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Tech-economic evaluation of CO_2 enhanced coalbed methane recovery technology—A case study of China

Xian Zhang[1,2 #], Mao Xu[1#], Shijie Wei[1], Jingli Fan[1, 3][1]

1 Center for Sustainable Development and Energy Policy Research (SDEP), School of Energy & Mining Engineering, China University of Mining & Technology, Beijing (CUMTB), Beijing, 100083, China.

2 The Administrative Centre for China's Agenda 21 (ACCA21), Ministry of Science and Technology (MOST), Beijing 100038, China

3 State Key Laboratory of Coal Resources and Safe Mining (China University of Mining and Technology),

Beijing, 100083, China

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ABSTRACT

With the rapid development of China's economy, the contradiction between the growing demand for fossil energy consumption and the increasingly urgent pressure of emission reduction has become increasingly prominent. As a potential option to address climate change, CO_2 enhanced coalbed methane recovery (CO_2-ECBM) technology has been widely concerned, which can inject the CO_2 captured into the coalbed to enhance coalbed methane recovery and store CO_2 at the same time. Therefore, CO_2-ECBM technology is of great significance for China's low-carbon development, especially after China put forward the goal of achieving carbon neutrality by 2060. In order to provide references for CO_2-ECBM technology deployment, the investment benefits of the CO_2-ECBM project in China under various scenarios was evaluated based on real options in this study, and the key factors influencing the economy of the CO_2-ECBM technology were also identified. The results showed that (1) without carbon trading, the investment benefits of CO_2-ECBM project is 2.58 billion CNY in low CO_2 source purchase price scenario(180 CNY/t); (2) if CO_2 source purchase price rises to 300 CNY/t (high CO_2 source price scenario), the CO_2-ECBM project has no investment value as its revenues cannot offset the total costs; (3) the net present value (NPV) of CO_2-ECBM project will decrease by 22.76 million CNY if the CO_2 source purchase price increases 1 CNY/t, and the critical CO_2 source purchase price is 293 CNY/t without carbon trading; (4) Carbon trading can greatly increase the investment income of CO_2-ECBM projects, and in the low CO_2 source purchase price scenario, the investment benefits of CO_2-ECBM projects would increase by 44.2% with the current carbon trading price (50 CNY/t). However, China has not yet incorporated CO_2 utilization technology into the emission trading system. The results of this study could provide theoretical support for CO_2-ECBM investment and the relevant policy-making.

Keywords: CO_2-ECBM; real option; investment evaluation; CO_2 emission reduction; CO_2 utilization

NONMENCLATURE

Abbreviations	
CO_2-ECBM	CO_2 enhanced coalbed methane recovery
CCUS	Carbon capture, utilization and storage
NPV	Net present value
TIV	Total investment value

1. INTRODUCTION

Fossil fuels have been widely used since the industrial revolution and a large amounts of CO_2, CH_4 and chlorofluorocarbon have been discharged into the atmosphere, resulting in the greenhouse effect. Among them, the contribution of CO_2 to the greenhouse effect accounts for 55%-60% (Jenkinson et al., 1991). Climate change will seriously threaten the survival of human beings, so it has attracted extensive attention of the international community.

One of the pressures and challenges facing developing countries in pursuing sustainable economic development is to seek cost-effective solutions to the contradiction between energy demand and GHG emission reduction. Carbon capture utilization and storage (CCUS) technologies are considered as

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[#] These authors contributed equally to this work and should be considered co-first authors.

[1] Corresponding author. Xueyuan street ding no. 11, Haidian District, Beijing. E-mail address: fjlldq@163.com(J.L. Fan).

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important and effective options to address climate change. CO_2 enhanced coal bed methane recovery (ECBM) technology is one of CCUS technologies, to be more specific, injecting the CO_2 captured into the deep unrecoverable coalbed to replace the coalbed methane (the main component is CH_4) and then CO_2 can be easily adsorbed on the coalbed surface, so that CO_2 can be permanently stored in the coalbed while coalbed methane can be recovered and utilized (Talapatra, 2020; Huo et al., 2017) .

In general, coalbed methane would be directly discharged into the atmosphere before coal mining in China. However, coalbed methane is a kind of unconventional natural gas, which is also a kind of greenhouse gas. The global warming potential of methane is 25 times that of CO_2 in 100 years (IPCC, 2007). Therefore, exploiting the coalbed methane can significantly cut CH_4 emissions from coal mining, as well as reduce the carbon footprint of coal production and provide more clean energy.

Some developed countries, such as United States, Canada, Poland and Japan, have taken CO_2 utilization and storage as one of the main means to reduce CO_2 emissions, and a series of investigations, experiments and pilot studies have been carried out. These countries are also pioneers in the micro pilot testing of the CO_2-ECBM technology (Saghafi, 2010). At present, the research of CO_2-ECBM technology has just started in China. During 2002-2006, the governments of China and Canada cooperated on CO_2-ECBM technology, and jointly carried out experimental research on CO_2 storage in coalbed and coalbed methane recovery technology in Qinshui Basin, which located in Shanxi Province, China. CO_2-ECBM technology can increase China's average coalbed methane recovery rate from 41.31% to 60.40%, and the production of coalbed methane would be increased by about 4.3×10^{12} m^3 (Zheng et al., 2016).

Many scholars have studied CO_2-ECBM technology. Zhang et al. (2005) briefly introduced the geological storage method of CO_2 and established the environmental benefit evaluation model of CO_2-ECBM technology. The evaluation results show that the environmental benefits of CO_2-ECBM are significant, and the greater the CBM recovery, the greater the environmental benefits. Liu et al. (2012) evaluated the economic indicators of Panzhuang ECBM project through fuzzy comprehensive evaluation method, and the results showed that the project is in good financial and economic condition, especially the investment profit and investment payback period were the leading levels in the industry. Zhang et al. (2016) based on Tieda DT26 Well geological conditions and actual production, evaluate the economic benefits generated by different drainage systems with numerical simulation and the NPV method. The results show that the ECBM project has the highest economic benefit under the condition that the injection-producing well is 200m away, the gas injection time is 163d and the injection pressure is 20 MPa and the CO_2 injection rate of 4000 m^3/d. Zhang et al. (2018) evaluated the economics of the entire chain of CO_2-ECBM project in Panzhuang coal mine using the NPV method, and the results show that in the absence of any subsidy, gas company has good economic performance as a result of its large capital costs can be offset by gas production income, although the NPV of capture and transport is negative.

With the rapid development of China's economy, the contradiction between the growing demand for fossil energy consumption and the increasingly urgent pressure of emission reduction has become increasingly prominent. Chinese President Xi Jinping delivered an important speech at the general debate of the seventy-fifth UN General Assembly on September 22, 2020, emphasizing that China will take more effective measures to peak CO_2 emissions before 2030, and achieve carbon neutralization by 2060. Given this situation, CO_2-ECBM technology may get good development opportunities. However, CO_2-ECBM technology lacks financial support at present, and this issue should be addressed from the perspective of the government and the market.

This paper aims to identify key factors influencing the investment benefits of the CO_2-ECBM project and provide policy recommendations on CO_2-ECBM technology for Chinese government.

2. PAPER STRUCTURE

2.1 Methods

Both the NPV of the underlying assets and the opportunity value of uncertainties are taken into consideration in the real option approach, which can increase the accuracy of investment decisions under uncertain conditions. Based on the real option theory, the total investment value of the project can be expressed as:

$$TIV = NPV + ROV \tag{1}$$

TIV represents the total value of the project; NPV represents the NPV of the project; ROV represents the value of delayed option. Delayed investment option means that the investors have the right to delay investment in the project; in the case of an unfavorable investment climate or inadequate market information, delayed investment option can reduce the risk of immediate investment. The investment decision-making rules based on real options are shown as Table 1 (Zhang et al., 2014).

Table 1 Investment decision-making rules based on the delayed real option.

NPV	TIV	Decision rules
NPV>0	TIV>NPV	Delay investment
NPV>0	TIV=NPV	Invest immediately
NPV≤0	TIV>0	Delay investment
NPV<0	TIV=0	Abandon investment

(1) Initial investment:

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$$C_{\mathrm{I}} = C_P + C_{IW} + C_{OW} + C_{MW} + C_{IE} + C_{ME} \tag{2}$$

where C_{I} represents initial investment costs; C_P is the investment costs of the construction of CO₂ transportation pipelines; C_{IW} is the construction costs of CO₂ injection wells; C_{OW} is the construction costs of coalbed methane drainage wells; C_{MW} is the construction costs of CO₂ injection monitoring wells; C_{IE} is the costs of injection equipment and C_{ME} is the costs of monitoring equipment.

(2) Operation & maintenance (O&M) costs

$$C_{\mathrm{O\&M}} = C_{\mathrm{P}\_O\&M} + C_{\mathrm{IW}\_O\&M} + C_{\mathrm{OW}\_O\&M} + C_{\mathrm{MW}\_O\&M} + C_{\mathrm{IE}\_O\&M} + C_{\mathrm{ME}\_O\&M} \tag{2}$$

where $C_{\mathrm{O\&M}}$ is O&M costs; $C_{\mathrm{P}\_O\&M}$, $C_{\mathrm{IW}\_O\&M}$, $C_{\mathrm{OW}\_O\&M}$, $C_{\mathrm{MW}\_O\&M}$, $C_{\mathrm{IE}\_O\&M}$ and $C_{\mathrm{ME}\_O\&M}$ represent yearly O&M costs of CO₂ transportation pipelines, CO₂ injection wells, coalbed methane drainage wells, CO₂ monitoring wells, injection equipment and monitoring equipment respectively.

(3) CO₂ purchase costs

$$C_{CO_2} = Q_{CO_2} * P_{CO_2} \tag{3}$$

where C_{CO_2} represents the annual CO₂ purchase costs; Q_{CO_2} represents the annual stored amount of CO₂ and P_{CO_2} is the unit CO₂ purchase price.

(4) Coalbed methane production costs

$$C_{CBM} = Q_{CBM} * (R_{CBM} + E_{CBM}) \tag{4}$$

where Q_{CBM} is the increased coalbed methane production and $Q_{CBM} = Q_{CO_2} / (\eta * \rho_{CBM})$; η is the replacement rate between coalbed methane and CO₂; ρ_{CBM} is the density of coalbed methane under standard conditions, i.e., 0.716 kg/m³; R_{CBM} is resource tax; E_{CBM} is coalbed methane compression and purification expenses.

(5) Income from CO₂ emission reduction

$$B_{CO_2} = Q_{CO_2} * P_{carbon} \tag{5}$$

where B_{CO_2} is the income from CO₂ emission reduction and P_{carbon} is the carbon trading price.

(6) Income from coalbed methane

$$B_{CBM} = Q_{CBM} * \left(P_{CBM} + S_{CBM}\right) \tag{6}$$

where B_{CBM} is the income from coalbed methane ; P_{CBM} is the coalbed methane price; S_{CBM} is fiscal subsidies for coalbed methane .

Investment returns of the CO₂-ECBM project are depicted by Equation (7):

$$Benefit = B_{CBM} + B_{CO_2} - C_{\mathrm{I}} - C_{\mathrm{O\&M}} - C_{CO_2} - C_{CBM} \tag{7}$$

Suppose the project's service life $\tau_2 = 20$ years, the investment and construction period is one year and the investment time $t = \tau_1$, then the project is put into use from $t = \tau_1 + 1$. The NPV of project investment is depicted by Equation (8).

$$NPV_{\tau_1} = \sum_{t=\tau_1+2}^{\tau_2} \left(B_{CBM} + B_{CO_2} T_{CO_2} - C_{\mathrm{O\&M}} - C_{CO_2} - C_{CBM}\right)(1+\mathrm{r}_0)^{\tau_1 - t} - C_{\mathrm{I}}(1+\mathrm{r}_0)^{\tau_1} \tag{8}$$

Given their fluctuations and uncertainty, carbon prices are believed to follow the geometric Brownian motion:

$$dP_{carbon} = \mu P_{carbon} dt + \sigma P_{carbon} d\omega \tag{9}$$

where μ is the drift rate of carbon trading price; σ is the volatility of carbon trading price; dt is time increments and $d\omega$ is increments of a standard Wiener process.

Suppose the investment delay period is 10 years. Carbon prices are unfolded within the delay period according to the triple tree pricing model to obtain the NPV of investment in the CO₂-ECBM project at each node within the delay period. The calculation formula for investment value at each node is listed below:

$$IV_{(i,j)} = \max\left\{0, \mathrm{NPV}_{(i,j)}\right\} \tag{10}$$

where, $IV_{(i,j)}$ and $NPV_{(i,j)}$ represent the investment value and investment NPV at each node respectively. If $NPV_{(i,j)} < 0$ then the investment value at this node is 0 and, in this case, investors will stop investment. If $NPV_{(i,j)} > 0$,then investors will continue to invest and NPV at the node equals to the investment value IV . Based on these, then the TIV could be calculated as Eq. (11).

$$TIV_{(i,j)} = \max\left\{IV_{(i,j)}, (P_u \times IV_{(i+1,j)} + P_m \times IV_{(i+1,j+1)} + P_d \times IV_{(i+1,j+2)}) * e^{-r\Delta t}\right\} \tag{11}$$

where $TIV_{(i,j)}$ represents the total investment value at the node $(i.j)$, P_u , P_m and P_d represent probabilities of the project value increases, remaining unchanged and decreases, respectively.

$$P_u = \frac{e^{r\Delta t}\left(1+d\right) - e^{\left(2r+\sigma^2\right)\Delta t} - d}{\left(d-u\right)\left(u-1\right)}; P_m = \frac{e^{r\Delta t}\left(u+d\right) - e^{\left(2r+\sigma^2\right)\Delta t} - 1}{\left(1-d\right)\left(u-1\right)};$$

$$P_d = \frac{e^{r\Delta t}\left(1+u\right) - e^{\left(2r+\sigma^2\right)\Delta t} - u}{\left(1-d\right)\left(d-u\right)}$$

where

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$$u = I+\sqrt{I^2-1};\ d = I-\sqrt{I^2-1};\ I = \frac{e^{r\Delta t}+e^{(3r+3\sigma^2)\Delta t}-e^{(2r+\sigma^2)\Delta t}-1}{2[e^{(2r+\sigma^2)\Delta t}-e^{r\Delta t}]}$$

and r is the risk-free interest rate.

2.2 *Case study and Scenarios setting*

In 2012, the Shanxi International Energy Group Co., Ltd launched a Feasibility Study on CCUS for 350 MW Oxygen-enriched Combustion for Power Generation, which was designed to capture CO_2 from Hudi Power Plant as an alternative to replace the exploitation of coalbed methane in Panzhuang section. During the 20-year service term, 2 million tons of CO_2 will be injected each year. The CO_2 transport pipeline is 40 km with a pressure of 15 Mpa. Besides, 940 wells are planned to be constructed (Zhang and Zhang, 2015), including 492 injection wells and 448 drainage wells (Zhang Ga et al., 2018). 492 monitoring wells are also planned to be built.

Table 2 Technical and economic parameters of CO_2-ECBM.

Parameters	Value	Unit	Description	Source
C_P	4794.4	10^4 CNY	Construction cost of CO_2 transport pipeline is 1198.6 thousand CNY/km	Zhang and Zhang, 2015
C_{IW}	39360	10^4 CNY	Construction cost of each injection well is 800 thousand CNY	Zhang and Zhang, 2015
C_{OW}	35840	10^4 CNY	Construction cost of each drainage well is 800 thousand CNY	Zhang and Zhang, 2015
C_{MW}	39360	10^4 CNY	Construction cost of each monitoring well is 800 thousand CNY	Zhang and Zhang, 2015
C_{IE}	9840	10^4 CNY	Injection equipment for each well will cost 200 thousand CNY	Zhang et al., 2016
C_{ME}	20172	10^4 CNY	Monitoring equipment for each monitoring well will cost 200 thousand CNY	Liu, 2012
$C_{P\_O\&M}$	48	10^4 CNY/a	Annual O&M of CO_2 transport pipelines will cost 12 thousand CNY/km	Zhang and Zhang, 2015
$C_{IW\_O\&M}$	2952	10^4 CNY/a	Annual O&M cost of each injection well is 60 thousand CNY	Zhang and Zhang, 2015
$C_{OW\_O\&M}$	2904	10^4 CNY/a	Annual O&M cost of each drainage well is 60 thousand CNY	Zhang and Zhang, 2015
$C_{MW\_O\&M}$	2952	10^4 CNY/a	Annual O&M cost of each monitoring well is 60 thousand CNY	Zhang and Zhang, 2015
$C_{IE\_O\&M}$	984	10^4 CNY/a	Annual O&M cost of the injection equipment for each well is 20 thousand CNY	10% of equipment investment
$C_{ME\_O\&M}$	4928	10^4 CNY/a	Annual O&M cost of the monitoring equipment for each well is 110 thousand CNY	Liu, 2012
Q_{CO_2}	200	10^4 t		Refer to Shanxi Panzhuang CO_2-ECBM Project
P_{CO_2}	180-300	CNY/t	CO_2 capture from coal-chemical plants will cost 180 CNY/t, and that from coal-fired power plants will cost approximately 300 CNY/t	MOST, 2019
R_{CBM}	0.006	CNY/m^3	—	Refer to the estimation of natural gases
E_{CBM}	0.05	CNY/m^3	—	Zhang and Zhang, 2015
E_{CO_2}	50	CNY/t	—	Fan et al., 2018
P_{CBM}	1.56	CNY/m^3	—	Zhang and Zhang, 2015
S_{CBM}	0.2	CNY/m^3	—	Zhang and Zhang, 2015
σ	0.34	—	—	Fan et al., 2018
r_0	5%	—	—	Zhang et al., 2014
r	4.43%	—	—	Fan et al., 2019
η	5.5	—	Replacement rate between coalbed methane and CO_2	Yu et al., 2017.

Four scenarios are set by the CO_2 source price and whether carbon trading is viable or not, as shown in Table 3.

Table 3 Scenarios setting

	Scenarios	CO_2 Source Purchase Price (CNY/t)	Carbon Trading is viable or not
Low CO_2 purchase price	**Scenario** 1 (S1)	180	×
	Scenario 2 (S2)	180	√
High CO_2 purchase price	**Scenario** 3 (S3)	300	×

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Scenario 4 (S4)	300	√

2.3 Results

Figure 1 shows that the NPV of CO_2-ECBM projects under S1, S2 and S4 are all positive and equal to the total investment values. According to the investment rules shown in Table 1, investment can be immediately made under the three scenarios. In S3, the NPV is about -154 million CNY, which indicates that the CO_2-ECBM projects are not profitable in this case and also have no investment values.

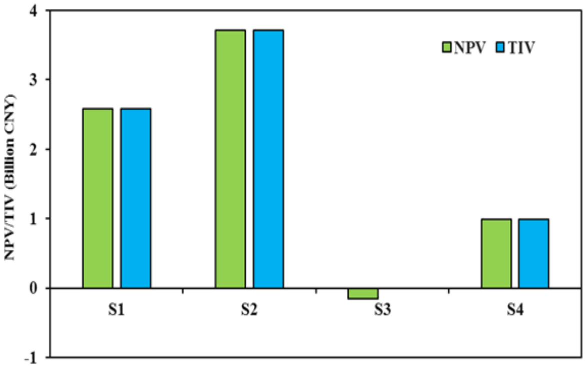

Figure 1 NPV and TIV of CO_2-ECBM in varied scenarios

By comparing S1 with S2, S3 and S4, it can be found that carbon trading can significantly increase the investment returns of CO_2-ECBM projects. During the 20-year of project operation period, the accumulative profits generated by carbon trading reaches 1.138 billion CNY, largely offsetting the CO_2-ECBM costs and improving the technical economy of CO_2-ECBM technology. The contrast between S1 and S3 as well as between S2 and S4 highlighted that the influence of CO_2 source price on the economic efficiency of CO_2-ECBM projects. When the CO_2 source price rises from 180 to 300 CNY/t, the NPV of CO_2-ECBM projects will drop by around 2.73 billion CNY, suggesting that the exploitation cost of coalbed methane per million metric meters would grow 27 CNY.

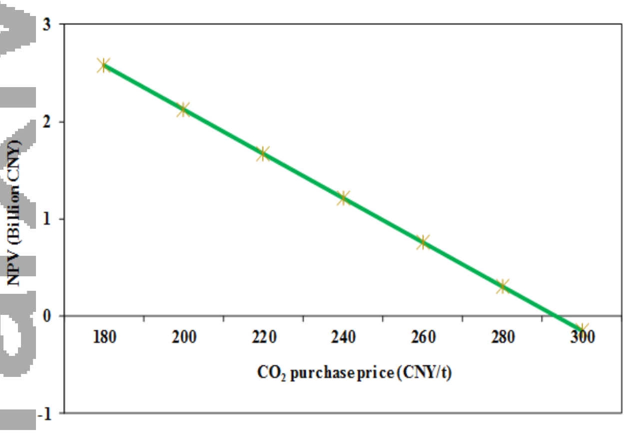

Figure 2 Influences of CO_2 source price on NPV (excluding carbon trading)

2.4 Conclusions

Coal consumption accounts for approximately 58% of the primary energy consumption in China in 2019 (NBS, 2020). The energy consumption structure dominated by coal restricts the sustainable development of China. The CO_2 emissions from natural gas is much lower than that from coal when providing the same heat. Therefore, increasing the use of natural gas can reduce CO_2 emissions and improve environmental pollution.

The environmental benefits of CO_2-ECBM technology are mainly reflected in two aspects. First, it can reduce CO_2 emissions by injecting CO_2 into coalbeds instead of emitting CO_2 into the atmosphere. Second, CO_2-ECBM technology can reduce the CH_4 emissions of coal mining, and the CH_4 recovered can be used as energy to reduce coal consumption .

There are a large number of early opportunities to deploy CO_2-ECBM projects with low-cost in China, because coalbed methane resources are rich in China and the widely distributed coal chemical plants can provide low-cost CO_2 source. The results of this study showed that investing CO_2-ECBM projects in China is feasible if the CO_2 source purchase price is cheap. Moreover, carbon trading could improve the investment benefits of CO_2-ECBM projects. However, the CO_2-ECBM technology in China is still in the demonstration stage with small-scale at present, and CCUS technologies have not yet been incorporated into the carbon market. In the future, the government and relevant enterprises should strengthen the research and development and demonstration of CO_2-ECBM to promote its deployment, so as to ensure national energy security and reduce greenhouse gas emissions. The Chinese government could also allow CCUS technologies to join the carbon trading system, promoting carbon emission reduction through market mechanism.

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