

Cost and Benefit Analysis of Desulfurization System in Power Plant

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Abstract

The economy of desulfurization system is of great significance for operation of desulfurization system and improving the environment quality in power plant. Based on the desulfurization power price policy, this paper analyzes the cost and benefit structure of the wet flue gas desulfurization system in Chinese power plant; that puts forward the calculation methods of total cost present value, total benefits present value and net present value during the life period of desulphurization system. Moreover using Cost-benefit sensitivity analysis to find out that there is sensitivity relationship between power generation hour and desulphurizer price. By applies these methods, the result shows that the economy of desulfurization system is better under the current designed scheme. But with the reduced power hour and risen price of limestone, the current desulfurization system power price policy of China cannot compensate the running cost of the desulfurization system in power plant rationally, and leads to lower economy of desulfurization system.

Keywords: Desulfurization power price; Wet flue gas desulfurization system; Cost and benefit analysis

1. Introduction

Wet flue gas desulfurization technology has become the most widely used desulphurization technology. The researchers have applied analytic hierarchy process to analyze three aspects of desulfurization system in power plant including technology, economy and sustainable development [1]. Abboud et al. [2] gave the detailed economic evaluation on the plans aiming at reducing sulfur dioxide emissions in power plant. Tong Gang and Deng Yongzhong[3] have put forward the corrective actions toward the problems that a Chinese power plant which has 600 MW supercritical coal-fired units encountered in applying the limestone-gypsum wet flue gas desulfurization. Tian Qiong[4] has evaluated the system operation conditions including desulfurizer consumption, electricity consumption, water consumption and the cost of operation system. The optimization scheme about the cost of wet limestone flue gas desulfurization technology was put forward by researchers [5]. Some problems about the gas desulfurization system such as influencing factors of economic operation, cost estimation model, economic evaluation methods, economic operation and benefit analytical methods have been studied by researchers [6,7]. At the same time, they have studied the variable cost of desulfurization system in the power plant. Xing Changcheng[8] has put forward the opinion that the changes of limestone consumption in power plant have a great effect on the benefits.

Based on dynamic fuzzy set theory, Sun Zhiao et al. [9] have set up the dynamic fuzzy mathematical model, which was mainly about synthetic performance evaluation of the flue gas desulfurization technology in the plant. By using dynamic fuzzy comprehensive evaluation method, they selected six different indexes to analyze the desulfurization process selection of a certain power plant. The six indexes were desulphurization efficiency, electricity price increase rate, unit cost, technology maturity level, example analysis of reconstruction costs in existing units FGD (wet flue gas desulfurization system) and investment costs in new unit FGD. With the increasing coal prices, the decreasing coal quality, the operation and maintenance cost of the desulfurization system was increasing greatly [10]

Tan S. et al.[11] have analyzed the influencing factors about desulphurization cost and electric price and established a calculation model which related to the desulphurization cost, electricity price, and emissions performance standards. They also suggested to classify

electricity price according to sulphur content and to settle accounts based on emission performance. Ren Xinfang [12] has studied the energy saving and emission reduction policies, conducted a deep and systematic study of the current desulfurization price, and confirmed the positive significance of the desulfurization electricity price to power plant. Yan Li [13] has pointed out that the cost and benefit of desulfurization played an important role in motivating the power generation enterprises to develop flue gas desulfurization. The present situation of sulfur dioxide emissions were studied by researchers. Li, Y. et al. [14, 15] who have researched the cost constitution of desulfurization system and put forward suggestions on desulfurization technology choice and electricity price policy. Considering the environmental benefits of desulfurization project which greatly reduced sulfur dioxide emission, Liu Jijiang and Jiang Suhong [16] have an analysis method based on dynamic economic evaluation. The researchers have affirmed the energy saving technology and economic policies enacted by the Chinese government and proposed constructive suggestions for China government to catch up with developed countries [17]. Daniel [18] has studied the emissions of sulfur dioxide and economic benefits of the old power plant in the United States with the application of new technology. The researchers have come up with a new performance optimization model based on traditional wet limestone flue gas system, and given some corresponding suggestions according to Chinese situation [19]. Ananth p. Chikkatur et al. [20] have made an analysis on Indian incentive policy to improve the efficiency of coal-fired power plants. The policy include cutting the costs, improving the utilization ratio of coal resources and reducing the emissions of sulphur.

To sum up, the wet flue gas desulfurization technology applied in power plants has significant environmental benefits based on the desulfurization power policy of China. But the installation and operation of desulfurization system have a big influence on the reliability of the power plant operation, which increases the operating costs. The implementation of the desulfurization power price policy brings certain economic compensation and stimulate the operation enthusiasm of desulfurization system. However, with the fierce compete, the power generation hours dropped, the desulfurizer price raised, the coal quality became lower, so the economy of the desulfurization system has changed a lot. The paper analyzes the cost-benefit of desulfurization system in the life period and puts forward the calculation method and sensitivity analysis method of total discounted cost, total benefits present value and net present value of desulfurization system. The applicability of the methods has been approved by an example. The paper plays an important role in improving the desulfurization electric power price policies and enhancing operation effectiveness of the desulfurization system.

2. Component And Computing Method Of Cost-Benefit In Desulfurization System

The cost of desulfurization system means the expenses of installation and operation of desulfurization system in power plant. It consists of the initial fixed investment, desulfurization cost, power consumption cost, water cost, large repairs cost, labor cost and the steam consumption cost. Effectiveness refer to the increased revenues and reduced losses of power station after installing and running the desulfurization system, including the saving costs of SO₂ emission, the sales revenue of the by-product gypsum and the allowances of desulfurization price.

2.1. Annual total costs of desulfurization system in its lifetime

The calculation method of each part costs is given as follows:

a. Initial fixed investment (C_F)

Generally it consists of own reserves and loans according to a certain portion. The own reserves as the capital must recover in the operating period. The loans are borrowed in the initial construction period, and should be repaid with the equal installments annually during the repayment period. The value is 0 after repayment period ends.

b. Annual desulfurizer cost (C_{CaCO_3})

In desulfurization process, the SO₂ formed during coal burning can be absorbed by the lime slurry and turn into CaSO₃ and CaSO₄. The sulfur in coal burning composition includes

combustible sulfur and non-combustible sulfur, and the percentage of combustible sulfur occupies about 85%.

The desulfurizer cost refers to the cost of limestone that is utilized for absorbing the SO₂ produced by the burning coal. It equals to the limestone consumption multiplied by its purchase price. When the sulfur in the coal and the desulfurizer utilized are certain, the consumption of the desulfurizer is in linear relationship with the operation time. Suppose the operation time is represented by t , the unit is the hour, and the unit-time consumption of desulfurizer is $K_{c_aCO_3}$, and the unit is ton per hour, then the annual desulfurizer consumption is written as

$$M_{c_aCO_3} = K_{c_aCO_3} t \quad (1)$$

The annual desulfurizer consumption costs can be calculated as follows:

$$C_{c_aCO_3} = M_{c_aCO_3} P_{c_aCO_3} = K_{c_aCO_3} P_{c_aCO_3} t \quad (2)$$

Where $M_{c_aCO_3}$ is the annual desulfurizer consumption, the unit is kg; t is power generation hours, the unit is hour; $P_{c_aCO_3}$ is the price of the limestone, the unit is yuan / kg

c. Annual power consumption costs (C_{Q_s})

The desulfurization process demands a certain amount of power; the cost equals to the amount of power consumption multiplied by on-grid price. This quantity of electricity will be sold on-grid if the desulfurization system is not set up. The value should be calculated according to the on-grid price instead of the power-generation cost, because the desulfurization system will reduce on-grid energy.

The annual power consumption of the desulfurization system is linear with the gross generation. It is generally calculated as the total power multiplied by definite ratio, which is due to the increased power consumption rate brought by the operation of the desulfurization system. The total generated power is equal to the product of the rated power and power-hour.

The power consumption cost of desulfurization system is calculated as follows:

$$C_{Q_s} = Q_s P_f = P_Q K_p P_f t \quad (3)$$

Where Q_s is the desulfurization power consumption, the unit is MW/h; P_Q is rated power of generation, the unit is MW; t is hours of power generation, the unit is hour; K_p is the increased power consumption rate for desulfurization; P_f is on-grid price, the unit is Yuan / kwh.

d. Annual desulfurization water costs (C_w)

The limestone-gypsum wet desulfurization process can eliminate the SO₂ by absorbing flue gas and spraying slurry to clean the exhaust gas, therefore it consumes large amounts of process water to maintain the operation of the FGD. The water, of which, 3% to 5% is absorbed by the gyp, roughly 6% is discharged as waste water and 90% or so is largely released into the atmosphere through the chimney. Therefore it is necessary to constantly replenish water in order to maintain the system operate regularly.

The formula for the annual desulfurization water cost is written here as

$$C_w = W_s P_w = W_0 P_w t \quad (4)$$

Where C_w is annual water consumption, the unit is Yuan; W_s is water consumption per unit time: the unit is ton; W_0 is operation hours, the unit is ton/h; t is operation hours, the unit is h; P_w is the price of water, the unit is Yuan/ton.

e. Annual desulfurization steam consumption costs (C_V)

When the gas heater uses the steam to heat or the GGH (gas gas heater) utilizes steam for the sweeping, a certain amount of steam will be consumed. Gas heater consumes much more steam; it is usually about 20t/h. The steam quantity used by the GGH steam sweeping is significantly less than this used by steam heater. But in terms of the equipment and installation costs, the latter is higher than the former.

The annual desulfurization steam consumption costs can be calculated as follows:

$$C_V = Q_V P_V = K_V P_V t \quad (5)$$

Where C_V is annual steam consumption cost, the unit is Yuan; Q_V is steam unit price, the unit is ton; P_V is steam consumption per unit time, the unit is Yuan/ton; K_V is steam consumptions unit time, the unit is ton/h; t is annual operation hours, the unit is h.

f. Overhaul expenses of annual fixed assets (C_r)

The annual overhaul expense of fixed assets refers to the expense of partially updating and renovating the fixed assets, such as the repairing of equipment and buildings. Due to the imbalance of overhaul expense, it is common practice to share or pre-withdraw this expense.

Since the gas-desulfurization of the power plants is still at its early stages, the desulfurization system discussed in the paper has only been adopted for a short period of time. Because of the lack of statistics in the overhaul expense, the overhaul expense in the paper is calculated according to the standardized rate of 30% in the petroleum and chemical industry.

The calculation formula of annual overhaul expense of fixed assets is as follows:

$$C_r = C_G K_R K_G \quad (6)$$

Where C_r is overhaul expense of fixed assets, the unit of C_r is Yuan; C_G is total investment of desulfurization system (static investment), the unit is Yuan; K_R is the rate of overhaul cost, the unit is %; K_G is the proportion according to which the total amount of investment in desulfurization system is transformed into fixed assets, and it is usually calculated as 95%.

g. Annual labor costs (C_{AE})

Labor costs are the salaries and benefits of operation and maintenance staff with the increasing desulfurization system operation, and is usually calculated by year. The calculation can be written as

$$C_{AE} = C_E N \quad (7)$$

Where C_{AE} is annual labor cost, the unit is Yuan; C_E is labor costs per person per year, the unit is Yuan; N is the number of the necessary personnel.

h. Total annual costs of desulfurization system in lifetime (C_A)

Annual total cost of desulfurization system in the lifetime can be constructed as follows:

$$C_A = C_F + C_{CaCO_3} + C_{Q_s} + C_w + C_V + C_r + C_{AE} \quad (8)$$

2.2. Annual total benefits of the desulfurization system in lifetime

The annual total benefits of desulfurization system in power station include the revenue brought by the desulfurization power price, the saved expenses for reducing the SO₂ emission and the sales proceed of by-product gypsum.

a. The annual revenue of desulfurization power price (G_t)

Desulfurization power price policy of China is the additional price based on original electricity price when the power plant installs the desulfurization system properly and reaches the environmental protection requirements.

According to regulation, the price of on-grid energy increases 1.5 cents/kwh based on current on-grid price after the power plant installing the desulfurization equipment. The desulfurization power price policy brings benefit to desulfurization system.

Annual desulfurization power price can be expressed as follows:

$$G_t = P_t Q_f = P_t P_Q t (1 - K_f) \quad (9)$$

Where P_t is desulfurization power price, the unit is Yuan/kwh; Q_f is on-grid energy of generation, the unit is kWh; P_Q is the total installed capacity of generation; K_f is power consumption rate; t is the hours of power generation.

b. The cost of reducing the SO₂ emission (G_{SO_2})

The environmental benefit is the saved cost of reducing the SO₂ emission after installing desulfurization equipment. The annual cost of reducing the SO₂ emission can be calculated as follows:

$$G_{SO_2} = P_{SO_2} Q_{SO_2} = P_{SO_2} K_{SO_2} t \quad (10)$$

Where P_{SO_2} is the emission fees of per unit weight of SO₂, the unit is Yuan/ton; Q_{SO_2} is the reduction of SO₂ emissions, the unit is ton; K_{SO_2} is emission reduction in unit time, the unit is ton/h; t is annual operating hours, the unit is h.

c. Annual sales revenue of gypsum (G_g)

Gypsum as the by-products of desulfurization system in power plant can be sold at the market price, its revenue is reckoned in the effectiveness of the desulfurization system. The annual sales revenue of gypsum can be written as :

$$G_g = Q_g P_g = K_g P_g t \quad (11)$$

Where G_g is the gypsum sales revenue, the unit is Yuan; P_g is the unit price for gypsum sales, the unit is Yuan/ton; Q_g is gypsum production, the unit is ton; K_g is gypsum production in per hour, the unit is ton/h; t is the hours of power generation, the unit is h.

d. The total annual benefits of the desulfurization system (G_T) .

It can be expressed as follows:

$$G_T = G_t + G_g + G_{SO_2} \quad (12)$$

2.3. Total cost present value, the total benefits present value and net present value of the desulfurization system

Present value, also known as the capital, refers that one or more cash flow which may happen in the future is equivalent to the value of current. Final value also can be called as the sum total of interest and capital. It means one or more cash flow which may happen at the moment or will happen on hand is equivalent to the value in a future time. In the practical work, present value and final value can be calculated by means of different discount rate to a certain point. And its economy efficiency can be compared and analyzed.

Net present value is one of the most important indicators about the dynamic evaluation of investment projects. It refers the cash flow that happens every year within the project life period. The accumulative value is the one that makes the annual net cash flow discount to the same date (usually is initial) according to certain discount rate. The expression is written as

$$NPV = \sum_{i=0}^N (CI - CO)_i (1+r)^{-i} \quad (13)$$

Where NPV is net present value, CI is the cash inflow of one year, CO is the cash outflow of the year. r is the discount rate, N is the life period, including the construction period and operation period.

The rule of using net present value index to evaluate single scheme is: if $NPV \geq 0$, it means the scheme is economic and reasonable; if $NPV < 0$, it means the scheme should be denied.

a. The total cost present value of the desulfurization system

Discount the annual cost to the beginning, and accumulate the total cost of the desulfurization system as follows:

$$GPC = \sum_{i=1}^N C_{Ai} (1+r)^{-i} \quad (14)$$

Where GPC is the total cost of present value; C_{Ai} is the total cost in the year; r is discounted rate; i is the year of lifetime, $i = 1, 2, \dots, N$.

b. The total benefit present value of the desulfurization system

Discount each year's benefit, namely the present value to the beginning, and then accumulate the total benefits value of desulfurization system as follows:

$$GB = \sum_{i=1}^N G_{Ti} (1+r)^{-i} \quad (15)$$

Where GB the total is benefit present value; G_{Ti} is the total benefit of the year; r is discounting rate.

c. Net present value of the desulfurization system

Net present value of the desulfurization system means the total benefits present value minus the total cost present value. The net present value can be calculated as follows:

$$GPV = GB - GPC = \sum_{i=1}^N (G_{Ti} - C_{Ai}) (1+r)^{-i} \quad (16)$$

3. Cost-Benefit Sensitivity Analysis Of Desulfurization System

Sensitivity analysis is a mostly used method to research uncertainty in economic evaluation. And it studies the influences of uncertain factors on the economic benefit. To be specific, it is based on the certain analysis to make in-depth analysis for the extent economic impact when the uncertain factors change. Once an uncertain factor changes in a small range

which it leads to have a lot of changes on economic benefit evaluation value, and causes the correctness of the original conclusion. Therefore, the uncertain factor is definite sensitivity factor.

It can be seen from the costs and benefits calculation formula that many factors affect the costs and benefits of desulfurization system, such as power generation hours, the desulfurizer price, the water price, electricity price and gypsum sales price. In the current power generation market, with the increasing competition and the decreasing power generation hours, the capacity of the power plant is greatly reduced. Consequently it causes adverse impact on the desulphurization electricity price income. At the same time with the widely used wet flue gas desulfurization technology and the quickly increased price of desulfurizer, the cost of desulfurizer raised highly. So it has serious negative effect on the economy operation of desulfurization system in power plant. The following sensitive analysis is related to costs and benefits of the desulfurization system from the perspective of generation hours and desulfurizer price.

When the hours of generation are reduced, the variable costs such as the limestone, the power consumption, the water consumption, the steam consumption of the desulfurization system would be reduced correspondingly. However, the revenue of desulfurization price, the reduced emission effectiveness and gypsum sales revenue also are decreased at the same time; the cost of limestone consumption are increased along with the risen of limestone price.

The power generation hour changes influence the total cost and total benefit of the desulfurization system

Suppose the hours of power generation reduced Δt , and calculate the total cost, total benefit, and net present value of the desulfurization system. Once the hours of power generation changed, it inevitably have effect on the desulfurizer consumption costs, power costs, water costs and steam consumption costs. Otherwise, it also influences the saving cost of SO₂ emission and the revenue of gypsum sales. All costs and benefits of desulfurization can be calculated as follows:

Consumption costs of desulfurizer

$$C_{C_aCO_3} = M_{C_aCO_3} P_{C_aCO_3} = K_{C_aCO_3} (t - \Delta t) P_{C_aCO_3} \quad (17)$$

Desulfurization power cost

$$C_{Q_s} = Q_s P_f = P_Q (t - \Delta t) K_p P_f \quad (18)$$

Desulfurization water-consuming costs

$$C_w = W_s P_w = W_0 (t - \Delta t) P_w \quad (19)$$

Desulfurization steam consumption costs

$$C_v = Q_v P_v = K_v (t - \Delta t) P_v \quad (20)$$

Income of desulfurization electricity price

$$G_t = P_t Q_f = P_t P_Q (t - \Delta t) (1 - K_f) \quad (21)$$

Saving the cost of SO₂ emission

$$G_{SO_2} = P_{SO_2} Q_{SO_2} = P_{SO_2} K_{SO_2} (t - \Delta t) \quad (22)$$

Revenue of gypsum sales

$$G_g = Q_g P_g = K_g (t - \Delta t) P_g \quad (23)$$

Net present value change of the desulfurization system

When the power generation hours reduced Δt , the calculation about net present value of desulfurization system depends on the above calculations of costs, benefits and the net present value,

$$GPV_{t-\Delta t} = \sum_{i=1}^N (G_T - C_A)_i (1+r)^{-i} = GPV_t - \sum_{i=1}^N (P_i P_Q (1-K_f) + P_{SO_2} K_{SO_2} + K_g P_g - K_{C_a CO_3} P_{C_a CO_3} - P_Q K_P P_f - W_0 P_w - K_V P_V)_i \Delta t (1+r)^{-i} \quad (24)$$

Where GPV_t is the net present value of desulfurization system when power generation hours is t hours; $GPV_{t-\Delta t}$ is the net present value when the hours of power generation reduced Δt .

When the hours of power generation reduced Δt h, the change of net present value can be expressed as flows:

$$NPV = - \sum_{i=1}^N (P_{SO_2} K_{SO_2} + K_g P_g - K_{C_a CO_3} P_{C_a CO_3} - P_Q K_P P_f - W_0 P_w - K_V P_V)_i \Delta t (1+r)^{-i} \quad (25)$$

The risen of limestone prices affect the costs and benefits of desulfurization system. The limestone prices risen only affect the cost of desulfurizer, when the price of limestone risen the $\Delta P_{C_a CO_3}$, the consumption cost can be written as

$$C_{C_a CO_3} = M_{C_a CO_3} (P_{C_a CO_3} + \Delta P_{C_a CO_3}) = K_{C_a CO_3} t (P_{C_a CO_3} + \Delta P_{C_a CO_3}) \quad (26)$$

Where $C_{C_a CO_3}$ is annual cost of desulfurizer, the unit is yuan; $M_{C_a CO_3}$ is the annual amount of desulfurizer, the unit is kg; $P_{C_a CO_3}$ is the price of limestone, the unit is Yuan/kg.

The effect of the rise of limestone price on the net present value:

$$NPV = - \sum_{i=1}^N (K_{C_a CO_3} t \Delta P_{C_a CO_3})_i (1+r)^{-i} \quad (27)$$

In conclusion, the change of power generation hours and limestone price cause a corresponding change on the net present value of desulfurization system. The above calculation methods can be applied to measure these changes.

4. Case Analyses

A Chinese power plant runs four 330-MW coal-fired sets, and the power generation hours are designed for 5100 hours. In order to meet the requirement of flue gas pollutants standard and improve peripheral environmental conditions. The power plant decided to conduct flue gas desulfurization for all generation sets.

A set of desulfurization public system and facilities were constructed by the four generators with the limestone-gypsum wet process. The construction period is three years and operation-term is 20 years.

4.1. Cost-benefit analysis

Cost analysis

Fixed-asset investment costs

The static investment based on the design report of desulfurization system is 417.5 million yuan and the annual investment plan of fixed-assets is that 30% for the first year, 55% for the second year and 15% for the last year. The own capital accounts for 30% and long-term loans occupy 70% with a 6.12% annual interest rate, 10 years repayment and 3 years grace period in financing. The own fund investment is 37.58 million yuan for the first year, 68.89 million yuan for the second year and 18.79 million yuan for the third year. Every year the power plant spends 38.21 million yuan to repay the principal and interest of long-term loans from the fourth year to the 13th year. The figure of fixed-assets investment spending shown in Table.1

Table 1. Fixed-assets investment spending unit: 100 million yuan

Periods	1	2	3	4	5	6	7	8	9	10	11	12	13
C_F	37.5	68.8	18.7	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2
	8	9	9	1	1	1	1	1	1	1	1	1	1

Source: Based on the design report of desulfurization system, 2010, (Internal data)

Desulfurizer costs

The limestone consumption is 4×9.62 tons per hour, unit price is 200 Yuan per ton, and thus the cost of purchasing the limestone can be calculated by formula (2) as follows:

$$C_{c,co_3} = M_{c,co_3} P_{c,co_3} = K_{c,co_3} t P_{c,co_3} = 38.48 \times 5100 \times 200 = 3924.96 \text{ million Yuan}$$

The Increased cost of power consumption

Unit rated power is $P_Q = 4 \times 330 = 1320$ MW, power consumption rate of desulfurization system is 1.37%, the on-grid price is $P_f = 0.2786$ yuan/kw·h.

Thus, according to the calculation method of desulfurization system, the power consumption cost can be expressed by the formula (3) as follows:

$$C_{Q_s} = Q_s P_f = P_Q t K_p P_f = 1320 \times 1000 \times 5100 \times 0.0137 \times 0.2786 = 25.694832 \text{ million Yuan}$$

Water costs

The water consumption of desulfurization system is $W_0 = 300$ tons per hour, the industrial water price is $P_w = 2.28$ yuan/ton. Thus, according to the calculation of annual water fee in desulfurization system, it is calculated by the formula (4) as follows:

$$C_w = W_s P_w = W_0 t P_w = 300 \times 5100 \times 2.28 = 3.4884 \text{ million yuan}$$

Steam consumption costs

The steam consumption per hour is $K_v = 1.65$ tons, unit steam price is $P_v = 50$ yuan/ton. Thus, according to the calculation by formula (5) of annual steam consumption in desulfurization system, it is written as

$$C_v = Q_v P_v = K_v t P_v = 1.65 \times 5100 \times 50 = 42.075 \text{ million yuan}$$

Maintenance costs of equipment

The investment of desulfurization system is 417.5 million yuan, of which the fixed assets is account for 96% and overhaul cost rate is 3%, the annual maintenance cost can be calculated by formula (6) as follows:

$$C_r = 41750 \times 96\% \times 3\% = 12.024 \text{ million Yuan}$$

Personnel wages and welfare

There are 30 people in the desulfurization workshop, the annual salary is $C_E = 65000$ Yuan. Then the annual labor costs can be written by the formula (7) as follows:

$$C_{AE} = C_E N = 65000 \times 30 = 1.95 \text{ million Yuan}$$

Benefit analysis

Desulfurization electricity price income (G_i)

The total capacity of the unit is 1320 MW and the total generation hour is 5100, and the annual energy output is 6.732 billion KWH. After installation of the desulfurization system, the power consumption rate is 7.57% and the annual power supply can be calculated by the formula (9) as follows:

$$Q_f = 1320 \times 5100 \times (1 - 0.0757) = 6222.388 \text{ million kw}\cdot\text{h}$$

Desulfurization electricity price is 0.015 Yuan/kw·h, thus, the income of desulfurization electricity is written by formula (9) as follows:

$$G_i = 0.015 Q_f = 0.015 \times 6222.388 \text{ million} = 93.3358 \text{ million yuan}$$

Cost of reducing the SO₂ emission (G_{so_2})

After the desulfurization system is implemented, the SO₂ emissions of the power plant per hour decreased from 15.92 t/h to 0.896 t/h and the reductive emissions per hour is $K_{so_2} = 15.024$ ton. The charge standard for SO₂ emissions is 0.6 Yuan/kg according to relevant local departments. Therefore, the cost of SO₂ emissions in the power plant could be saved each year can be expressed through the formula (22).

$$G_{so_2} = P_{so_2} \square Q_{so_2} = P_{so_2} \square K_{so_2} \square T = 15.024 \times 5100 \times 1000 \times 0.6 = 45.9734 \text{ million yuan}$$

The total benefit (G_T)

As gypsum sales income is 0 in the case, the annual total benefits of power plant can be expressed by the formula (12) as follows:

$$G_T = G_i + G_{so_2} + G_g = 93.335814 + 45.97344 = 139.3093 \text{ million Yuan}$$

Annual cash flow analysis

According to the calculation above, the cash flow of desulfurization system in the construction period and operation-term can be shown in Table 2.

Table 2. The cash flow statement of desulfurization system in construction and running period
unit: 100 million Yuan

periods	cash outflow	cash inflow	net inflow
1	37.58	-	-37.58
2	68.89	-	-68.89
3	18.79	-	-18.79
4	125.7675822	139.3093	13.5417
5	125.3875822	13930.93	13.9217
6	125.3875822	139.3093	13.9217
7	125.3875822	13930.93	13.9217
8	125.3875822	139.3093	13.9217
9	121.0875822	139.3093	18.2217
10	121.0875822	139.3093	18.2217
11	121.0875822	139.3093	18.2217
12	121.0875822	139.3093	18.2217
13	121.0875822	139.3093	18.2217
14	82.8775822	139.3093	56.4317
15	82.8775822	139.3093	56.4317
16	82.8775822	139.3093	56.4317
17	82.8775822	139.3093	56.4317
18	82.8775822	139.3093	56.4317
19	82.8775822	139.3093	56.4317
20	82.8775822	139.3093	56.4317
21	82.8775822	139.3093	56.4317
22	82.8775822	139.3093	56.4317
23	82.8775822	139.3093	56.4317

Analyzing on total cost present value, total benefits present value and net present value

Suppose the discount rate r is 10%, and calculating the total cost present value, total benefits present value and net present value based on above formulas and data in Table 2.

Total cost present value can be calculated by the formula (14) as follows:

$$GPC = \sum_{i=1}^N C_{Ai} (1+r)^{-i} = 906.6563 \text{ million Yuan}$$

Total benefits present value can be calculated by the formula (15) as follows:

$$GB = \sum_{i=1}^N G_{Ti} (1+r)^{-i} = 980.1803 \text{ million Yuan}$$

Net present value can be calculated by the formula (16) as follows:

$$GPV = GB - GPC = \sum_{i=1}^N (G_{Ti} - C_{Ai}) (1+r)^{-i} = 73.524 \text{ million Yuan}$$

The results show that under the current desulfurization price policy, the net present value of desulfurization system is more than 0, namely total benefit present value is larger than cost present value, so the power plant has a good economic benefits. The operation of desulfurization system not only improves the environmental quality, but also increases economic benefits for the enterprise. Therefore, the power plant has a great incentive to install and operate the desulfurization system actively.

4.2. Sensitivity analysis

The following sensitivity analysis is based on the changing of power generation hours and limestone price.

Table 3. The sensitivity analysis of cash flow of desulfurization system unit: 100 million Yuan

years	power generation hours reduced by 20%			power generation hours reduced by 40%		
	limestone prices risen 10%			limestone prices risen 30%		
	cash outflow	Cash inflow	Net inflow	cash outflow	Cash inflow	Net inflow
1	37.58	-	-37.58	37.58	-	-37.58
2	68.89	-	-68.89	68.89	-	-68.89
3	18.79	-	-18.79	18.79	-	-18.79
4	114.768	111.4474	-3.32052	105.0144	83.5856	-21.42884
5	114.388	111.4474	-2.94052	104.6344	83.5856	-21.04884
6	114.388	111.4474	-2.94052	104.6344	83.5856	-21.04884
7	114.388	111.4474	-2.94052	104.6344	83.5856	-21.04884
8	114.388	111.4474	-2.94052	104.6344	83.5856	-21.04884
9	110.088	111.4474	1.35948	100.3344	83.5856	-16.74884
10	110.088	111.4474	1.35948	100.3344	83.5856	-16.74884
11	110.088	111.4474	1.35948	100.3344	83.5856	-16.74884
12	110.088	111.4474	1.35948	100.3344	83.5856	-16.74884
13	110.088	111.4474	1.35948	100.3344	83.5856	-16.74884
14	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
15	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
16	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
17	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
18	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
19	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
20	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
21	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
22	71.878	111.4474	39.5695	62.12439	83.5856	21.4612
23	71.878	111.4474	39.5695	62.12439	83.5856	21.4612

Suppose the discount rate r is 10%, according to the data in table 3 and various calculation formulas, the total cost present value, total benefits present value and net present value of desulfurization system can be obtained in Table 4.

Table 4. Cost-benefit sensitivity analysis form of desulfurization system unit: 100 million Yuan

	power generation hours	
	reduced by 20%	reduced by 40%
	limestone prices risen by 10%	limestone prices risen by 30%
discounted cost	829.2626	760.6368
Present value of benefits	784.1443	588.1082
NPV	-45.11837	-172.5286

From the above analysis, it can be seen that with the decreased of power generation hours and increase of desulfurizer price, total benefits value of desulfurization system is lower than the current total cost present value and net present value of desulfurization system is negative value.

It is proved that with the changes of power generation hours and desulfurizer price, the economics of the desulfurization system undoubtedly become poorer and seriously dampen the enthusiasm of desulfurization system operation for the power plant. The reason is that the Chinese current price policy is the compensation according to the output of power plant. With the hours of generation power reducing and on-grid energy cutting, the income and interest of power plant are greatly reduced, which bring more pressure on the cost of desulphurization system operation.

5. Conclusion

The paper analyzes the cost and benefit constitute of the coal-fired power plant wet flue gas desulfurization system. The costs include the early fixed investment, desulfurizer cost,

electricity and water consumption expenses, the cost of steam expenses, repairs and artificial cost. Benefits include desulfurization electricity price subsidies income, saved SO₂ emission costs and by-product gypsum sales income. The paper gives the equation of how to calculate the cost and benefit per year in lifespan, and puts forward the calculation methods of total cost present value, total benefit present value and net present value. The sensitivity analysis method on the economy of desulphurization system studies the power generating hours and desulfurization system price. It proves that the above methods are feasible by application.

As the power generation market competition intensifies, power generating hours sharply reduced and raw material price increasing rapidly as well. such as limestone. The total cost present value of desulfurization system is greater than the total benefits present value, which leads to the uneconomic of the desulfurization system.

The cost of desulfurization system is not effectively compensated. It has negative influence on the economic benefits of power generation enterprise, even the enthusiasm of the desulfurization system running. In order to ensure the desulfurization cost in power plant to be better compensated and make the desulphurization system run preferably, the paper suggests that it is necessary to make an adjusted policy based on the existing power price and set up the dynamic desulfurizer electricity price compensation mechanism.

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[21] The source of Table 1 is based on the design report of desulfurization system, 2010. (Internal data)