Economic Analysis and Simulation of Carbon Capture Projects in the Power Industry

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Abstract. The power industry is a major contributor to CO_2 emissions in China, and hence its low-carbon development plays an important role in the nation's initiatives to build a low-carbon economy and reach the goal of emissions reduction. Based on the analysis of existing carbon capture technologies in the power industry, an economic analysis method of incremental cost accounting for carbon capture projects in the power industry is proposed. In addition, the project economic theory is analysed from two aspects—initial investment incremental cost and annual operating expense incremental cost, and simulation is carried out based on data from post-combustion carbon capture projects. These efforts are expected to provide a reference for the economic analysis of the construction of carbon capture projects and boost low-carbon development in the power industry.

Keywords: Power industry · Low-carbon development · Engineering project management · Carbon capture project · Economic analysis · Data simulation analysis

1 Introduction

China's power industry is dominated by coal electricity, and carbon emissions from this sector account for about 40% of the nation's total energy carbon emissions. Low-carbon development of the power industry, a key industry to achieve the goals of carbon neutralization and the carbon peak, plays a significant role in the implementation of a low-carbon economy and the realization of emission reduction goals in China. Carbon capture, utilization and storage (CCUS) is a technology with the potential to reduce CO_2 emissions on a large scale, which is universally recognized as one of the most important technologies to deal with global climate change and control greenhouse gas emissions. International Energy Agency (IEA) estimates that the total amount of CO_2 captured globally by carbon capture technology will increase by more than 100 times from about 40 million tonnes in 2020 to about 7.6 billion tonnes in 2050. Sustainable development requires the world to reach net zero emissions by 2070, in which CCUS technology will

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contribute 15% of cumulative emission reductions. To achieve full decarbonization in the power industry, it is necessary to reduce electricity consumption from the demand side, innovate low-carbon electricity varieties, increase the substitution rate of low-carbon energy in fuels, and promote CCUS technology to offset process emissions that are difficult to eliminate. In 2013, the National Development and Reform Commission issued *Notice on Promoting the Demonstration of Carbon Capture, Utilization and Storage Trials*, which explicitly demands that pilot projects of carbon capture be carried out and CCUS integrated demonstration projects be constructed in thermal power, coal chemical, steel, and other industries [1–3].

At the current stage, three kinds of carbon capture technologies are widely used in the power industry, namely post-combustion capture technology, pre-combustion capture technology, and oxyfuel combustion capture technology. The costs and energy consumption of the CO2 capture process account for 70–80% of those of carbon capture and storage, which is its key link and research focus [4, 5]. Therefore, this research focuses on the economic analysis of CO2 capture projects in the power industry, studies its economic analysis methods, and calculates and verifies through cases.

2 CO_2 Capture Technologies in the Power Industry

According to the different carbon emission sources, the power industry can capture CO_2 in different stages of power generation [4, 5]. The three main technologies are as follows:

1) Post-combustion capture technology

Post-combustion capture is the separation of CO_2 from flue gases produced by burning fossil fuels. Since the post-combustion separation process is located at the rear of the power generation system, a reform with simple principles, wide adaptability, technical convenience, and suitability for built power plants can be realized without changing the body of the power generation device.. However, the high energy consumption and the lower power generation efficiency, which is reduced by 8–13 percent, are the main defects of post-combustion capture.

2) Pre-combustion capture technology

Pre-combustion capture technology, also known as fuel decarbonization, is based on converting carbon from fossil fuels into CO_2 through a shift reaction, and then captures CO_2 from the shifted fuel gases. Pre-combustion capture technology can merely be applied to Integrated Gasification Combined Cycle (IGCC) power plants. Compared with post-combustion capture, pre-combustion CO_2 capture has lower energy consumption (power generation efficiency is reduced by about 7–10 percentage points) and the potential for much lower energy consumption and higher efficiency, which is the prime feature of pre-combustion capture technology.

3) Oxyfuel combustion capture technology

The technology separates oxygen from the air and then feeds the high-purity oxygen into the combustion process, avoiding the dilution of CO_2 by nitrogen. The oxyfuel combustion produces only CO_2 and water vapour, which leads to the obtaining of high-purity CO_2 by mere condensation without separation. Oxyfuel combustion technology can be applied to built power plants through retrofitting boilers or combustion chambers at costs and energy consumption higher than pre-combustion separation (10–12 percent). At present, hotspots about oxyfuel combustion research on oxygen rich combustion are mainly high-efficiency air separation technology, combustion stability, and inert gas purification.

3 Economic Analysis Methods of Carbon Capture Projects

The economics of carbon capture projects in the power industry are reflected mainly through costs and benefits [6–9]. The economic evaluation of carbon capture projects focuses on project cost accounting, and the income comes mainly from the sale of CO_2. The relatively simple analysis of project income makes the analysis of project costs become the focus of economic analysis. It is necessary to determine the cost boundary of carbon capture and the analysis method. As a part of cost management in engineering project management, cost accounting analysis is of great significance to the cost control of the whole project.

3.1 Cost Boundary Determination Principles

The principles of determining the cost boundary of carbon capture are:

(1) The principle of relevance. All the costs within the cost boundary are associated with a certain link of carbon capture, while the unrelated costs, such as the production costs of power plants, are out of the cost boundary.
(2) The principle of comprehensiveness. The costs of all links of carbon capture in the construction and operation periods are within the boundary, including both the direct costs and indirect costs caused by the technological process. For instance, waste heat generation loss resulting from CO_2 capture should also be included in the costs of the capture link.
(3) Both technical costs and economic costs are taken into account. When the costs of a carbon capture project are calculated, the costs brought by the project should be considered comprehensively, including the construction and operation expenses for the technology itself, the capital cost of the project construction, the tax, and other costs.

3.2 Incremental Cost Boundary

As is shown in Fig. 1, the boundary of the incremental cost of the CO_2 capture units is shown as the dashed lines, including the CO_2 separation device (mainly consisting of the absorber and the stripper) and the CO_2 compression device. The heat required by the stripper is derived from the steam of the power plant and calculated at the internal cost. The flue gases entering the capture system are based on the parameters at the discharge time from the plant. The CO_2 compression device usually adopts the way of multi-stage compression and intercooling, in which the final CO_2 emission pressure is 130 kPa and there is no specific requirement for the temperature (usually about 50 °C).

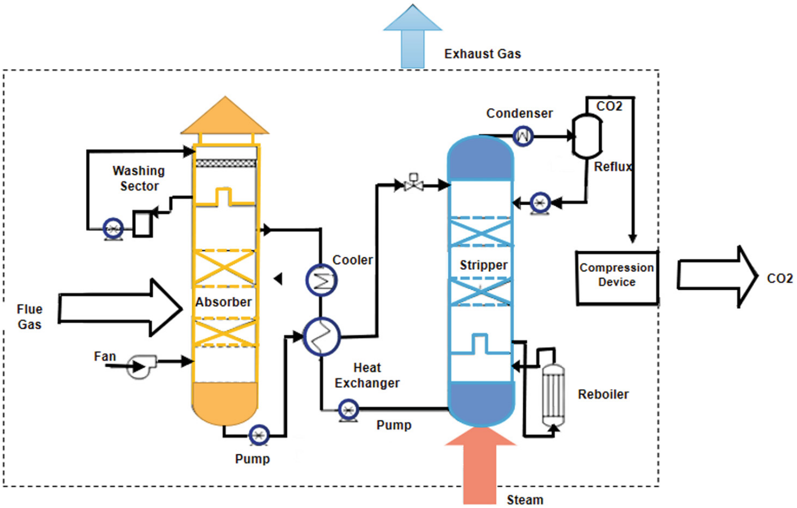

Fig. 1. Schematic diagram of the boundary (dashed line) of the incremental costs of CO2 capture units

3.3 Cost Accounting Principles

The principles of the cost accounting of carbon capture projects are as follows:

(1) The incremental principle. For the cost of carbon capture projects, only the costs caused by adding carbon capture devices are calculated, excluding the original construction costs and production facility costs of power plants.
(2) The cash basis principle. The actual cash flow is taken into account when project costs for each period are calculated, excluding depreciation, amortization, and so on.
(3) The mark-to-market principle. By default, materials consumed in construction and operation activities are purchased in the current periods. The costs of material consumption are calculated according to the current market prices.
(4) The phased accounting principle. When the costs of a carbon capture project are calculated, the construction and operation of the project should be divided into different periods, whose costs and benefits should be calculated separately. Generally, a year is taken as one period to account for the current cash flow.

3.4 Cost Accounting Method

For different carbon capture technologies, the incremental cost method can be adopted in corresponding project accounting. Incremental cost, referring to all the costs added to the power plant during the transformation of carbon capture, can be divided into initial investment incremental cost and annual operating expense incremental cost. The former cost is invested once in the initial stage of transformation, while the latter cost is invested continuously and annually after completing the transformation. The formula is:

Carbon capture project costs = Initial investment incremental costs + Annual operating expense incremental costs.

Initial investment incremental costs include:

A. Additional device costs: the total costs of each device of the additional CO_2 capture equipment, including purchase and installation costs.

The additional devices mainly include an absorption tower, a stripper tower, a CO_2 compression device, a heat exchanger, a pump, a wind turbine, a cooler, a pipeline, and other devices.

B. Original device transformation costs: costs of the original power device transformation due to the addition of CO_2 capture equipment.

The transformation contents mainly include dust removal device transformation, waste heat boiler transformation, pipeline transformation, power control system transformation, and so on.

C. Civil construction costs: the costs of land needed to add the CO_2 capture equipment, including land costs, construction costs, road construction costs, and so on.

Annual operating expense incremental costs include:

A. Annual operation and maintenance costs of additional devices: annual operation and maintenance costs of additional CO_2 capture equipment.
B. Additional annual labour costs: personnel costs for operation and maintenance of CO_2 capture equipment.
C. Annual price of consumed steam: this price is calculated at the cost of steam supplied by the power plant, namely the internal price, which reflects the change in the waste heat generation efficiency of power plants caused by the transformation.

4 Economic Analysis of a Capture Project Study Cases

4.1 Carbon Capture Method Selection and Economic Analysis

The economics of relevant projects is calculated based on the most commonly-used post-combustion capture technology. In post-combustion capture cases, the capture devices are added based on the original power plants, which relatively reduces changes in the plants. The costs of the projects mainly include initial investment incremental costs, annual operation expense incremental costs, and tax. Specifically, the costs include:

(1) Initial investment incremental costs

The initial investment incremental costs consist of construction costs, device purchase costs, installation costs, basic reserve costs, other costs, reserve costs of the price difference, loan interest during the construction period, and production working capital, as shown in Fig. 2.

(2) Annual operation expense incremental costs.

Annual operation expense incremental costs (namely the annual costs including loan interest) consist of production cost and financial expense, and the specific composition is shown in Fig. 3.

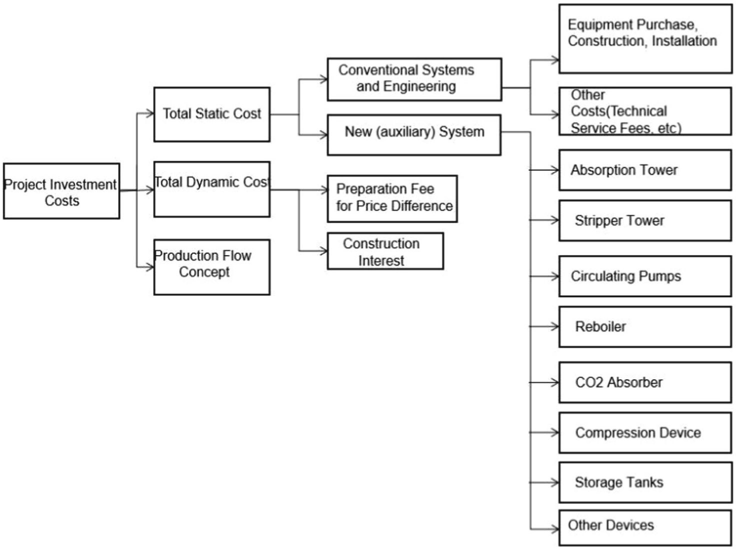

Fig. 2. Schematic diagram of initial investment incremental costs composition in post-combustion capture

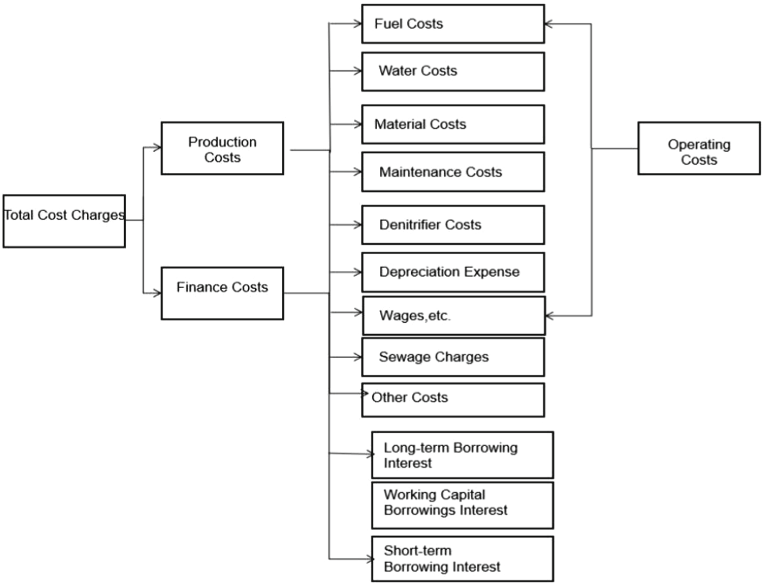

Fig. 3. Schematic diagram of annual operation expenditure incremental costs composition in post-combustion capture

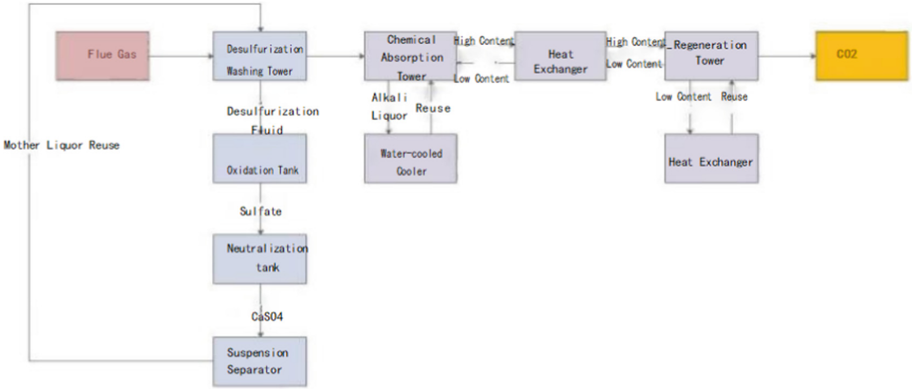

Fig. 4. CO2 capture stage technological process

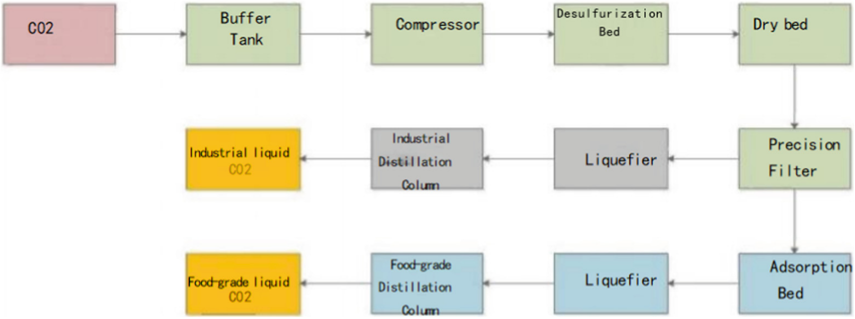

Fig. 5. CO2 purification stage technological process

4.2 Case Analysis

4.2.1 Technological Process

The CO_2 in the flue gases of power plants is captured by the chemical absorption method, which is the most commonly used method in post-combustion capture. The method is divided into two stages: in the carbon capture stage, the concentration of CO_2 is increased from about 20% to about 95% by chemical absorbents, and in the purification stage, the concentration is purified to more than 99.9% by adsorption distillation. The former stage is divided into the quench-wash desulfurization process and the absorption and desorption process. The specific process is shown in Fig. 4.

The latter stage is divided into the compression adsorption process, the distillation process, and the cooling liquefaction process. The specific technological process is shown in Fig. 5.

4.2.2 Project Design

The technical applicability standard and costs are the main factors affecting the installation of CCUS in existing coal power units. Technical applicability criteria determine

Table 1. Technical characteristics of the chemical absorption method

Method	Fundamentals	Types	Application	Advantages	Disadvantages
Chemical absorption method	The CO_2 reacts with the absorbents to form unstable salts, which are heated to release CO_2 again.	Ammonia solution absorption method, Hot potassium-alkali method, Organic amine absorption method, Lithium salt absorption method	Industries with low CO_2 emission concentration, including conventional coal-fired power plants, natural gas processing, and so on	Mature technological process, good selectivity, high absorption efficiency	Higher absorbent regeneration heat consumption, greater absorbent loss, high operating cost, high device investment

whether a power plant can be a candidate for transformation, which to be considered in the transformation of coal-fired power plants include unit capacity, remaining service life, unit load rate, capture rate setting, CCUS technology maturity, and so on, at the current stage. The carbon capture project intends to rely on a 350 MW power plant for reconstruction. The technical characteristics of the chemical absorption method are shown in Table 1, and the technical applicability of the power plant is analysed in Table 2 [10].

Table 2. Power plant CCUS technical applicability analysis table

Number	Selected technology	Evaluation index	Index data	Applicability evaluation
1	Post-combustion–chemical absorption method	Unit type	Coal-fired	☑
2		Unit capacity	350 MW	☑
3		Remaining service life	25 years	☑
4		Unit annual load rate	80%	☑
5		Number of operating hours per year	Over 7000	☑
6		Set capture rate	Over 90%	☑
7		CCUS technology maturity	Commercial application	☑
8		Transport conditions	Convenient transportation	☑
9		Application field	Chemical utilization	☑
10		Location	Urban suburbs	☑
11		Environmental impacts	Low	☑

Based on the chemical absorption method, the carbon capture project, with a one-and-a-half- year construction period, has an annual operation of 7, 000 h and a capture target of 100, 000 tonnes per year.

(1) Flue gases

Flue collecting pipelines are installed behind the dust removal device. According to the statistics of the historical flue gas volume, the flue gas volume of the exhaust gas of the power plant is about 730, 000 m^3/h, and the smoke volume extracted by the 100, 000 tonnes/year CO_2 capture device is 60, 000 m^3/h, accounting for 8.2% of the total flue gas volume.

The main components of flue gases after dust removal are shown in Table 3.

(2) Steam

The steam required by the CO_2 capture system is saturated steam at a temperature of about 130 °C, which can be extracted from waste heat steam and has corresponding saturation pressure of about 0.17 MPa (G). The steam extraction volume of 100, 000 tonnes/year CO_2 capture device is 60 t/h.

(3) Circulating water

The designed water demand of the project is about 67.7 m^3/s, equaling 243, 720 t/h, and the water demand of the 100, 000 tonnes/year CO_2 capture system is about 7, 500 t/h, increasing the water consumption by about 3%.

(4) Layout and occupation of land

The overall layout of the project is based on the principle of meeting the technological process requirements and reducing engineering costs and operation costs as much as possible. The main devices in the capture area and compression liquefaction area are

Table 3. Flue gases main components table

Item	Unit	Numerical value
Flue gases temperature	°C	91.5
Flue gases pressure	Pa	-80
CO_2	(v/v) %	19.7
N_2	(v/v) %	70.5
O_2	(v/v) %	9.7
CO	(v/v) %	0.0597
SO_2	mg/m^3	24.0
NO	mg/m^3	102.75
NO_2	mg/m^3	2.7
Dust	mg/m^3	20.4
Note: The above data is estimated according to the survey of a power plant.		

Table 4. Plan table of project land occupation

Project composition	Project content	Covering area/m^2
Main project	Pre-treatment area	130
	Carbon capture area	320
	Compression area	410
	Liquefaction and purification area	150
	Storage tank area	600
Auxiliary project	Circulating pump area	120
	Control area	260
Total		1990

installed by adopting the tiling principle. Through the reasonable layout, the estimated area of the 100, 000 tonnes/year scale devices is shown in Table 4.

4.2.3 Economic Analysis of Carbon Capture Projects

Based on the principles and the method of economic analysis of carbon capture projects, economic analysis of this carbon capture scheme is carried out. The main data sources mainly include:

1) Research data of domestic demonstration projects;
2) Cost data of related similar devices;
3) Domestic and foreign literature data.

According to the aforementioned technological process and design parameters, the following data are obtained:

(1) System capture efficiency

The flue gas extraction volume of 100, 000 tonnes/year CO_2 capture device is 60, 000 m^3/h, and the project's annual operation time is 7, 000 h. The concentration of CO_2 in the flue gases is about 19.7%. Therefore, the system's capture efficiency is about 62.1%.

(2) Accounting of initial investment incremental costs

The incremental cost of the initial investment includes all devices, civil engineering, installation, and other costs. The accounting results of initial investment incremental costs are shown in Table 5.

The procurement costs of the main subsystems of the capture system are shown in Table 6.

Table 5. Statement of initial investment incremental costs

Cost type		Cost (ten thousand yuan)
Additional device construction costs	Mechanical devices	13748.79
	Electrical devices	213.48
	Automatic instruments	253.18
	Device installation costs	1137.24
	Construction management costs	165.20
Original device transformation costs		362.51
Civil engineering costs		1172.7
Other costs	Trial operation and debugging costs	118.38
	Bidding, design, taxes, and so on	1243.27
	Reserve costs	538.02
Total costs		18952.77

Table 6. Capture system procurement costs

System	Subsystem	Price (ten thousand yuan)
CO_2 capture system	Flue gas absorption system	5360.02
	CO_2 separation system	6522.93
	Thermal control system	1121.59
	Power control system	236.12
	Storage tank	796.92
	Pipeline and other facilities	177.86
	Total	14215.45

(3) Accounting of annual operating expense incremental costs.

The operation consumption in CO_2 capture includes solvent consumption, power consumption, steam consumption, and so on. Furthermore, labour and system maintenance costs are taken into consideration. The detailed accounting results are shown in Table 7.

(4) Calculation of the investment payback period

According to the investigation, there is a large gap in the market price of CO_2 among different regions. During operation, the project can choose to produce food-grade or industrial-grade liquid CO_2 according to the situation of the local market and price. The project has an annual output of 100, 000 tonnes of liquid CO_2, and the tentative

Table 7. Statement of annual operating expense incremental costs of carbon capture demonstration projects

Cost type	Unit	Number	Unit price (yuan)	Total price (yuan)
Solvent consumption	ton	30	40000	1200000
Power consumption	kw/h	1750000	0.56	980000
Fresh water consumption	ton	30000	3	90000
Steam consumption	ton	420000	80	38400000
Labour	person	18	65000	1170000
System maintenance	/	/	/	687440
Other (such as interest)	/	/	/	648000
Total costs				38312440
Average capture cost	yuan/t CO_2			383.12

price is 550 yuan/tonne, regardless of price changing with years and other factors. The cost-benefit analysis of the project is shown in Table 8.

(5) Actual project emission reduction

The steam used in the project can be supplied by waste heat steam, while the original production of power remains unchanged. Therefore, the major increase in emissions of the project comes from those generated by the additional electricity consumption.

The annual increase in power consumption of the project is 1750 MWh, and the emission factor is 0.5810 t CO_2 /MWh, which is the latest national power grid. Therefore, the annual increase in emissions of the project is 1016.75 t CO_2.

Annual actual project emission reduction = annual project capture - annual additional project emission = 98, 983.25 t CO_2.

Table 8. Project cost-benefit analysis

Index	Unit	Numerical value
Total investment cost	ten thousand yuan	18952.77
Annual operating cost	ten thousand yuan	3831.24
Annual sale revenue	ten thousand yuan	5500
Annual income tax	ten thousand yuan	417.19
Total annual profit	ten thousand yuan	1251.57
Payback period	year	15.14

Table 9. Economic analysis results

Index	Overview of economic analysis
Project scale (t CO_2 /year)	100000
Project footprint (m^2)	1990
Capture efficiency	61.10%
Total investment cost (ten thousand yuan)	18952.77
Average annual capture cost (yuan/t CO_2)	383.12
Payback period (year)	15.14
Actual emission reduction (t CO_2)	98983.25

5 Conclusion

By adopting the incremental cost definition principle, this research analyses the economic evaluation method of carbon capture projects in the power industry, which is divided into initial investment costs and annual operating costs. In addition, the economic analysis is carried out in combination with the transformation project of the chemical absorption method of post-combustion capture in existing power plants, and the applicability of the method is verified. The specific economic analysis results are shown in Table 9.

It can be found that:

1) High construction and installation costs of carbon capture devices make CO_2 capture in the power industry a high-cost project, which also limits the rapid development of CO_2 capture projects;
2) This economic analysis mainly considers the perspective of cost increment, excluding the additional influence of reduced power generation efficiency and other factors. On the whole, the total costs and annual profits of the chemical absorption and capture scheme are considerable, and the payback period of investment is long.

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