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Optimization of carbon mitigation paths in the power sector of Shenzhen, China

Xin Li, Guangxiao Hu, Ying Duan and Junping Ji*

Key Laboratory for Urban Habitat Environmental Science and Technology, School of Environment and Energy, Peking University Shenzhen Graduate School, Shenzhen 518055, China

*Author to whom any correspondence should be addressed. E-mail: jackyji@pku.edu.cn

Abstract. This paper studied the carbon mitigation paths of the power sector in Shenzhen, China from a supply-side perspective. We investigated the carbon mitigation potentials and investments of seventeen mitigation technologies in the power sector, and employed a linear programming method to optimize the mitigation paths. The results show that: 1) The total carbon mitigation potential is 5.95 MtCO₂ in 2020 in which the adjustment of power supply structure, technical improvements of existing coal- and gas-fired power plant account for 87.5%, 6.5% and 6.0%, respectively. 2) In the optimal path, the avoided carbon dioxide to meet the local government's mitigation goal in power sector is 1.26 MtCO₂. The adjustment of power supply structure and technical improvement of the coal-fired power plants are the driving factors of carbon mitigation, with contributions to total carbon mitigation are 72.6% and 27.4%, respectively.

1. Introduction and literature review

As one of the special economic zones, Shenzhen has undergone rapid economic development. The GDP of Shenzhen reached 1750 billion CNY in 2015 with a growth rate exceeding 8%. The main industries in Shenzhen are high-end manufacturing and the tertiary industries, so the dominant energy used is electricity. The power demand reached 815.5 kWh in 2015 and its CO₂ emission accounted for around 60% of total CO₂ emissions in Shenzhen. According to *China-U.S. Joint Presidential Statement on Climate Change*, Shenzhen announced to reach the CO₂ emission peak in 2022. To achieve this target, we should focus on the carbon mitigation in the power sector. The 13th Five-year Plan of Shenzhen was completed according to national and provincial government plans, so the carbon mitigation path for Shenzhen is influenced by a combination of national, provincial and municipal emission mitigation targets. About two-thirds of power demand is supplied by the *China Southern Power Grid Corp*, whose planning also has a great impact. Overall, the carbon mitigation plan in the Shenzhen power sector contains three parts: the plan for the adjustment of the power supply structure, the installation capacity of each kind of power plants and the improvement of existing power generation.

The power sector can achieve its carbon mitigation goal from supply-side, demand-side and grid-side perspectives. There are three methods to achieve carbon mitigation from a supply-side perspective. Firstly, technical improvement of existing power plant may lower the carbon emissions [1]. The second method is the adjustment of power supply structure, such as replacing coal-fired power with renewable power [2]. We can also employ the *carbon capture and storage* (CCS) technology [3]. From the demand-side perspective, power demand is reduced mainly through the *tiered pricing* [4], *carbon emission trading* and so on [5]. From the grid-side perspective, the main options are the *smart grid* [6] and the



improvement of power transmission efficiency. This study focuses on the carbon mitigation technology from a supply-side perspective, particularly the technical improvement of existing power plants and the adjustment of power supply structure. Because CCS technology is relatively new and expensive, it is exclusive. This study estimates the carbon mitigation potential and investment of the two above technologies and explores an optimal path for carbon mitigation in the power sector.

2. Methods and data

This study carried out the research into the optimization of CO₂ mitigation paths in the Shenzhen power sector with the base year being 2015 and the target year being 2020. Through a survey of the industry, we obtained 17 carbon mitigation technologies, which included the adjustment of power supply structure (No.1~4), the improvement of coal-fired power plant generation efficiency (No. 5~13), and improvement of gas-fired power plant generation efficiency (No. 14~17). The power demand and supply data, as well as carbon emission data in the Shenzhen power sector were obtained from the *Shenzhen Statistical Yearbook* and *China Southern Power Grid Corp*.

2.1. Calculating Carbon Mitigation Potential and Investment

For power supply structure adjustment, we can increase internal power generation and reduce power supplied by the *China Southern Power Grid Corp*. The corresponding investment c_i is based on a typical project scale and then expanded to the target year. The carbon mitigation potential is calculated by equation (1):

$$e_i = s_i \times (h_i \times f_s - \text{energy}_{i,j} \times f_j) \quad (1)$$

Where i is the number of carbon mitigation technologies (No. 1~4), s_i is the largest installed capacity of generation mode i , h_i is the annual power generation per unit installation of generation mode i , f_s is the carbon emission coefficient of power generation the from *China Southern Power Grid Corp*, $\text{energy}_{i,j}$ is the annual consumption of energy j per unit installation of generation mode i , and f_j is the carbon emission coefficient of energy j .

The improvement of existing coal- and gas-fired power plants efficiency can enhance power plants technology to reduce energy consumption, thus reducing carbon emissions. The carbon mitigation potential is calculated by equation (2):

$$e_i = \text{scale}_i \times \sum_j \text{fuel}_{i,j} \times f_j \quad (2)$$

Where i is the number of carbon mitigation technologies (No. 5~17), e_i is the carbon mitigation potential of technology i , scale_i is the existing power plant installation scale that can implement technology i , $\text{fuel}_{i,j}$ is the amount of energy j saving using unit technology i , and f_j is the carbon emission coefficient of energy j .

2.2. Linear programming

This study establishes an optimization model with the aim of minimizing investment referring to the carbon mitigation plan of the Shenzhen government on the power sector, as is shown in equation (3):

$$\min C = \sum_{i=1}^{17} (x_i \times c_i) \quad (3)$$

$$\text{s. t.} \begin{cases} \text{Elec}_0 + \sum_{i=1}^4 (x_i \times s_i \times h_i) + \text{Elec}_s \geq D & (4) \\ \text{Elec}_R + \sum_{i=1}^2 (x_i \times s_i \times h_i) + r_s \times \text{Elec}_s \geq \text{Per}_{\text{obj}} D & (5) \\ x_i \times s_i \geq S_{i,\text{obj}}, i = 1, 2, 3, 4 & (6) \\ \sum_{i=5}^{13} (x_i \times e_i) \geq F_{\text{obj}} & (7) \\ 0 \leq x_i \leq 100\%, i = 1, 2, \dots, n \end{cases}$$

Where C is the total amount of investment; i is the number of carbon mitigation technologies (No. 1~17), c_i is the amount of investment of technology i , and x_i is the popularization rate and also the decision variable of this model.

Equation (4) indicates that the power supply should meet power demand D (combining the elastic coefficient method with the governmental economic growth plan in Shenzhen, it is estimated that the demand will reach 81.6 billion kWh by 2020 [7]). Power supply contains three parts: annual power supplied by the existing installation $Elec_0$ (assuming that annual power supply unchanged). Power supplied by a new installation, represented by the product of popularization rate x_i , maximum installed scale s_i , and the annual power generation per unit installation h_i . And the power supplied by the China Southern Power Grid Corp $Elec_s$.

Equation (5) indicates that the proportion of power supplied by non-fossil energy to total power should reach to Per_{obj} (a proportion of 25%). Power supplied by non-fossil energy is separated into three parts: power supplied by local existing non-fossil energy $Elec_R$ (1.1 billion kWh generated by waste-to-energy plants), the newly increased power supplied by non-fossil energy, and the power supplied by external non-fossil energy. The proportion of power supplied by non-fossil energy to total energy is r_s (according to the plan of *China Southern Grid Corp*, this proportion is 50% in 2020).

Equation (6) indicates that the installation capacities of power supply structure adjustment should exceed those in the government plan $S_{i,obj}$ (the planned installation capacities for *distributed photovoltaic generation*, *waste-to-energy generation*, *newly established gas-fired plant generation* and *CCHP system* are 300 MW, 205 MW, 4800 MW and 3 MW, respectively).

Equation (7) indicates that the amount of carbon mitigation of existing coal-fired power plant should reach a target amount F_{obj} (to achieve the goal of an energy consumption of 310 grams of coal equivalent per kWh, we need to reduce it by 0.34 MtCO₂).

3. Results and discussions

3.1. Results of Carbon Mitigation Potential and Investment.

As shown in Table 1, the total CO₂ mitigation potential of the power sector reaches to 5.95 MtCO₂ by 2020. The largest contribution to this originates from the adjustment of the power supply structure, accounting for 87.5%, followed by the technical improvement of existing coal- and gas-fired power plants, 6.5% and 6.0%, respectively.

The total amount of investment required for reaching the carbon mitigation potential is 107.7 billion CNY in total. The technology of the adjustment of power supply structure needs the largest amount of investment, a total of 106.9 billion CNY, which includes building new gas-fired plants and distributed photovoltaic generation, which require 79.0 and 22.7 billion CNY, respectively. The amounts of investment needed for the improvement of the technology in existing coal- and gas-fired power plants are relatively low, which are 316 million CNY and 486 million CNY, respectively.

3.2. Optimization of Carbon Mitigation Path

Based on the model, we estimate that the minimum amount of investment in the power sector will be 84.2 billion CNY in 2020. The investment of *building new gas-fired plant*, *waste-to-energy generation* and *distributed photovoltaic generation* are high, reaching 79.0, 4.3 and 0.7 billion CNY, respectively. The total carbon mitigation of the power sector will be 1.26 MtCO₂ by 2020, in which the adjustment of power supply structure and technical improvement of coal-fired power plants account for 72.6% and 27.4%, respectively. This suggests that the adjustment of power supply structure is a key measure for carbon mitigation. In the view of detailed technology, the contributions of *building new gas-fired plants*, *waste-to-energy generation* and *distributed photovoltaic generation* are large, 0.49 MtCO₂, 0.25 MtCO₂ and 0.13 MtCO₂, respectively.

It is important to note that: 1) The popularization rate of existing gas-fired plant technical improvement is 0%, mainly due to a lack of relevant policy. 2) The popularization rate of *increasing generation capacity enlargement* should be 100% rather than 64.1% as there is only one coal-fired plant

in Shenzhen. 3) The popularization rates of *building gas-fired plant* and *waste-to-energy generation* are both 100% due to the planning of the government. Although the investment in *building gas-fired plant* is high, it can increase the self-sufficiency rate of Shenzhen power sector. 4) The popularization rate of *distributed photovoltaic generation* is only 3.2%, achieving the minimum planning goal of the government. According to equation (5), the proportion of power supplied by non-fossil energy to total power should reach 25%. This proportion in the *China Southern Grid Corp* is 50%, which is the main resource of power supply to Shenzhen. There is no constraining pressure for the Shenzhen government to increase the popularization rate of *distributed photovoltaic generation*.

Table 1. The mitigation potential, investment, and optimization mitigation path of power sector in 2020.

Technology	Mitigation Potential and Investment			The Optimal Mitigation Path		
	Mitigation Potential (Thousand tCO ₂)	Ratio	Investment (Billion CNY)	Popularization rate	Emission Mitigation (Thousand tCO ₂)	Investment (Billion CNY)
1 Distributed photovoltaic generation	409.8	68.9%	226.80	3.2%	13.1	7.26
2 Waste-to-energy generation	25.1	4.2%	42.61	100.0%	25.1	42.61
3 Building new gas-fired plant	49.4	8.3%	789.60	100.0%	49.4	789.60
4 CCHP ^a system	36.1	6.1%	9.63	10.0%	3.6	0.96
Sub-total	520.4	87.5%	1068.62	- ^b	91.2	840.40
5 Boiler intelligent blowing optimization	2.8	0.5%	0.02	100.0%	2.8	0.02
6 Gas ignition system	0.2	0.0%	0.09	0.0%	0.0	0.00
7 Retrofitting of boiler air preheater	2.2	0.4%	0.57	0.0%	0.0	0.00
8 Steam seal modification for steam turbine	0.6	0.1%	0.02	100.0%	0.6	0.02
9 Condenser energy saving system	10.0	1.7%	0.32	100.0%	10.0	0.32
10 Retrofit of steam turbine flow passage	18.0	3.0%	1.33	100.0%	18.0	1.33
11 Generation capacity enlargement	4.2	0.7%	0.50	64.1%	2.7	0.32
12 High voltage variable frequency speed	0.3	0.1%	0.03	100.0%	0.3	0.03
13 High efficiency motor replacement	0.8	0.1%	0.28	0.0%	0.0	0.00
Sub-total	39.0	6.5%	3.16	-	34.4	2.10
14 Increasing the heating surface of the boiler	5.2	0.9%	1.25	0.0%	0.0	0.00
15 Retrofitting of condensing steam turbine	26.2	4.4%	1.85	0.0%	0.0	0.00
16 Waste heat utilization of gas turbine rotor	2.8	0.5%	0.50	0.0%	0.0	0.00
17 Inlet air cooling of gas turbine	1.4	0.2%	1.26	0.0%	0.0	0.00
Sub-total	35.6	6.0%	4.86	-	0.0	0.00
Total	595.0	100.0%	1076.70	-	125.6	842.50

^a CCHP system refers to the combined cooling, heating and power generation system.

^b “-” represents that the popularization rate cannot be summed up directly.

4. Conclusions and Policy Recommendations

This study focused on carbon mitigation from a supply-side perspective in the Shenzhen power sector, and chose 17 carbon mitigation technologies, including power supply structure adjustment as well as the improvement of existing coal- and gas-fired power plants generation efficiency. We then estimated the carbon mitigation potentials and investments required for each technology. The results show that the total CO₂ mitigation potential of power sector is 5.95 MtCO₂. We employed linear programming approach to determine the optimal path for reduce carbon emissions according to the governmental planning for the power sector. The investment and avoided carbon dioxide in the optimal path are 84.3 billion CNY and 1.26 MtCO₂, respectively. The adjustment of power supply structure is a key method for carbon mitigation.

Considering the optimal path for reducing carbon emissions, this study proposes the following policy recommendations: 1) Promote the technical improvement of existing gas-fired power plants, whose carbon mitigation potential is large, while their corresponding investment is relatively low; 2) The improvement of coal-fired power plants technology can be further promoted; 3) The amount of investment in building new gas-fired plants is large, so the government should provide support such as low-interest loans or subsidies; 4) Waste-to-energy generation may cause air pollution, so the

government should provide environmental regulation; 5) *CCHP system* may be related to the problems like construction land property rights and pipeline renovation, so the government need to address these; 6) The popularization rate of *distributed photovoltaic generation* is only 3.2%, and it can be promoted further to achieve greater carbon mitigation in the power sector.

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