Prediction of Coal-Fired Power Generation Cost

Yixiao Wang
Imperial College London
E-mail: wyx980128@163.com

Abstract. China is not only a big country with coal production, but also a big country with coal consuming. The amount of coal used in coal-fired power generation in China accounts for 30% of the total production each year, but its power generation accounts for 75% of the total power generation. Although all kinds of coal is still the main energy source in China, the proportion of coal-fired power generation will gradually decrease from 2020, and the use of renewable energy will increase. CPPs in China are mainly distributed in the north and the east of China. However, coal reserves are distributed in the northern and western part on a national scale. The cost of coal-fired power generation has always been a hot topic. It is necessary to add fresh water cost and environmental cost to the total cost of coal-fired power generation. However, there are few studies to precisely consider all kinds of possible cost in the CPPs and estimate the cost of coal-fired power generation in the future. This article firstly revises the resources cost estimation in the existing literature. Water consumption for coal extraction, transportation, combustion and circulating cooling is estimated at 0.018 CNY/kWh. Based on the internal resources cost and external environmental cost, this paper established a fitting model to obtain the trend of cost over time. Lastly, it is predicted that the cost growth trend of coal-fired power generation will reach the peak in 2020 at around 0.908 CNY/kWh, and then it will rapidly decrease year by year.

1. Introduction
China is a big country of coal production and coal-fired power generation. However, coal-fired power generation will bring a series of environmental problems. According to the survey and prediction by Zhao, et al. [1], Coal-fired power plants (CPPs) generated 16097 kt SO2, 6965 kt NOx, 1842 kt PM10 and 994 kt PM2.5 in 2005, 11801 kt SO2, 9680 kt NOx, 1824 kt PM10 and 1090 kt PM2.5 in 2010. In addition, Coal combustion also releases a lot of volatile heavy metals like Hg, As and Se. Cumulative emissions of Hg, As and Se from all CPPs in China are 132.35 t, 550.08 t and 786.83 t respectively in 2007 [2]. It can be seen that environmental pollution caused by CPPs is a persistent social problem and it has not been solved. In addition, coal combustion also releases a lot of CO2. Greenhouse gases (GHGs) emissions by all kinds of related power sectors in China account for around 50% of China's total GHGs [3]. Global warming caused by GHGs is also a global well-known problem. On a global scale, 13% of the original paleoplant carbon can be extracted as coal. Among them, China uses about 30% of its coal to generate electricity more than 5 trillion kWh [4], accounting for more than 70% of total power generation in China, and occupying an absolute dominant position. It can be seen that coal-fired power plants (CPPs) will create serious pollution problems. Previous studies have estimated the cost of coal-fired power generation in China in the past two decades. It is generally believed that the price of coal is low and the quantity is large, so coal power generation is a kind of power generation mode with high economic benefits. Besides the cost of energy consumption,
the cost of water consumption and environmental protection should also be taken into account. Wang et al. [4] only considered the internal and external costs of a specific year, and the environmental factors they considered are very limited. Nie and Lv [5] only estimated and fitted the energy consumption cost and the cost of pollutant treatment in recent years, and they also did not take into account the life-cycle water use of electricity generation. So far, there are few studies to precisely estimate the cost of CPPs in the future.

This study will firstly introduce the current situation of coal structure and distribution in the world and in China. Then, the cost of coal-fired power generation in the whole life-cycle including the coal extraction, transportation, combustion and cooling systems will be estimated and fitted with a regression curve. Lastly, future cost of coal-fired power generation will be predicted according to the cost-year fitting model. The research results of this paper can help decision makers and researchers to better understand the cost status and prospects of coal-fired power generation, so as to further develop energy-saving and emission reduction measures.

2. Analysis of coal structure and distribution

2.1. Global coal structure and distribution

In current world, although many clean energy sources, such as wind energy, nuclear energy, solar energy get more attention, and some potential energy sources, such as tidal energy, are gradually discovered, coal is still the main energy source of mankind. From Figure 1A, coal-fired power generation accounted for more than 40% of the world's total power generation before 2020. Although it is predicted that the dominant position of coal will decline in the next decade, it will still be consumed by human beings as the main energy. Although coal reserves are huge globally, 80% of the world's coal storage is mainly concentrated in 10 countries and regions, China contains about 114.5 billion tons of coal, followed by the United States (237.3 billion tons) and Russia (157 billion tons) (Figure 1B).
2.2. Energy structure and spatial distribution of coal and CPPs in China

In the past 20 years, China's energy consumption started less than other countries and regions, but grew rapidly. Although new energy sources such as hydro power and nuclear energy have been developed and utilized, coal combustion for power generation was still the main energy source in China (Figure 1C). According to the report by Dai [7], coal-fired power generation accounts for about 75% of China's total power generation, far higher than the international average of 28%. Moreover, coal accounts for 97% of the total fossil fuel storage in China, with the rest of 3% in oil and natural gases [8]. However, China was predicted to actively adjust its energy structure, increase the proportion of clean energy use and reduce fossil fuel combustion in the near future under the premise of ensuring continuous growth of production capacity.

CPPs in China are mainly distributed in the northern and eastern coastal provinces (Figure 2), which largely depends on the degree of industrialization of a city. However, China's coal production is mainly distributed in the northern and western regions (Figure 3), which is related to the terrain and population rarity. The western region has been in the undeveloped stage for a long time, so the natural
resources are widely distributed.

Figure 2. Spatial distribution of CPPs in China [9].

Figure 3. Spatial distribution of coal in China.

3. Estimation of future coal-fired power generation cost

3.1. Energy and water use
In the whole life-cycle of coal-fired power generation, there are mainly two kinds of costs: internal resources cost and environmental protection cost. The cost of internal resources include the cost of coal extraction, transportation, combustion and the use of fresh water. About 19 billion square meters of fresh water is used for CPPs each year [10]. It is estimated that in the next 30 years, water consumption in CPPs will increase by 3.2 times [11]. During the whole life-cycle of coal-fired power generation, fresh water will be used in several processes. (1) Most importantly, water will be used as working fluid to drive the steam engine to do work, converting heat energy into mechanical energy, and thus into electrical energy. (2) Water is used as coolant, which is the most water consuming step.
According to the survey by Marknick [12]. Water consumption in closed-loop cooling is 1.87 m³/MWh. And water consumption in open-loop cooling will achieve 0.39 m³/MWh. Nie and Lv [5] fitted the cost of coal-fired power generation, but the use of freshwater is not taken into account in the estimation of internal resources consumption of power plants. The water cost formula is roughly as follows:

\[ P = (Q + (WE + WT) * Y + QC) * J \]

Where \( P \) is the water cost in CNY/kWh, \( Q \) is the amount of water needed to produce 1 kWh (g/kWh), \( WE \) is water consumption of coal extraction (g/MJ), \( WT \) is the water consumption of coal transportation (g/MJ), \( Y \) is the coal needed in coal-fired power generation using 2011 national practice (MJ/kWh). \( J \) is the unit price of industrial and commercial water (CNY/m³). \( QC \) is the water use in closed-loop cooling (m³/kWh). According to the survey by Chang et al. [13], CPPs using national standard technology require 2340 g of freshwater to produce 1 kWh electricity. Water consumption for 1 MJ coal extraction and coal transportation are respectively 30 g and 0.4 g. Coal use is 9.63 MJ/kWh. \( QC \) is the water consumption in closed-loop cooling (0.00187 m³/kWh). The unit price of industrial water is 4.10 CNY/m³. So \( P = 0.018 \) CNY/kWh. Further details can be found in Table 1.

**Table 1.** Internal resources cost of coal-fired power generation from 2000 to 2013 (CNY/kWh).

| Year  | Coal use cost (Nie & Lv [5]) | Total internal cost including fresh water consumption cost |
|-------|------------------------------|----------------------------------------------------------|
| 2000  | 0.151                        | 0.169                                                   |
| 2001  | 0.163                        | 0.181                                                   |
| 2002  | 0.164                        | 0.182                                                   |
| 2003  | 0.164                        | 0.182                                                   |
| 2004  | 0.212                        | 0.230                                                   |
| 2005  | 0.214                        | 0.232                                                   |
| 2006  | 0.215                        | 0.233                                                   |
| 2007  | 0.227                        | 0.245                                                   |
| 2008  | 0.3                          | 0.318                                                   |
| 2009  | 0.27                         | 0.288                                                   |
| 2010  | 0.28                         | 0.298                                                   |
| 2011  | 0.27                         | 0.288                                                   |
| 2012  | 0.227                        | 0.245                                                   |
| 2013  | 0.204                        | 0.222                                                   |

### 3.2. Total life-cycle cost including environmental cost

If only considering the internal resources cost of CPPs, electricity produced from CPPs is not that expensive. But the most intuitive economic cost is only one angle to evaluate the energy cost. It is necessary to pay more attention to the hidden cost of energy throughout the life-cycle of energy production, such as environmental costs. Perhaps the environmental damage caused by coal-fired power generation is no longer a new problem, such as acid rain, haze and global warming. Therefore, it is very important to convert these environmental damages into costs and consider the "affordability" of coal-fired power generation in connection with the electricity price.
Table 2. Estimate the cost of coal-fired power generation for the whole life-cycle (CNY/kWh).

| Year | Internal cost | Environmental cost (Nie & Lv [5]) | Total life-cycle cost |
|------|---------------|------------------------------------|-----------------------|
| 2000 | 0.169         | 0.453                              | 0.622                 |
| 2001 | 0.181         | 0.454                              | 0.635                 |
| 2002 | 0.182         | 0.458                              | 0.640                 |
| 2003 | 0.182         | 0.454                              | 0.636                 |
| 2004 | 0.230         | 0.459                              | 0.689                 |
| 2005 | 0.232         | 0.477                              | 0.709                 |
| 2006 | 0.233         | 0.486                              | 0.729                 |
| 2007 | 0.245         | 0.509                              | 0.754                 |
| 2008 | 0.318         | 0.539                              | 0.857                 |
| 2009 | 0.288         | 0.535                              | 0.823                 |
| 2010 | 0.298         | 0.553                              | 0.851                 |
| 2011 | 0.288         | 0.583                              | 0.871                 |
| 2012 | 0.245         | 0.598                              | 0.843                 |
| 2013 | 0.222         | 0.601                              | 0.823                 |

Wang et al. [3] has proposed five major sources of environmental costs. Among them, the main cost are the destruction of ecological environment caused by various pollutants and the funds needed to repair these damages. This paper uses the statistical data of Nie and Lv [5] to estimate the total life-cycle cost, further details can be found in Table 2. According to the above data, the cost curve of coal-fired power generation with the total cost summarized in this paper as the leading variable are fitted in Figure 4. The dots represent the actual data of coal-fired power generation cost, and the curve represents the fitted quadratic function graph. And the regression equation is as follows.

![Figure 4. Cost curve fitting of coal-fired power generation including internal resources cost and external environmental cost.](image-url)
Take year 2000 as $x = 0$, the relationship between cost change and year approximately fits quadratic function. The regression equation is $y = -0.0008 x^2 + 0.0319 x + 0.5897$. The black dots represent the original data, and the curve represents the fitting function curve. The coefficient of determination of the fitting equation is more than 89%. The fitted equation can accurately reflect the change of coal-fired power generation cost. Among the fitness parameters, the fitting error is 0.02344, which indicates that the selected fitting equation is suitable and the predicted results are relatively accurate. Based on the fitting model, the possible costs in the near future can be estimated. In order to more accurately reflect the trend of cost changes, the data of the last two years are also listed. Further details can be found in Table 3.

**Table 3.** Cost forecast of coal-fired power generation from 2018 to 2025 (CNY/kWh)

| Year | Total life-cycle cost of coal-fired power generation |
|------|-----------------------------------------------------|
| 2018 | 0.905                                               |
| 2019 | 0.907                                               |
| 2020 | 0.908                                               |
| 2021 | 0.907                                               |
| 2022 | 0.904                                               |
| 2023 | 0.900                                               |
| 2024 | 0.895                                               |
| 2025 | 0.887                                               |

According to the cost-year regression function, it can be estimated that the cost of coal-fired power generation in the future. As the data shown in the Table 3, the cost will climb to the peak at 2020 with 0.908 CNY/kWh, and the cost of coal-fired power generation will rapidly decrease in the next five years.

4. **Conclusion**

At first, this article summarizes the situation of coal-fired power generation in the world and in China. In the world, the proportion of coal-fired power generation will continue to decline, but it will still dominate compared with other energy sources. China is the third largest coal storage country of the world, and coal-fired power generation is still China's energy base, but the proportion of fossil fuel used in China will gradually decrease after around 2020 under the premise of increasing total energy demand.

Many stages in the life-cycle of CPPs will generate non-ignorable cost, such as coal extraction, transportation, combustion, working fluid use and coolant use. Many existing studies have not fully considered the cost of water in coal-fired power generation and the environmental hazards caused by power generation. In view of this, this paper estimate the use of fresh water in each process and the total is around 0.018 CNY/kWh.

After precisely calculating the cost of fresh water, this paper using fitting model further modifies and improves the cost function of coal-fired power generation. It can be seen that the cost increases year by year, but the trend gradually slows down. Finally, the future cost is predicted by the model and it will climb to the peak this year at around 0.908 CNY/kWh. Over the next five years, the cost will rapidly drop below 0.9.

5. **Suggestion**

This article estimates the future cost of coal-fired power plants to a certain extent. It can be used as a reference for environmental scholars, but it has some limitations. (1) The data of 2000-2013 are mainly used for modeling, but the data of recent years are not taken. (2) The environmental pollution
discussed in this article mainly includes sulfide, nitride, PM and carbon dioxide. In addition, the cost of water and heat pollution treatment should also be taken into account. Davidson and Bradshaw [14] stated that thermal pollution will lead to the increase of water temperature and the decrease of dissolved oxygen content, which will seriously threaten the balance of water ecosystem. High doses of Hg, As and Se also have adverse effects on humans and plants, such as embryonic malformations. (3) The water consumption in this paper is limited to closed-loop cooling systems. Open-loop cooling systems will consume less water than closed-loop cooling systems but withdraw more since the cooling water is extracted from the water bodies such as rivers and reservoirs and released after the cooling process. Therefore, CPPs with open-loop cooling systems will bring more complicated cost calculation.

2020 is the last year of China's 13th Five Year Plan (FYP), and it is probably the turning year of total coal-fired power generation cost. China once announced that it would reach the peak of carbon emissions by 2030 [15]. Now it is likely to achieve less coal-fired power generation cost in advance. However, the use of coal is still very large, replacing the dominant position of thermal power generation is still an important challenge facing China, and the pollution caused by coal is also very prominent in the horizontal comparison of the same industry. The country should formulate new requirements for the emission of coal-fired plants in the 14th FYP, requiring the exhausted gas and wastewater to be discharged after treatment. It is also necessary to further adjust the energy structure, vigorously develop new energy, reduce the proportion of energy supply of thermal power generation, and eliminate backward power generation facilities.

6. References
[1] Zhao, Y., Wang, S., Duan, L., Lei, Y., Cao, P., & Hao, J. (2008). Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction. Atmospheric Environment, 42(36), 8442–8452.
[2] Tian, H., Wang, Y., Xue, Z., Qu, Y., Chai, F., & Hao, J. (2011). Science of the Total Environment Atmospheric emissions estimation of Hg, As, and Se from coal-fired power plants in. Science of the Total Environment, The, 409(16), 3078–3081. https://doi.org/10.1016/j.scitotenv.2011.04.039
[3] IEA. World Energy Outlook 2011; International Energy Agency: Paris, 2011
[4] Wang, J., Wang, R., Zhu, Y., & Li, J. (2018). Life cycle assessment and environmental cost accounting of coal-fired power generation in China. Energy Policy, 115(June 2017), 374–384.
[5] Nie, Yan, & Lv, Tao., (2015) A Comparative Study on the Cost of Coal-fired with Considering the Environmental Cost and Photovoltaic Power Generation. CHINA POPULATION, RESOURCES AND ENVIRONMENT Vol.25 No.11 2015
[6] BP Energy Outlook 2019 edition The Energy Outlook explores the forces shaping the global energy transition out to 2040 and the key uncertainties surrounding that. (2019).
[7] Dai, C.L., 2014. Study on Motivation of Vertical Integration of China Coal and Electricity Enterprises—An Empirical Analysis of Listed Enterprises.
[8] Aden, N. T., Fridley, D. G., & Zheng, N. (2008). Outlook and Challenges for Chinese Coal ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY. (June).
[9] Xie, L., Huang, Y., & Qin, P. (2018). Spatial distribution of coal-fired power plants in China. Environment and Development Economics, 23(4), 495–515. https://doi.org/10.1017/S1355770X18000098
[10] The great water grab. (2016) How the coal industry is deepening the global water crisis. Greenpeace International; 2016
[11] Liao XW, Hall JW, Eyre N. Water use in China's thermoelectric power sector. Glob Environ Change-Hum Policy Dimens 2016;41:142–52.
[12] Macknick J, Newmark R, Heath G, Hallett KC. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett 2012;7(4)
[13] Chang, Y., Huang, R., Ries, R. J., & Masanet, E. (2015). Life-cycle comparison of greenhouse
gas emissions and water consumption for coal and shale gas fired power generation in China. Energy, 86, 335 – 343. https://doi.org/10.1016/j.energy.2015.04.034

[14] Davidson, B., & Bradshaw, R. W. (1967). Thermal Pollution of Water Systems. https://doi.org/10.1021/es60008a606

[15] He, G., Avrin, A. P., Nelson, J. H., Johnston, J., Mileva, A., Tian, J., & Kammen, D. M. (2016). SWITCH-China: A Systems Approach to Decarbonizing China’s Power System. Environmental Science and Technology, 50(11), 5467 – 5473. https://doi.org/10.1021/acs.est.6b01345

Acknowledgments
The author is very grateful to Professor Budimir Rosic for his guidance on the topic and the content of the article.