 and A2. For example, in Scenario S0, changes in total abatement cost range from -2.34% to 11.41% and 322 power plants' total abatement cost increase. But the aggregate abatement cost of all power plants falls in all three Scenarios S0, A1 and A2. This is because the amount of abatement cost reduced by Datang group is greater than it increased by price-taking power plants. In addition, it should be noticed that emission trading role changes quite distinctly as the carbon allowance allocation policy changes. In Scenarios A1 and A2, there are 157 and 263 power plants respectively change their emission trading role, while only three coal-fired power plants increase their CO2 emissions from permits seller to permits buyer in Scenario S0.

Table B.1. Datang group with market power under different carbon permits allocation schemes

			S0	A1	A2
Carbon price (yuan/tCO2)			12.93	13.13	13.30
The average cost-saving effect			11.67%	12.05%	12.14%
The aggregate abatement cost			-0.10%	-0.50%	-0.60%
The feature of power plant	Datang group with market power	Changes in emission reductions	25.14%	13.61%	4.05%
		Changes in emissions	-0.56%	-0.30%	-0.09%
		Changes in total abatement cost	0.39%	-4.17%	-5.38%
		Changes in trading cost	-16.66% (buyer)	-17.02% (buyer)	-1131.76% (seller)
	The lowest initial carbon intensity	Changes in emission reductions	-3.29%	-1.78%	-0.53%
		Changes in emissions	0.05%	0.03%	0.008%
		Changes in total abatement cost	-2.30%	-1.24%	-0.37%
		Changes in trading cost	4.67% (buyer)	187.92% (from buyer to seller)	4993.08% (buyer)
	The highest initial carbon intensity	Changes in emission reductions	-3.29%	-1.78%	-0.53%
		Changes in emissions	0.02%	0.01%	0.003%
		Changes in total abatement cost	-2.23%	-1.20%	-0.37%
		Changes in trading cost	4.58% (buyer)	-21.92% (buyer)	2320.38% (buyer)

(2) Huadian group with market power

Table B.2 shows the simulation results when Huadian group with market power and other power plants are price-taker. Compared with the scenario that all power plants are price-takers, the following conclusions can be drawn. First, ETS with different carbon permits allocation schemes will bring about a downturn in carbon price and the average cost-saving effect. Second, as a strategic enterprise, by manipulating carbon price, Huadian group with market power reduces its total abatement cost in all three Scenarios S0, A1 and A2. For example, Huadian group with market power significantly reduce its total abatement cost by 11.30% and trading cost by 45.81% in Scenario S0. Third, more than 75% of price-taking power plants increase their total abatement costs in all three Scenarios S0, A1 and A2. For example, changes in total abatement cost range from -3.67% to 17.33% and the total abatement costs of 323 power plants increase in Scenario S0. However, the aggregate abatement cost of all power plants falls in all three Scenarios, because the amount of abatement cost reduced by Huadian group is greater than it increased by price-taking power plants. Furthermore, emission trading role changes obviously as changes in the carbon allowance allocation policy. For example, 15 power plants change their emission trading role in Scenario A1, among them, 8 power plants reduce their carbon emissions from permits buyer to permits seller. But in Scenarios S0 and A2, there are just 3 and 5 power plants respectively increase their CO2 emissions from permits seller to permits buyer.

Table B.2. Huadian group with market power under different carbon permits allocation schemes

			S0	A1	A2
Carbon price (yuan/tCO2)			12.68	12.89	13.15
The average cost-saving effect			11.33%	11.24%	11.22%
The aggregate abatement cost			-1.81%	-1.24%	-1.69%
The feature of power plant	Huadian group with market power	Changes in emission reductions	9.77%	4.85%	10.98%
		Changes in emissions	-2.00%	-0.10%	-0.23%
		Changes in total abatement cost	-11.30%	-11.20%	-11.43%
		Changes in trading cost	-45.81% (buyer)	17.81% (seller)	147.80% (from seller to buyer)
	The lowest initial carbon intensity	Changes in emission reductions	-5.13%	-3.60%	-1.62%
		Changes in emissions	0.08%	0.05%	0.02%
		Changes in total abatement cost	-3.62%	-2.53%	-1.12%
		Changes in trading cost	4.97% (buyer)	-3.72% (seller)	1.52% (buyer)
	The highest initial carbon intensity	Changes in emission reductions	-5.13%	-3.60%	-1.62%
		Changes in emissions	0.09%	0.02%	0.01%
		Changes in total abatement cost	8.16%	-2.45%	-1.09%
		Changes in trading cost	4.94% (buyer)	-3.55% (buyer)	-1.09% (buyer)

(3) Guodian group with market power

Table B.3 shows the simulation results when Guadian group with market power and other power plants are price-taker. Compared with the scenario that all power plants are price-takers, the following conclusions can be drawn. First, ETS with different carbon permits allocation schemes will bring about a downturn in carbon price and the average cost-saving effect. Second, the total abatement cost of Guadian group changes quite obviously as the carbon allowance allocation policy changes. For instance, in Scenario S0, Guadian group with market power reduce its total abatement cost by 1.45% and significantly reduces trading cost by 99.71%. However, in Scenarios A1 and A2, Datang group reduces its total abatement cost in a certain extent. Third, more than 75% of price-taking power plants increase their total abatement costs in all three Scenarios S0, A1 and A2. For example, in Scenario S0, changes in total abatement cost range from -3.30% to 15.70% and 315 power plants' total abatement cost increase. But the aggregate abatement cost of all power plants falls in Scenarios S0 and A1. This is because the amount of abatement cost reduced by Guodian group is greater than it increased by price-taking power plants. Moreover, changes in emission trading role have subtle difference under different carbon permits allocation schemes. In Scenarios S0 and A2, there are 3 and 3 power plants respectively increase their CO2 emissions from permits seller to permits buyer. But all sampled power plants don't change their emission trading role in Scenario A1.

Table B.3. Guodian group with market power under different carbon permits allocation schemes

			S0	A1	A2
Carbon price (yuan/tCO2)			12.75	13.30	13.26
The average cost-saving effect			12.11%	11.99%	12.00%
The aggregate abatement cost			-0.07%	-0.95%	0.15%
The feature of power plant	Guodian group with market power	Changes in emission reductions	33.36%	3.73%	10.98%
		Changes in emissions	-0.77%	-0.09%	-0.23%
		Changes in total abatement cost	1.45%	-8.54%	-11.43%
		Changes in trading cost	-99.71% (buyer)	16.65% (seller)	147.80% (from seller to buyer)
	The lowest initial carbon intensity	Changes in emission reductions	-4.62%	-0.51%	-0.78%
		Changes in emissions	0.07%	0.008%	0.011%
		Changes in total abatement cost	-3.26%	-0.34%	-0.54%
		Changes in trading cost	-4.46% (buyer)	-0.57% (seller)	0.77% (buyer)
	The highest initial carbon intensity	Changes in emission reductions	-4.62%	-0.51%	-0.78%
		Changes in emissions	0.03%	0.003%	0.004%
		Changes in total abatement cost	-3.15%	0.06%	-0.52%
		Changes in trading cost	-4.57% (buyer)	-0.76% (buyer)	-0.55% (buyer)

(4) State power investment group with market power

Table B.4 shows the simulation results when State power investment group with market power and other power plants are price-taker. Compared with the scenario that all power plants are price-takers, the following conclusions can be drawn. First, ETS with different carbon permits allocation schemes will bring about a downturn in the average cost-saving effect. Second, as a strategic enterprise, by manipulating carbon price, State power investment group with market power reduces its total abatement cost in all three Scenarios S0, A1 and A2. For example, State power investment group reduce its total abatement cost by 1.67% and significantly reduces trading cost by 99.35% in Scenario S0. Third, more than 75% of price-taking power plants increase their total abatement costs in Scenarios S0 and A2, while less than 25% of price-taking power plants increase their total abatement costs in Scenario A1. For example, in Scenario S0, changes in total abatement cost range from -2.49% to 12.10% and 342 power plants' total abatement cost increase. Additionally, the aggregate abatement cost of all power plants falls in all three Scenarios, because the amount of abatement cost reduced by State power investment group is greater than it increased by price-taking power plants. However, changes in total abatement cost range from -0.45% to 0.09% and just 96 power plants' total abatement cost increase. Besides, changes in emission trading role are not obvious in all three Scenarios S0, A1 and A2. Be specific, all sampled power plants don't change their emission trading role in Scenario A1 and there are only two and one power plants respectively increase their CO2 emissions from permits seller to permits buyer in Scenarios S0 and A2.

Table B.4. State power investment group with market power under different carbon permits allocation schemes

			S0	A1	A2
Carbon price (yuan/tCO2)			12.90	13.38	13.33
The average cost-saving effect			11.72%	11.60%	11.62%
The aggregate abatement cost			-0.18%	-0.21%	-0.23%
The feature of	State power investment	Changes in emission reductions	16.10%	6.38%	4.19%
		Changes in emissions	-0.30%	0.04%	-0.08%

power plant	group with market power	Changes in total abatement cost	-1.67%	-2.40%	-2.71%
		Changes in trading cost	-99.35% (buyer)	-2.19% (seller)	-25.85% (buyer)
	The lowest initial carbon intensity	Changes in emission reductions	-3.50%	0.13%	-0.28%
		Changes in emissions	0.05%	-0.002%	0.004%
		Changes in total abatement cost	-2.45%	0.09%	-0.20%
		Changes in trading cost	-3.38% (buyer)	0.079% (seller)	0.28% (buyer)
	The highest initial carbon intensity	Changes in emission reductions	-3.50%	0.13%	-0.28%
		Changes in emissions	0.02%	-0.001%	0.002%
		Changes in total abatement cost	-2.38%	0.08%	-0.19%
		Changes in trading cost	-3.47% (buyer)	0.073% (buyer)	-0.20% (buyer)