Economic Evaluation of Flue Gas CO_2 Capture Systems in Coal-Fired Power Plants

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Abstract. The impact of the greenhouse effect induced by CO_2 has demonstrably influenced the trajectory and sustainability of human society. In the preceding decades, the atmospheric concentration of carbon dioxide has escalated from 277 PPM in the industrial era to 412.4 PPM in 2020. In 2020, China, ranking among the globe's foremost contributors to greenhouse gas emissions, discharged in excess of 11 billion tons of carbon through fuel combustion and industrial procedures, constituting approximately 90% of the nation's overall greenhouse gas emissions. Given that coal-fired power plants constitute a prominent origin of CO_2 emissions, the effective capture of CO_2 from their flue gas is imperative to mitigate anthropogenic CO_2 emissions. Presently, large-scale capture of CO_2 from flue gas encounters challenges, including elevated capture costs and suboptimal economic returns. Furthermore, the scarcity of operational demonstration projects for capturing CO_2 from flue gas has resulted in an absence of detailed economic analyses encompassing construction costs, operating costs, and other facets of the CO_2 capture process. In response to these challenges, this paper concentrates on conducting an economic analysis of the CO_2 capture system from flue gas within a specific power plant. This research addresses both the construction costs and operating costs associated with the CO_2 capture system, concurrently highlighting the social and monetary benefits emanating from the capture of CO_2 in flue gas. The objective is to furnish data support and guidance for the expansion and operation of flue gas CO_2 systems, along with the investment budget required for the construction of new capture systems.

Keywords: Power plant, CO_2, Capture, Economic.

1 Introduction

Global warming is a major concern, and CO_2 is widely recognized as an important cause of global warming due to its greenhouse effect,According to the estimates from the US Energy Information Administration (EIA)[1], the global total primary energy supply surged by approximately 150% between 1971 and 2015, primarily relying on fossil energy. The reduction of CO_2 emissions has emerged as a shared global challenge, making it a common imperative for humanity. In China, electricity and heat emissions stand out as the leading contributors to CO_2 emissions[2].

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Globally, China stands as a major emitter of CO_2 [3], with its total CO_2 emissions reaching 9.1 billion tons in 2016, constituting 27.3% of the total global CO_2 emissions[4]. To address climate change, Carbon Dioxide Capture, Utilization, and Storage (CCUS) technology are recognized as pivotal measures for achieving low-carbon and sustainable economic development. In its 12th Five-Year Plan, China has incorporated CCUS technology into its national strategy for carbon emission reduction[5]. Simultaneously, CO_2 serves as a significant resource with wide-ranging applications in production and daily life. Large-scale capture and reuse of CO_2 from power plant flue gas can yield substantial social and economic benefits[6].However, the primary challenge confronting flue gas CO_2 capture lies in its high capture costs, impeding the widespread adoption and development of this technology globally.

During the operational phase, we can deduce that the total system investment ranges from 2.779 billion yuan, excluding CCS devices, to 3.417 billion yuan after their incorporation. Consequently, there is a 13% reduction in net power generation efficiency. The primary driver behind the cost increase is attributed to the tower, heat exchanger, and other equipment, with the absorption tower accounting for 27% of the total investment and regeneration energy consumption constituting 70% of the total operating costs. These factors markedly elevate the overall system investment, underscoring the imperative for conducting an economic analysis to curtail investment costs. However there are few demonstration projects and even fewer economic analyses of flue gas CO_2 capture systems[7].

In light of this situation, this paper focuses on the flue gas CO_2 capture system of a power plant, providing a detailed economic analysis. It examines the construction and operational costs of the capture system, as well as the social and financial benefits it generates. This study represents a pioneering effort in the domestic industry, marked by its high level of originality.

2 Carbon dioxide capture system process flow.

The operational workflow of a carbon dioxide capture system encompasses distinct processes, including the combustion process, post-combustion gas treatment, carbon dioxide capture, regeneration process, compression and transportation, as well as storage and utilization.

(1) Combustion Process

The inaugural phase entails the combustion of fuel, such as coal, within the power plant to produce energy. This process gives rise to the emission of gases, prominently featuring carbon dioxide (CO_2).

(2) Post-Combustion Gas Treatment

Prior to entering the carbon dioxide capture system, the discharged combustion gas undergoes essential treatments, including water scrubbing and alkaline scrubbing, to eliminate pollutants and particulates from the post-combustion flue gas. This ensures the effective functionality of the subsequent carbon capture system.

(3) Carbon dioxide capture

Within a capture system, the specifically chosen absorbent selectively extracts $CO_2$from the processed flue gas. Common capture methods encompass chemical absorption, physical absorption, and membrane separation techniques, with chemical absorption being the predominant and widely employed approach.

(4) Regeneration process

The extraction of captured carbon dioxide from the absobent solution is commonly termed as regeneration. This phase typically entails the heating of the absorbent solution, facilitating the release of carbon dioxide from the absorbent.

(5) Compression and transportation

Normally, the captured carbon dioxide undergoes compression, transforming into a liquid or high-pressure gas for convenient storage and transportation. This step necessitates dedicated compression equipment and an intricate network of interconnected pipelines.

(6) Storage or Utilization

The captured CO_2 may be stored in underground geological formations or conveyed through pipelines to suitable utilization sites, for example, to produce liquid CO_2, dry ice, methanol, and so forth. dioxide capture and purification system.

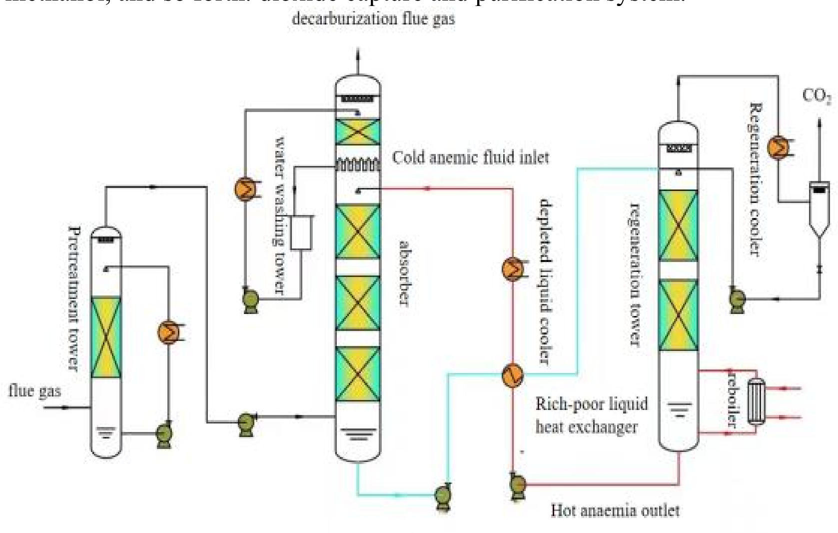

Fig. 1. Process flow diagram of carbon

The CO_2 capture and purification system process flow is illustrated in Fig. 1 The flue gas from the Victory Power Plant, after desulfurization, has a temperature of 180°C. The flue gas undergoes cooling in a pre-treatment tower and subsequent processes, including dust removal, deep desulfurization, and denitrification, reducing the temperature to 40-50°C. Following flow rate adjustments, the flue gas is directed to the absorption tower for CO_2 absorption facilitated by an induced draft fan.

Table 1. Technical parameters of the main flow of the process.

Parameters	Unit	Value
Type of absorber		MEA
Absorbent mass concentration	w.t.%	30
CO_2 lean liquid load	mol CO_2/molMEA	0.25
CO_2 rich liquid load	mol CO_2/molMEA	0.504
Absorption tower inlet lean liquid temperature	°C	40
Absorption tower inlet flue gas temperature	°C	40
Regeneration energy consumption	GJ/t CO_2	3.02
Absorbent circulation flow	t/t CO_2	18.4
Total cooling water usage	t/t CO_2	76.84
MEA absorbent supplement	kg/tCO_2	1.93

The primary technical parameters of the process system are presented in Table 1. Building upon optimized operating conditions, an interstage cooling process has been incorporated into the absorption tower. This addition serves to ensure a uniform temperature distribution within the absorption tower, thereby enhancing the reaction between the absorbent and CO_2. This particular modification represents a key feature of the process. Simultaneously, to minimize both the water vapor content at the outlet of the regeneration tower and the load on the reboiler, the regeneration system employs a rich liquid graded flow process. This strategic adjustment effectively reduces the overall energy consumption during the regeneration process.

3 Economic analysis model

3.1 System energy consumption

The energy consumption of the system is primarily categorized into two components: regeneration heat consumption and system electricity consumption. Regeneration heat consumption refers to the energy needed for regenerating the rich liquid in the regeneration tower, calculated based on the reboiler load obtained from the Aspen Plus simulation results. Alternatively, the approach proposed by Leites et al [8,9] can be applied, dividing the energy consumption into three segments: sensible heat, reaction heat, and latent heat. These are determined using Equations 1 to 4.

$$Q_c = \left(Q_{\text{sens}} + Q_{\text{reac}} + Q_{\text{strp}}\right)/G_{\text{CO}_2} \tag{1}$$

$$Q_{\text{sens}} = m_s c \Delta t_h \tag{2}$$

$$Q_{\text{reac}} = G_{\text{CO}_2} \Delta H_{\text{abs}} \tag{3}$$

$$Q_{\text{strp}} = G_{\text{CO}_2} r_{H_2O} \frac{P_{H_2O}}{P_{\text{CO}_2}} \tag{4}$$

Calculate the system power consumption according to the formula for calculating the power consumption of ventilator and pumps[10], as shown in Equations 5-6.

$$E = \frac{QRTN\gamma}{(\gamma-1)\eta}\left[\left(\frac{P_d}{P_s}\right)^{\frac{(\gamma-1)}{N\gamma}} - 1\right] \tag{5}$$

$$E_P = \frac{\rho_L g h L}{\eta_P} \tag{6}$$

In the formulas

Q -represents the molar flow rate of gas,mol/s; R -represents the gas constant;

T -represents the temperature,K; N -represents the compression ratio;

γ -represents the adiabatic index; η -represents the efficiency of the fan or compressor;

P_d and P_s -represent the pressure of the gas after compression and the initial gas pressure, respectively, bar.

ρ_L - the fluid density, kg/m^3; g - the acceleration of gravity, m/s^2;

h - the range, m; L - the fluid flow rate, m^3/s; η_P - the efficiency of the pump.

3.2 System investment and operating cost

The cost of the decarbonization system is divided into two major components: the decarbonization system investment and the annual operating cost.

The decarbonization system investment encompasses direct equipment investment and other costs, as determined by the percentage relationships outlined in Table 2 [11]. Direct equipment investment covers the expenses associated with each piece of equipment, with the size of the equipment determined through Aspen Plus simulation.

In specific calculations, the investment in the absorption tower, regeneration tower, and heat exchanger equipment is derived by calculating material usage based on equipment size and multiplying it by design, profit, and transportation coefficients. The price of fan and pump equipment is computed using existing reference manufacturers' quotations and follows the scale factor method, as detailed in Equation 2-3. Other costs are calculated based on direct equipment investment, proportionate to the cost distribution.

This comprehensive breakdown ensures a thorough understanding of both the direct equipment investment and additional costs associated with the decarbonization system. The provided details offer a clear overview of the financial aspects involved in implementing and operating the decarbonization system.

C_2 represents the target equipment investment, where C_1 denotes the existing reference equipment investment. Similarly, X_2 corresponds to the target equipment size, and X_1 represents the existing equipment size, with 'n' serving as the impact factor.

The annual operating cost encompasses the replenishment cost of supplies, loss of generation cost, plant power consumption cost, and manual operation and maintenance cost. The labor operation and maintenance cost includes repair and maintenance expenses (accounting for 4% of the total investment per year), insurance and tax (equivalent to 2% of the total investment per year), and labor wage costs [12].

Table 2. Percentage distribution of costs in investments

<table>
<tr><th colspan="4">Cost item</th><th>Proportions</th></tr>
<tr><td rowspan="10">Total investment (CAPEX)</td><td rowspan="8">Total construction cost(TIC)</td><td rowspan="2">Direct on-site costs(DFC)</td><td>Direct equipment investment</td><td>41.862%</td></tr>
<tr><td>Installation and construction costs</td><td>27.91%</td></tr>
<tr><td rowspan="5">Indirect site costs(IFC)</td><td>Construction management costs</td><td>1.395%</td></tr>
<tr><td>Commissioning fee</td><td>1.395%</td></tr>
<tr><td>Spare parts for commissioning</td><td>0.349%</td></tr>
<tr><td>Temporary facilities costs</td><td>3.489%</td></tr>
<tr><td>Transportation, taxes, insurance, etc.</td><td>0.698%</td></tr>
<tr><td>Engineering costs(EC)</td><td></td><td>8.372%</td></tr>
<tr><td colspan="3">Unforeseen expenses</td><td>8.55%</td></tr>
<tr><td colspan="3">Patent tax and owner's cost management fee</td><td>5.98%</td></tr>
</table>

$$C_2 = C_1 \left(\frac{X_2}{X_1}\right)^n \tag{7}$$

Assuming a depreciation life of 30 years for fixed assets, with an estimated net salvage rate of 0%, the depreciation amount is calculated using the annual life averaging method to determine the total cost of CO_2 capture.

4 Trapping system economic analysis

In this system, based on the construction sequence, the overall construction investment can be divided into three main components: the capture and purification part, the compression, drying, and liquefaction part, and the storage part, as illustrated in Fig. 2. From Fig. 2, it is evident that, due to the complex process, numerous pieces of equipment, and intricate machinery, the construction cost of the capture and purification part constitutes 56% of the total construction costs, making it the largest portion of the construction investment for the entire capture system. Following closely is the compression, drying, and liquefaction part, accounting for 32%. Conversely, the storage part involves relatively fewer pieces of equipment and simpler installation, representing only 12% of the construction cost of the system.

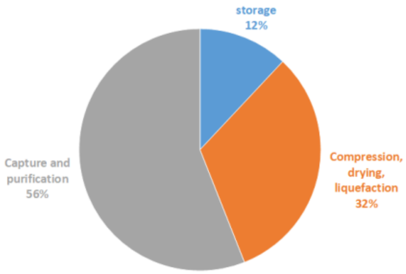

Fig. 2. Construction cost of each process of CO_2 capture system

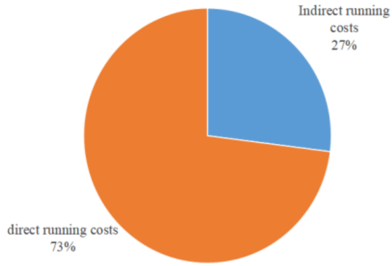

Fig. 3. Proportion of direct and indirect operating costs

4.1 System investment and operating cost

The running costs required during the operational stage consist of two main parts. One is the direct running cost, encompassing the raw materials and energy consumed during equipment operation, including electricity, steam, demineralized water, and absorbent. The other is the indirect running cost, covering the manpower or material resources needed to maintain the normal operation of the equipment. This includes workers' wages and benefits, equipment maintenance and repair costs, management costs, amortization costs, and other expenses.

As depicted in the proportions shown in Fig. 3, the direct operating costs constitute 73% of the total operating costs, while the indirect operating costs account for a smaller proportion of 27%.

4.2 Direct operating cost analysis

As depicted in the Fig. 4., the cost of electricity and steam constitutes 37% and 39% of the direct operating cost, respectively. The combined total of these two components is 76%, representing three-quarters of the direct operating cost. The consumption of electricity and steam costs corresponds to the energy usage in the capture process, indirectly highlighting a significant issue in current flue gas capture—namely, the high energy consumption of the capture process.

During equipment operation, aside from the regular consumption of the absorber, degradation and deterioration occur, necessitating the periodic addition of the absorber. Given that demineralized water is used to dilute the agent, the agent and demineralized water can be considered as the consumption cost of the absorbent. It can be assumed that, in the direct operating cost, the absorbent accounts for approximately one-fourth of the total.

4.3 Analysis of indirect operating costs

As observed from the Fig. 5, indirect operating costs do not constitute a significant proportion of the overall operating costs. Among the various components of indirect operating costs, workers' wages and maintenance and repair costs of the equipment account for larger shares, amounting to 32% and 30%, respectively. Workers' wages are determined based on the average income of power plant employees, while maintenance and repair costs are calculated at 2% of the original value of fixed assets, considering the operating time of the entire set of equipment as 15 years, serving as the basis for the calculation of equipment repair and maintenance.

Due to the limited share of indirect operating costs and a relative absence of prominent items within this category, the potential breakthrough point for reducing indirect operating costs is not readily apparent.

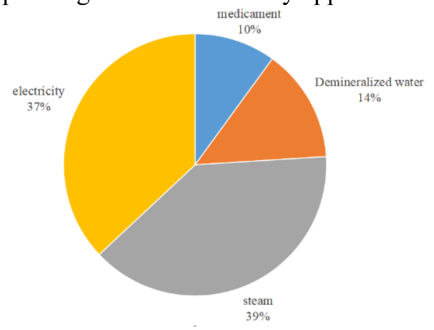

Fig. 4. Composition of direct operating costs

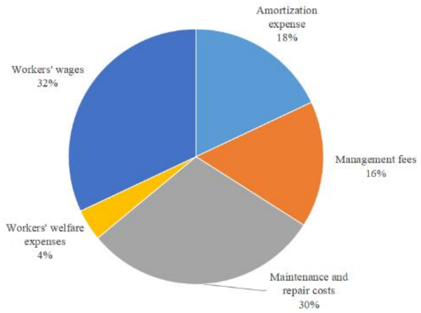

Fig. 5. Components of indirect operating costs

5 Benefits of Flue Gas CO_2 Capture Systems

The flue gas CO_2 capture system can generate multiple benefits, broadly categorized into social and monetary gains. Social benefits arise from the system's operation, creating a positive social impact and garnering social reputation, along with relevant policy support for the enterprise. On the monetary front, there are diverse avenues for realizing financial gains. For instance, captured CO_2 can be repurposed as a resource, employed in oilfield tertiary oil recovery processes, among other applications. Additionally, CO_2 can be directly sold as a commodity.

5.1 Social benefits

The implementation of the CO_2 capture project will effectively reduce a substantial amount of CO_2 emissions every year, contributing significantly to the cause of environmental protection. Simultaneously, this initiative not only plays a positive role in emission reduction but also establishes a commendable corporate image for the power plant. This social benefit extends beyond environmental protection, positively impacting the further development of the enterprise. Through the reduction of carbon emissions, the power plant has garnered public recognition, fulfilling its social responsibility and laying a solid foundation for its future sustainable development.

5.2 Economic benefits

CO_2 captured in flue gas not only represents an environmental protection initiative but also holds the potential as an economically valuable resource with reusable value. This potential can be realized by introducing the captured CO_2 into the market for monetary benefits. The key challenge, however, lies in the scenario where the cost of capturing CO_2 from flue gas is excessively high, surpassing the prevailing market price. In such cases, the economic benefit may diminish or become unattainable.[13]

On the international market, food-grade CO_2 is priced at approximately $600 per ton, while industrial-grade CO_2 is valued at roughly $300 per ton. The current relationship between the cost and profitability of CO_2 capture is illustrated in Figure 6. Therefore, in the development of a CO_2 capture strategy, a comprehensive consideration of the relationship between cost and market price is imperative to ensure the feasibility and economic efficiency of the project.

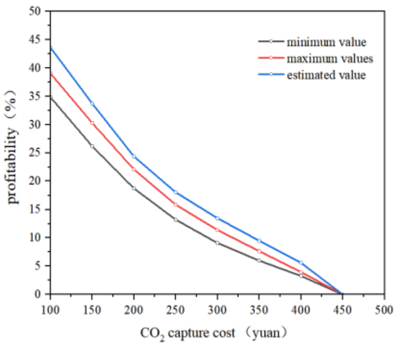

Fig. 6. Relationship between profitability and capture costs

As illustrated in Fig.6, the profit margin of CO_2 capture decreases as its cost increases. Currently, in the power plant flue gas CO_2 capture system, the cost of CO_2 capture is relatively low, with a profit margin of approximately 15%.

6 Summary

This paper analyzed the economic aspects of a power plant flue gas CO_2 capture system. In summary, the following conclusions can be drawn:

Investment Cost: The larger the scale of capture, the lower the unit investment cost. If the capture scale reaches one million tons, the unit investment cost can be reduced to 450 yuan/ton CO_2.

Construction Cost: Among the three processes of the capture system, the construction cost invested in the capture and purification part accounts for more than half of the total construction cost, while the proportion of the storage part is only about 1/10.

Operation Cost: The direct operation cost constitutes more than 3/4 of the total cost, with electricity and steam being the major contributors. This presents a detailed entry point for reducing the cost of the capture system. In contrast, the proportion of indirect operating costs is small, with uniform costs for each item.

Profit Margin: The coal-fired power plant studied in this paper reuses the captured CO_2 with a profit margin of about 15%. If the capture scale is further expanded or technological innovation is carried out, the profit margin could increase, making the economic benefits more pronounced.

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