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Original Paper

A more efficient subsidy policy for CO_2 enhanced oil recovery: Insights from a vertically integrated business model

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ABSTRACT

Although carbon dioxide enhanced oil recovery (CO_2-EOR) is a technically and economically viable option within carbon capture, utilization, and storage (CCUS), its transition from demonstration to commercial application still requires subsidies. Existing research mainly focuses on carbon capture, overlooking the impact of stakeholder interest distribution and subsidy demand differences across the industrial chain. To address this issue, we first investigated the factors influencing subsidy requirements for CO_2-EOR projects under a vertically integrated business model. Utilizing the dynamic feedback relationships among these factors, we developed a system dynamics model to assess subsidy demand. Considering CO_2-EOR decision flexibility, we used real options analysis to evaluate the value of flexible decisions. Simulation identified three key factors for subsidy stratification: capture method, reservoir depth, and oil displacement efficiency. By calculating from the economic break-even point, we defined subsidy thresholds and developed a graded scheme linked to crude oil prices, considering their impact on policy effectiveness. Using the subsidy intensity of Section 45Q tax credit as a reference for simulation, the results indicate that when crude oil prices reach a certain level, the subsidy demand for projects can drop to zero. Differentiated subsidies reduced the amount required to achieve the same policy objectives by 25%, significantly enhancing policy efficiency.

1. Introduction

Fossil fuels continue to play a significant role in China's energy structure, and against the backdrop of the carbon neutrality goal, CCUS (carbon capture, utilization, and storage) technology has emerged as a foundational and critical pathway. CO_2-EOR not only improves oil and gas recovery rates, thereby increasing production, but also enables CO_2 storage, making it a technically mature and potentially economically viable option for CCUS in suitable contexts (Yuan et al., 2022). Basins suitable for CO_2-EOR, such as the Bohai Bay Basin in North China and the Songliao Basin in the Northeast, possess tremendous potential and have been prioritized for CCUS project implementation. The Ordos Basin in Central China and the Junggar and Tarim Basins in the Northwest are also key areas for CO_2-EOR deployment (Cai et al., 2021). It is estimated that approximately 13 billion tons of China's geological oil reserves are suitable for CO_2-EOR, which could result in an additional recovery of 1.92 billion tons of oil and the storage of 4.7–5.5 billion tons of CO_2 (Mi and Ma, 2019).

Despite this vast potential, the transition from geological potential to successful commercial application remains a significant challenge, with high costs being the primary obstacle for early-stage demonstration projects. Incentive policies, particularly subsidy policies, play a pivotal role in enhancing the profitability of CO_2-EOR projects and fostering their development (Edmonds et al., 2020; Song et al., 2022). Existing studies have employed real options methods to quantitatively evaluate the impact of different incentive policies on investment decisions (Sheikhtajian et al., 2024; Lee et al., 2023; Agaton, 2021). Fan explored the incentive effects of three unified subsidy models for CCUS projects in China by referencing the U.S. Section 45Q tax credit (Fan et al., 2019). However, their study did not address the issue of

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differentiation in subsidy policy design. A major shortcoming in subsidy policy research is the lack of designs tailored to address the variance in subsidy demands at the project level. Although scholars have recognized the importance of differentiated incentive policies (Liu et al., 2021; Ma, 2020; Wang and Tang, 2022), uniform subsidies risk overfunding high-quality projects while leaving those with higher subsidy demands underfunded, thereby significantly reducing policy efficiency. This issue has already been observed in the subsidy implementation for unconventional natural gas production (Yin, 2018; Xia et al., 2019).

Policy practices, such as the U.S. 45Q tax credit, which provides different credit levels for saline aquifer storage and EOR projects, further demonstrate the necessity and value of differentiated subsidies. However, the 45Q tax credit does not explore internal differences among CO_2-EOR projects. Moreover, unlike conventional oil and gas extraction, CO_2-EOR involves a longer and more complex value chain. This complexity requires that policy formulation fully account for the influencing factors across each segment of the value chain, as traditional net present value (NPV) calculations often fail to capture the dynamic feedback relationships among value-chain participants.

In this context, the vertically integrated business model, which enables comprehensive management of the entire value chain, has become a prevalent approach in China's current CCUS demonstration phase. This model is particularly suitable for early-stage projects because it aligns the interests of stakeholders and provides a clear framework for assessing costs and subsidy demand. Currently, a significant portion of China's full-chain CCUS projects (over half, according to Rui et al. (2025)) are independently invested and constructed by large oil companies such as CNPC, Sinopec, CNOOC, and Yanchang Petroleum, operating under a vertically integrated business model. Only a small number of projects adopt alternative business models (Rui et al., 2025).

Therefore, we focus on the critical demonstration phase of CCUS development, as designing guiding policies for this stage is an urgent priority. For small-scale pilot demonstrations, the conditions for applying a vertically integrated business model can be met, and it is feasible for the government to grasp the technical information of several typical projects to formulate targeted differentiated subsidy policies. In contrast, during the large-scale deployment phase, implementing differentiated subsidies on an annual timescale rather than at the project level may be a more practically meaningful approach (Yao et al., 2020). Accordingly, this study explores the design of a differentiated subsidy policy for CO_2-EOR projects operating under a vertically integrated model. Using a system dynamics (SD) approach, it reveals the dynamic feedback relationships among segments of the value chain, identifies key factors influencing subsidy demands, and proposes policy solutions to enhance the fiscal efficiency and fairness of subsidy allocation for this crucial initial phase.

2. Influencing factors of CO_2-EOR subsidy demand from a vertically integrated business model

The value chain of CO_2-EOR is divided into three segments: capture, transportation, and enhanced recovery and storage. The costs and benefits of each link affect the investment profit gap of CO_2-EOR projects, that is, the subsidy demand of CO_2-EOR projects. The influencing factors can be categorized into three main groups: resource endowments, development technology schemes, and economic factors (such as crude oil prices). The following outlines the factors influencing the subsidy demands of each segment of the CO_2-EOR value chain from a value-chain perspective.

2.1. Capture segment

The cost of the capture segment is influenced by the concentration and total amount of CO_2 emissions, the capture technology, and capture efficiency. Among these, the capture technology and the concentration of emissions are the most critical factors. Based on the timing of CO_2 capture, capture technologies can be further divided into post-combustion, pre-combustion, and oxy-fuel combustion. Pre-combustion capture is typically for new power plants, while the other two technologies can be applied to both new and existing power plants and chemical plants (Mi and Ma, 2019; Ye et al., 2018). Currently, post-combustion capture is the most widely deployed at industrial scale and is relatively easier to retrofit in existing facilities (Wen et al., 2022), making it a primary focus of current capture technology research. The choice of capture technology is influenced not only by the type of combustion but also by factors such as the CO_2 concentration in the feed gas. In China, emission sources primarily consist of low-concentration sources from coal-fired power plants, gas-fired power plants, and petrochemical refineries, with relatively fewer medium- to high-concentration sources. Presently, the costs of different capture technologies generally range from low to high as follows: pre-combustion capture, post-combustion capture, and oxy-fuel combustion. According to the China CCUS Annual Report (2021) (Cai et al., 2021), the expected CO_2 capture cost by 2030 is between 90 and 390 CNY per ton, and by 2060, it could reduce to 20–130 CNY per ton, covering both fixed and operational costs.

2.2. Transportation segment

The transportation segment's costs are significantly influenced by the mode of transportation and the distance covered. Currently, CO_2-EOR projects predominantly utilize truck transport, which is relatively expensive, costing between 0.8 and 1.0 CNY per ton-kilometer (Yuan et al., 2022). In future scenarios involving large-scale, long-distance CO_2 transportation, pipeline transport emerges as the most economical and reliable method, with projected transportation costs potentially decreasing from 0.8 CNY per ton-kilometer in 2025 to 0.4 CNY per ton-kilometer by 2060. Regarding transportation distance, CO_2 emission sources and oil reservoirs are often not located in the same region, necessitating source-sink matching analysis. Due to the lack of project-level source-sink matching data, this study assumes ideal matching and adopts a fixed representative distance of 250 km—the maximum pipeline length without intermediate CO_2 compression stations and a common distance limit in China's source-sink matching analyses (Cai et al., 2021). In practice, the development of CO_2-EOR projects presupposes completed source-sink matching, hence the transportation segment considers only the factors of transportation mode and distance.

2.3. Enhanced oil recovery and storage segment

The primary factors impacting the input and output of the enhanced oil recovery and storage phase are the geological conditions of the reservoir and the price of crude oil. Reservoir geological conditions influence project investment and revenue through storage conditions, the effectiveness of CO_2 utilization, and reservoir depth. This includes how the lithology, porosity, permeability, formation pressure, temperature, mineralization, and pH value of the reservoir affect the matched storage volume and CO_2 utilization factor after considering source-sink matching. Additionally, reservoir depth impacts the cost of surface equipment, drilling and completion, and operational maintenance costs. Tax policies, carbon trading income, and crude oil sales revenue constitute the main sources of revenue for CO_2-EOR projects. Low well productivity can lead to limited overall enhanced oil production, while high CO_2 wellhead prices and low crude oil prices make the cost of enhancing recovery with CO_2 prohibitively high; subsidy policies can effectively mitigate these costs (Zhao et al., 2018). Moreover, research indicates that CO_2 might leak during the storage process through potential risk points such as wellbores,

$$Q_{\text{oil}}^{t} = Q_{\text{oil-peak}} e^{-D_{\text{w}} t} = F_{\text{gw}} Q_{\text{W}} e^{-D_{\text{w}} t} \tag{5}$$

The investment in the CO_2-EOR and storage phase mainly includes exploration investment and the investment in modifying and constructing production and injection wells. Exploration incentive policies for CO_2-EOR has commonly taken into account the option value of such projects (Ozdemir et al., 2018). Given the irreversibility of project investment costs and the uncertainty of returns, investors can add new value to projects through flexible investment, treating it as an option to adjust decisions based on changes in uncertain factors. The pricing of flexible investments can be quantified using the real options approach. In the context of CO_2-EOR projects, crude oil sales revenue currently constitutes the main source of income, and the value of the investment right lies in realizing the value of crude oil development and utilization. This means that decision-makers have the right to pursue CO_2-EOR with the expectation of future revenues from crude oil sales. An increase in crude oil prices might delay the ex

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The sensitivity analysis of the total investment value (TIV), as illustrated in Fig. 3, reveals that the TIV is highly sensitive to critical factors such as reservoir depth, capture method, and production rate. In contrast, the influence of the transportation mode is significantly lower. This latter finding is directly linked to the fixed 250 km transport distance assumed in our model (Section 2.2).

This disparity in sensitivity is

in the cost per ton of CO_2 capture. The costs associated with different capture methods, referenced from a report (Cai et al., 2021), demonstrate through fitting that there's an approximate linear relationship between the cost per ton of CO_2 capture and the TIV. Furthermore, this linear relationship between the capture method and investment value persists across different intensities of storage subsidies, as depicted in Fig. 5.

(2) The impact of reservoir depth on investment value

Selecting suitable reservoirs is a prerequisite for developing CO_2-EOR projects. Currently, the static indicators used for selection both domestically and internationally include reservoir parameters such as depth, temperature, and original formation pressure, as well as fluid properties like crude oil gravity and viscosity. According to the CO_2-EOR reservoir depth selection criteria proposed by scholars, suitable reservoir depths for CO_2-EOR range between 600 and 4074 m (W unit to enter the development sequence are classified as Category II, and so on, as detailed in Table 5.

During this period, the market environment must also be taken into account. Crude-oil prices directly determine revenue from oil sales, and the crude-oil market environment is driven by macroeconomic and industry conditions without project-specific differences (He and Zhao, 2018). Therefore, as crude-oil prices fluctuate, the subsidy demand for each project category adjusts accordingly. Fig. 8 clearly shows how subsidy demand for CO_2-EOR projects varies with oil-price changes (post-combustion capture example): when the price rises from 50 to 80 USD/bbl, the subsidy for Category I projects falls from 270 to 0 CNY/ton; when the price further increases to 90 USD/bbl, only Category III and IV projects still require subsidies (88 and 188 CNY/ton, respectively), while Category I and II projects can proceed without subsidy.

To operationalize this automatic adjustment, the CCUS-EOR Management Center calculates the three-month rolling average Brent crude price at the start of each quarter and, based on predefined price thresholds, publishes the corresponding subsidy tiers. Project operators then report monthly CO_2 injection and oil-production data; the Management Center multiplies the applicable subsidy rate by the reported injection volume to compute the quarter's subsidy

Level III, requiring a storage subsidy of 200 CNY/ton when the crude oil price is 75 $/bbl and the carbon price is 60 CNY/ton.

To compare the effects of a uniform subsidy policy with a differentiated subsidy policy, let's assume that China currently implements a uniform subsidy of $20.22 per ton of CO_2 sequestered through EOR, based on the subsidy amount of Section 45Q tax credit before 2026. Under this subsidy rate, the block would not qualify for development. If the subsidy is increased to $35 per ton of CO_2 sequestered through EOR, referencing the post-2026 subsidy amount of Section 45Q tax credit, the storage amount would be 103,600 tons, requiring a total subsidy of 22.8438 million CNY. However, under a differentiated subsidy policy, only 20.72 million CNY would be needed to stimulate investment and development in the block, resulting in a 9.3% increase in subsidy policy efficiency.

To further analyze the impact of changes in different scenarios on the effectiveness of subsidies, scenario simulations were conducted for variations in carbon trading prices and crude oil prices. The base scenario for carbon prices was established by referring to national carbon price surveys and literature research, with expectations that China's carbon price level will rise from 58 CNY/ton in 2025 to 70 CNY/ton, reach 100 CNY/ton by 2030, and increase to 180 CNY/ton by 2035 (Zhao et al., 2021; Zhang et al., 2022). In both optimistic and pessimistic scenarios, the carbon price is adjusted by $\pm$15%. The benchmark for crude oil prices is set at 60 $/bbl, with optimistic and pessimistic scenario prices at 42 and 78 $/bbl, respectively. Assuming the block is invested in 2020, with a construction period of one year and a production period of 15 years, other basic parameter settings can refer to Table 7. Fig. 9 illustrates the net benefit changes of the CO_2-EOR project under different combinations of crude oil prices and carbon trading prices, indicating that the project successfully enters the devkqSDXDz(Fw..xDhe evaluate and provide differentiated support based on both a project's objective, 'innate' difficulties and its 'acquired' technological pathways.

The study also highlights the significant influence of crude oil prices on the effectiveness of differentiated subsidies. This finding aligns with a broad consensus in the literature that CO_2-EOR project

Ren, B., Ren, S., Zhang, L., et al., 2016. Monitoring on CO_2 migration in a tight oil reservoir during CCS-EOR in Jilin oilfield China. Energy 98, 108–121. https://doi.org/10.1016/j.energy.2016.01.028.

Ren, B., Male, F., Duncan, I.J., 2022. Economic analysis of CCUS: accelerated development for CO_2 EOR and storage in residual oil zones under the context of 45Q tax credit. Appl. Energy 321, 119393. https://doi.org/10.1016/j.apenergy.2022.119393.

Rui, Z., Zeng, L., Dindoruk, B., 2025. Challenges in the large-scale deployment of CCUS. Engineering 44, 17–20. https://doi.org/10.1016/j.eng.2024.11.031.

Sheikhtajian, S., Bagherinejad, J., Mohammadi, E., 2024. Investment in CCUS under technical uncertainty considering investor's risk aversion: an exotic compound real-options approach. Int. J. Greenh. Gas Control 138, 104241. https://doi.org/10.1016/j.ijggc.2024.104241.

Song, X.K., Zhang, J.T., Wang, C., 2022. Analysis of the business model for carbon capture, utilization and storage (CCUS) technologies. Chin. J. Environ. Manag. 14 (1), 38–47. https://doi.org/10.16868/j.cnki.1674-6252.2022.01.038 (in Chinese).

Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill, Boston.

Wang, H., Luo, D.K., Zheng, Y.H., 2006. Optimal model of oilfield development plan based on real options theory. Petroleum Geology and Recovery Efficiency (1), 5–7+10 (in Chinese).

Wang, G.F., Hu, Y.L., Song, X.M., et al., 2013. New theory of oil production prediction in gas flooding tight reservoirs. Sci. Technol. Eng. 13 (30), 8905–8911 (in Chinese).

Wang, G.F., Zheng, X.J., Zhang, Y., et al., 2015. A new screening method of low permeability reservoirs suitable for CO_2 flooding. Petrol. Explor. Dev. 42 (3), 358–363 (in Chinese).

Wang, X.P., Tang, R., 2022. Research on business model and policy incentives for carbon capture, utilization and storage in coal-fired power plants. Therm. Power Gener. 51 (8), 29–41. https://doi.org/10.19666/j.rlfd.202201017 (in Chinese).

Wei, N., Li, X., Dahowski, R.T., et al., 2015. Economic evaluation on CO_2-EOR of onshore oil fields in China. Int. J. Greenh. Gas Control 37, 170–181. https://doi.org/10.1016/j.ijggc.2015.01.014.

Wen, H., Han, W., Che, C.X., et al., 2022. Progress of post-combustion carbon dioxide capture technology development and applications. Fine Chem 39 (8), 1584–1595. https://doi.org/10.13550/j.jxhg.20220167 (in Chinese).

Xia, L., Yin, Y., Yu, X., et al., 2019. An approach to grading coalbed methane resources in China for the purpose of implementing a differential production subsidy. Pet. Sci. 16 (2), 447–457. https://doi.org/10.1007/s12182-019-0303-0.

Yang, Y., Li, Y., Zhang, S., et al., 2017. Monitoring the impact of fugitive CO_2 emissions on wheat growth in CCS-EOR areas using satellite and field data. J. Clean. Prod. 151, 34–42. https://doi.org/10.1016/j.jclepro.2017.03.058.

Yang, Y.Z., Zhou, J.S., Hu, H.W., et al., 2025. Development status, economic benefits and future prospects of CCUS-EOR industry. China Mining Magazine 34 (2), 190–203. https://doi.org/10.12075/j.issn.1004-4051.20242290.

Yao, X., Zhong, P., Zhang, X., et al., 2018. Business model design for the carbon capture utilization and storage (CCUS) project in China. Energy Policy 121, 519–533. https://doi.org/10.1016/j.enpol.2018.06.019.

Yao, X., Fan, Y., Zhu, L., et al., 2020. Optimization of dynamic incentive for the deployment of carbon dioxide removal technology: a nonlinear dynamic approach combined with real options. Energy Econ. 86, 104643. https://doi.org/10.1016/j.eneco.2019.104643.

Yao, X., Yuan, X., Yu, S., 2021. Economic feasibility analysis of carbon capture technology in steelworks based on system dynamics. J. Clean. Prod. 322, 129046. https://doi.org/10.1016/j.jclepro.2021.129046.

Ye, Y.Y., Liao, H.Y., Wang, P., et al., 2018. Research on technology directions and roadmap of CCS/CCUS for coal-fired power generation in China. Strategic Study of CAE 20 (3), 80–89. https://doi.org/10.15302/J-SSCAE-2018.03.012 (in Chinese).

Yin, Y.J., 2018. The Optimization Method of Production Subsidy for Coalbed Methane Based on the Resources Grades. Master's Thesis. China University of Petroleum (Beijing) (in Chinese).

Yuan, S.Y., Ma, D.S., Li, J.S., et al., 2022. Progress and prospects of carbon dioxide capture, EOR-utilization and storage industrialization. Petrol. Explor. Dev. 49 (4), 1–7 (in Chinese).

Zhang, X.L., Huang, X.D., Zhang, D., 2022. Research on the pathway and policies for China's energy and economy transformation toward carbon neutrality. Journal of Management World 38 (1), 35–66. https://doi.org/10.19744/j.cnki.11-1235/f.2022.0005 (in Chinese).

Zhao, X.L., Wang, Y., Li, J.,