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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, faults, and cap rocks (Ren et al., 2016; Yang et al., 2017). Currently, the operational period for field-implemented CO_2-EOR and storage projects ranges approximately from 10 to 20 years, with no incidents of CO_2 leakage reported thus far. However, safe CO_2 storage is a long-term endeavor, and considering the cost of monitoring within the factors affecting subsidy policies is essential for future considerations.

3. Construction of a CO_2-EOR subsidy demand assessment model under flexible investment

The traditional NPV method, which focuses on the project as a whole, treats cash inflows and outflows as independent, without considering the feedback relationships between different segments and ignoring the decision-makers' managerial flexibility under uncertain conditions (Wang et al., 2006). In contrast, SD enables the construction of feedback relationships between these segments. Existing research has applied SD to the economic feasibility assessment of CCUS technologies (Yao et al., 2021; Proaño et al., 2020; Liang et al., 2012), acknowledging the multitude of uncertainties CO_2-EOR projects face in terms of technology, costs, and policies. Therefore, the assessment of CO_2-EOR project subsidy demand through SD, coupled with the Black-Scholes real options pricing model, is proposed, where the investment value of a CO_2-EOR project is comprised of the benefits derived post-development and the value of options.

This paper aims to construct a CO_2-EOR subsidy demand assessment model under flexible investment using SD. This involves quantifying the influencing factors into assessment indicators, identifying key factors affecting CO_2-EOR project subsidy demand through sensitivity analysis, and categorizing the subsidy targets accordingly. In building the SD subsidy demand assessment model, the following premises and assumptions are proposed: 1) Since source-sink matching is completed prior to the development of CO_2-EOR projects, this paper no longer considers source-sink matching in the transportation segment, and the storage volume in the EOR and storage segment is represented by the matched storage volume. 2) In the EOR and storage segment, a portion of the injected CO_2 is produced with the oil and re-injected after oil-gas separation and purification. We assume that during the project operation period, through effective monitoring and management, the majority of injected CO_2 can achieve safe storage in the formation after the project ends, with potential CO_2 leakage risks accounted for through monitoring costs. This approach equates CO_2 transport volume with CO_2 injection and storage volume for modeling purposes. 3) From a business model perspective, studies have shown that due to lower interest rates and transaction costs, the vertical integration model is the most suitable choice for early-stage CCUS deployment in China (Yao et al., 2018; Wang et al., 2013). Compared to the operator model, the cumulative revenue of the vertical integration model is lower after about 35 years (Wang and Tang, 2022). However, since CO_2-EOR project operation cycles are often 20 years, this paper, based on the vertical integration model, explores differentiated subsidies for CO_2-EOR projects of vertically integrated companies that include capture, transportation, and enhanced recovery and storage.

3.1. CO_2-EOR cost-benefit analysis

Given that CO_2-EOR projects are typically associated with retrofitting or expansion efforts, it is critical to account for an input-output system comprised of incremental costs and benefits, which are primarily reflected in the incremental benefits from crude oil production and CO_2 emission reductions, as well as the time value of money. Therefore, the cumulative net benefit of CO_2-EOR projects can be expressed by Eq. (1). All variables and their definitions detailed in Supplementary Table S1.

Specifically, U denotes the cumulative net benefit, I_Z is the investment, N is the number of evaluation periods, i is the discount rate (12%), $U^t_{CO_2}$ and U^t_{oil} are, respectively, the CO_2 storage benefits in year t and the crude oil increase benefit in year t, and C^t_Z is the incremental cost in year t.

$$U = -I_Z + \sum_{t=0}^{N} \left(U^t_{CO_2} + U^t_{oil} - C^t_Z\right)(1+i)^{-t} \tag{1}$$

Adopting an industrial chain perspective, the composition of project cost-effectiveness can be divided into two parts: one is the carbon capture project at the CO_2 emission source, and the other is the project at the oil and gas field that utilizes CO_2 for enhanced oil recovery while simultaneously storing CO_2. On the capture side, the project cash flow is primarily influenced by capture costs, which include both fixed and operational costs (Eq. (2)). Then, in Eq. (2) C^t_{CAP} is the capture cost in year t (CNY), P_{CO_2} is the unit CO_2 capture cost (CNY/ton), and $q^t_{CO_2}$ is the storage capacity in year t (ton).

$$C^t_{CAP} = P_{CO_2} \times q^t_{CO_2} \tag{2}$$

The CO_2-EOR and storage segment influence the project cash flow through investment, operational and maintenance costs, monitoring costs, EOR and storage revenues, and taxes. Prior to this, the transportation segment connects the capture side with the CO_2 storage and EOR side, affecting the project value through transportation investments, as detailed in Eq. (3). The operational and maintenance costs incurred in this segment are integrated into the CO_2-EOR and storage phase. Accordingly, in Eq. (3), I_t denotes the transportation investment (CNY), L is the transportation distance (km), i_t is the construction investment per ton of gas unit (CNY/(km·ton)), and $q_{co_2\text{-peak}}$ is the peak CO_2 storage capacity.

$$I_t = L \times i_t \times q_{co_2\text{-peak}} \tag{3}$$

The peak volume of CO_2 injection can be approximated through substitution ratio of CO_2 to oil and the gas-driven oil production (assuming the peak of gas-driven production occurs in the first year after commencement). Eq. (4) defines the substitution ratio of CO_2 to oil and introduces R as the oil change rate, given by $q^t_{co_2}$ (CO_2 storage capacity in year t) divided by Q^t_{oil} (CO_2 flooding crude oil production in year t). Eq. (5) allows for the calculation of the peak oil production from gas drive by using the gas drive enhanced production multiplier and the concurrent water flooding production (Liang et al., 2012). By combining this with substitution ratio of CO_2 to oil, the peak CO_2 injection volume can be determined. $Q_{oil\text{-peak}}$ is the peak crude oil production (ton), F_{gw} is the gas drive production increase multiple (value 1.5[3]), Q_W is the water flooding production during the same period (ton), and D_w is the (water flooding) decline rate.

$$R = \frac{q^t_{co_2}}{Q^t_{oil}} \tag{4}$$

$$Q^{t}_{\text{oil}} = Q_{\text{oil-peak}} \cdot e^{-D_w t} = F_{gw} Q_W e^{-D_w t} \tag{5}$$

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 investment follows Eq. (6), where i_{site} (survey cost per unit area, CNY/km^2) and A (average survey area per well, km^2) are specified. Investment in equipment modification and construction primarily consists of the capital costs for new injection wells, production wells, and the modification of existing wells. These modification and construction costs are related to the reservoir depth and topographical conditions. The capital cost coefficients for wells are referenced from (Chen, 2019). Based on data from the Qilu Petrochemical-Shengli Oilfield demonstration project, the ratio of production wells to injection wells is approximately 3:1, with one backup well required for every ten production and injection wells (Dahowski et al., 2012). The ratio of new wells to converted wells is 0.15 (Kwak and Kim, 2017). The retrofit investment calculation method is shown in Eq. (7), where I_{gz} denotes the total renovation and construction investment, $C_{\text{new-inj}}$ and $C_{\text{new-prod}}$ are the unit capital costs for new injection and new production wells. $n_{\text{wo-inj}}$ and $n_{\text{wo-prod}}$ represent the numbers of modified injection and production wells, respectively; n_{other} is the number of spare wells.

Eq. (10) derives the average retrofit investment per well, $\bar{I}_{gz}$, based on the proportion of different well types. The coefficients in Eq. (10), such as 0.0296, are weighting factors derived from the well-type shares so as to accurately reflect the investment attributable to each type. Additional cost items used in these calculations include $C_{\text{D\&C}}$ (drilling and completion costs, CNY), C_{lease} (rental equipment cost, CNY), and the equipment costs for injection and production wells, $C_{\text{inj-E}}$ and $C_{\text{prod-E}}$.

$$I_{\text{site}} = i_{\text{site}} A \tag{6}$$

$$\begin{aligned} I_{gz} = {} & n_{\text{new-inj}} C_{\text{new-inj}} + n_{\text{new-prod}} C_{\text{new-prod}} \\ & + n_{\text{wo-inj}} \left(0.48 C_{\text{D\&C}} + 0.5 C_{\text{new-inj}}\right) \\ & + n_{\text{wo-prod}} \left(0.48 C_{\text{D\&C}} + 0.5 C_{\text{new-prod}}\right) \\ & + n_{\text{other}} \left(C_{\text{D\&C}} + C_{\text{lease}}\right) \end{aligned} \tag{7}$$

$$C_{\text{new-inj}} = C_{\text{D\&C}} + C_{\text{lease}} + C_{\text{inj-E}} \tag{8}$$

$$C_{\text{new-prod}} = C_{\text{D\&C}} + C_{\text{lease}} + C_{\text{prod-E}} \tag{9}$$

$$\begin{aligned} \bar{I}_{gz} = {} & 0.0296\left(C_{\text{D\&C}} + C_{\text{lease}} + C_{\text{new-inj}}\right) + 0.0889\left(C_{\text{D\&C}} + C_{\text{lease}} + C_{\text{new-prod}}\right) \\ & + 0.1976\left(0.48 C_{\text{D\&C}} + 0.5 C_{\text{new-inj}}\right) + 0.5929\left(0.48 C_{\text{D\&C}} + 0.5 C_{\text{new-prod}}\right) + 0.0909\left(C_{\text{D\&C}} + C_{\text{lease}}\right) \end{aligned} \tag{10}$$

The costs associated with the CO_2-EOR phase primarily include operational and maintenance costs as well as monitoring costs. Operational and maintenance costs cover injection charges for EOR agents, CO_2 recycling and reuse costs, maintenance expenses, and oil and gas processing fees. These costs are estimated through capital costs in Eq. (11), where $C_{\text{O\&M}}$ denotes the operating and maintenance cost and is assessed as a proportion of three capital components: I_{site} (exploration investment), I_{gz} (renovation and construction investment) I_{ys} (pipeline construction investment). Monitoring costs are based on the research by (Wei et al., 2015), which suggests that the normalized unit CO_2 monitoring cost for commercial-scale EOR projects in China is 63 CNY per ton (Eq. (12)).

$$C_{\text{O\&M}} = 0.1 \times \left(I_{\text{site}} + I_{gz} + I_{ys}\right) \tag{11}$$

$$C^t_{jc} = 0.63 \times q^t_{CO_2} \tag{12}$$

Finally, the revenue from the EOR and storage phase are computed from Eqs. (13)–(15): R^t_{Oil} (oil sales revenue in year t), $R^t_{CO_2}$ (carbon trading revenue in year t), and R^t_{sub} (carbon storage subsidy in year t). In Eq. (13), P_{oil} (crude oil price), w (commodity rate), and Q^t_{oil} (oil output in year t) determine oil income. In Eq. (14), $q^t_{CO_2}$ is the amount of CO_2 stored in year t, and s is the unit storage subsidy (CNY/ton). In Eq. (15), $P_C(t)$ is the carbon price in year t (CNY/ton). The carbon tax deduction used in Eq. (17) is given by Eq. (16). Taxation considerations include resource tax, value-added tax, income tax, special oil income levy, and carbon tax deductions. In summary, the cost-benefit analysis of a CO_2-EOR project, initially presented by Eq. (1), can be further detailed into Eq. (17), incorporating the aforementioned components.

$$R^t_{\text{Oil}} = P_{\text{oil}} \times w \times Q^t_{\text{oil}} \tag{13}$$

$$R^t_{\text{sub}} = q^t_{CO_2} \times s \tag{14}$$

$$R^t_{CO_2} = P_C(t) \times q^t_{CO_2} \tag{15}$$

$$T^t_c = q^t_{co_2} \times t_c \tag{16}$$

$$U = -\left(I_t + I_{\text{site}}\right) + \sum_{t=0}^{N} \left[R^t_{\text{Oil}} + R^t_{CO_2} + R^t_{\text{sub}} - C^t_{\text{cap}} - C_{\text{O\&M}} - C^t_{jc} - \left(T^t_x - T^t_C\right)\right] (1+i_0)^{-t} \tag{17}$$

3.2. CO_2-EOR real options analysis

Compared to traditional NPV approaches, which evaluate project profitability under the assumption of fixed and static decision paths, the real options approach explicitly captures the managerial flexibility available under uncertainty. In practice, decision-makers are not passive, they may defer, expand, abandon, or switch strategies in response to volatile conditions. Such flexibility is especially valuable in CO_2-EOR projects, which face multiple uncertainties in oil prices, carbon pricing mechanisms, and policy environments. Traditional NPV models fail to account for this flexibility and thus tend to underestimate project value in dynamic and uncertain settings.

The formulation of subsidy policies needs to consider not only the industrial economic viability of the project but also the micro-level decisions of the enterprises involved. Current research on 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 exercise of the option. Therefore, CO_2-EOR projects can be viewed as holding an American-style call option. The following discussion uses the Black-Scholes real options pricing model to represent the option value of CO_2-EOR projects (Eqs. (18–20)), where volatility is approximated by the variance in historical crude oil price data to represent the project value's volatility. ROV is the real option value, determined by the underlying asset's present value V, the exercise price X, the risk-free rate r, the time to expiration T, the annualized volatility σ, and the cumulative standard normal distribution.

$$\mathrm{ROV} = VN(d_1) - X\mathrm{e}^{-rT}N(d_2) \tag{18}$$

$$d_1 = \ln(V/X) + T\left(r + \sigma^2 \Big/ 2\right) \Big/ \sigma\sqrt{T} \tag{19}$$

$$d_2 = d_1 - \sigma\sqrt{T} \tag{20}$$

3.3. *Flexible investment-based CO_2-EOR subsidy requirement assessment model*

To reflect how the cumulative net benefit is influenced by changes in enhanced oil production and storage volumes, as well as the feedback relationships between the capture, transportation, and EOR and storage phases, this study utilizes the internal feedback mechanisms and dynamic operation mode of SD to account for yearly variations in internal factors. This process accounts for production increases and scale expansion driven by technological innovation and learning effects, which ultimately reduce production costs across the capture, transportation, and storage phases. Using cost assessment data from the "China CCUS Report (2021)", the learning rates for CO_2 capture, transportation, and storage technologies were fitted. For example, the cost fitting curves for different capture methods are shown in Fig. 1, yielding a cost reduction rate (e.g., 0.031 for pre-combustion capture) and corresponding technology learning rates (Table 1). To ensure numerical stability and improve the interpretability of the regression coefficients, the time variable was normalized. The year 2020 was set as the base year, such that the variable x in the exponential decay models represents the number of years elapsed since 2020 (i.e., x=Year−2020). These rates are incorporated into the SD model to affect the project cash flow, as detailed in Eqs. (21) and (22). Here, C_{TP}^{t} is the capture cost under the technical conditions in year t, C_{TP}^{0} is the capture cost under current technical conditions, ∂ is the cost reduction rate driven by technological progress, and LR is the learning rate.

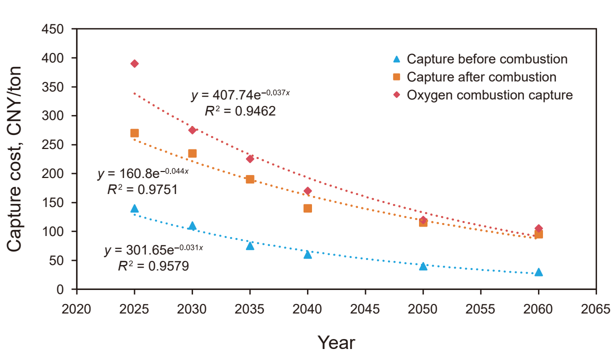

Fig. 1. Carbon capture cost fitting results.

Regarding the capture phase, there are significant differences in the technological costs among different methods. This paper focuses on post-combustion capture, the most mature technology. The annual capture volume considered is 1.8 million tons.

$$C_{\mathrm{TP}}^{t} = C_{\mathrm{TP}}^{0}\mathrm{e}^{-\partial t} \tag{21}$$

$$LR = 1 - 2^{-\partial} \tag{22}$$

Integrating external environmental factors such as oil prices, carbon trading prices, and subsidy policies, along with the feedback among members within the system, the final investment value can be obtained (Eq. (23)). The subsidy demand for CO_2-EOR projects can be calculated based on the investment value gap of CO_2-EOR projects.

$$\mathrm{TIV} = U + \mathrm{ROV} \tag{23}$$

Fig. 2 presents the stock and flow diagram of the SD model, viewed from the perspective of investment decision-makers, indicating the subsidy amount that just suffices to render the CO_2-EOR project value positive. From the standpoint of policy formulation, as long as the presence of subsidies effectively encourages decision-makers to invest, the policy is deemed effective. On the premise of effective subsidy policies, the government's objective should be to initiate more projects with a lower subsidy budget. As depicted in Fig. 3, when other parameters are fixed, the subsidy amount that just makes the project investment value positive is the subsidy demand for the project and also represents the optimal subsidy from the policy formulation perspective.

Before conducting the simulation analysis, it is necessary to check the integrity and validity of the model (Sterman, 2000). In VENSIM software, we set the initial time to 0 and simulate continuously for 50 years, with the time unit set to 1 year. By executing the "check model" command in the software, if the interface prompts "Model is OK", it indicates that the model has passed both the model check and unit check.

4. Differentiated subsidy scheme design and effect analysis

4.1. *Design of differentiated subsidy schemes for CO_2-EOR*

4.1.1. *Impact of key factors on the investment value of CO_2-EOR projects*

Building upon the CO_2-EOR project subsidy demand assessment model, it's possible to analyze the relationship between influencing factors and economic value, which in turn helps identify key factors for categorization. Subsequently, based on the identified influencing factors, a graded strategy can be formulated. Given the significant impact of crude oil prices on project subsidy demand, a subsidy scheme that links subsidy levels to crude oil prices has been established, under the premise that the gradation of subsidy amounts remains unchanged. The foundational data required for calculations by this model are presented in Table 2.

Table 1
Technology learning rate fitting results.

Type	Unit	Technique	Decline rate	Learning rate
Capture techniques	CNY/ton	Capture before combustion	0.031	0.0213
		Capture after combustion	0.044	0.0300
		Oxygen combustion capture	0.037	0.0253
Transportation method	CNY/(ton·km)	Pipeline transportation	0.020	0.0138
		Tank truck transportation	0.012	0.0083
Storage costs	CNY/ton	CO_2-EOR	0.025	0.0172

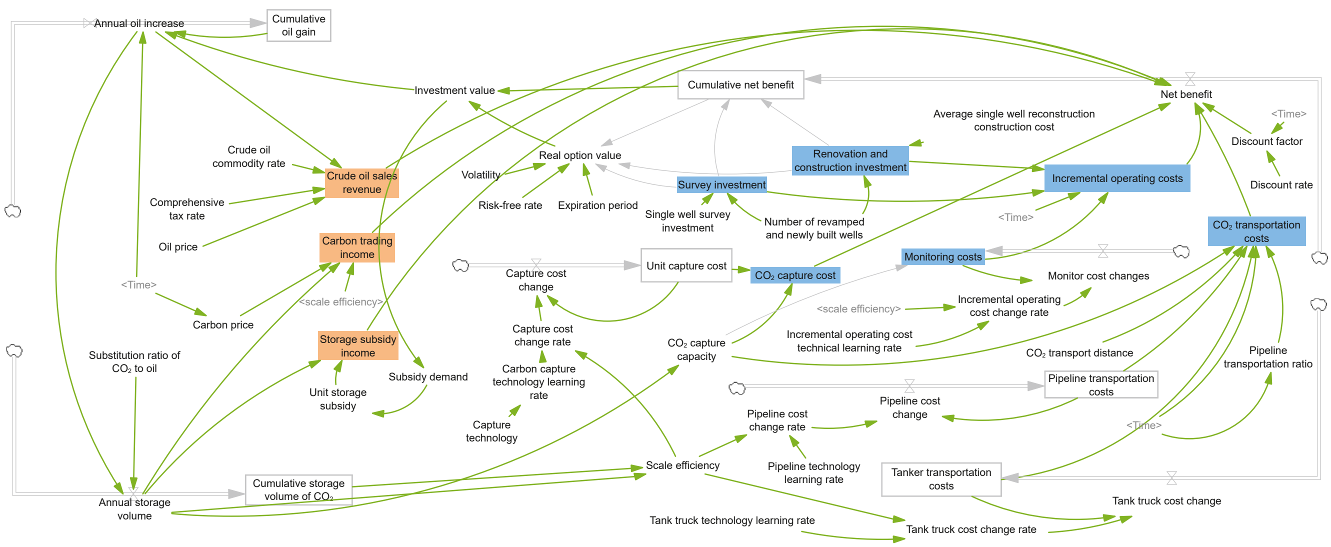

Fig. 2. Stock flow diagram.

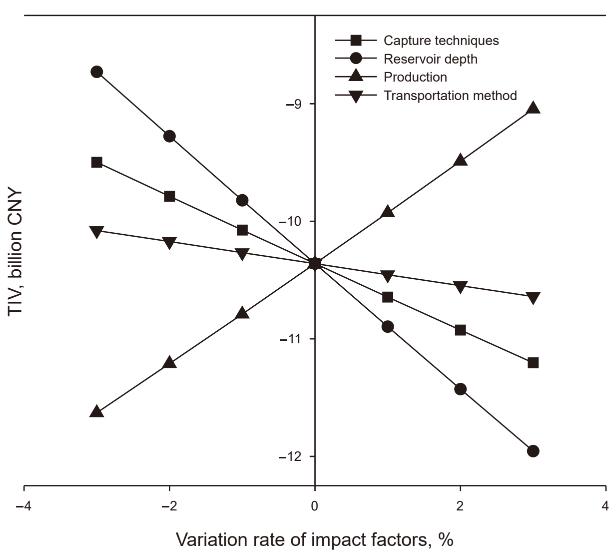

Fig. 3. Sensitivity analysis.

Table 2
Basic data table.

Main parameters	Unit	Value
Operational lifespan	years	15
Cost per well for exploration	10,000 CNY	6.05
Storage capacity per well	10,000 tons	0.84
Reservoir depth	meters	1500
Cost per ton of CO_2 capture	CNY/ton	310
Investment per ton of CO_2 transportation	CNY/(ton·km)	1.15
Oil displacement ratio	ton/ton	3.6
Subsidy per ton of storage	CNY/ton	220
Crude oil price	USD/barrel	75
Maturity period	years	10
Base discount rate	%	12
Carbon tax	CNY/ton	120

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 an expected outcome, stemming from both the project's cost structure and the nature of the analysis itself. Crucially, the results of a sensitivity analysis are inherently influenced by the base value of each parameter; a percentage change in a larger cost component will naturally have a greater absolute impact than the same percentage change in a smaller one. In our model, the capture segment's costs constitute the vast majority of the TIV. Consequently, its large base value means that any variation in capture costs has a much more pronounced effect on the project's overall investment. To precisely model this, our analysis operationalizes the 'capture method' variable by varying the 'unit CO_2 capture cost (CNY/ton)' within a defined range (e.g., ±x%).

(1) Impact of capture cost on investment value

Assuming all other project conditions are held constant, the variation in the TIV due to changes in the capture method is analyzed. As illustrated in Fig. 4, the TIV decreases with an increase

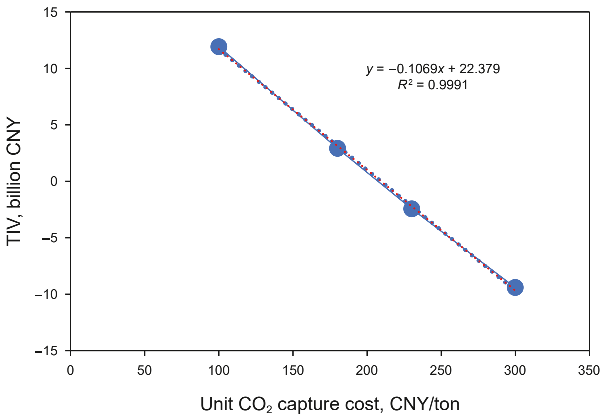

Fig. 4. The relationship between capture cost and TIV.

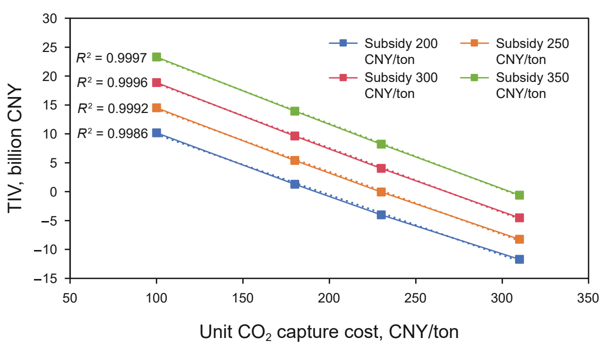

Fig. 5. The relationship between capture cost and TIV under different subsidy levels.

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 (Wang et al., 2015; He et al., 2020). Reservoir depth influences project investment and operational costs. When other conditions are held constant, the relationship between reservoir depth and the TIV under different storage subsidy levels can be calculated, indicating that reservoir depth and the project's investment value also maintain an approximate linear relationship (Fig. 6).

(3) The impact of output on investment value

To explore the relationship between production and investment value, this study fits the relationship between a 1% change in production under different subsidy amounts and the TIV, assuming a constant oil displacement ratio. The range of oil

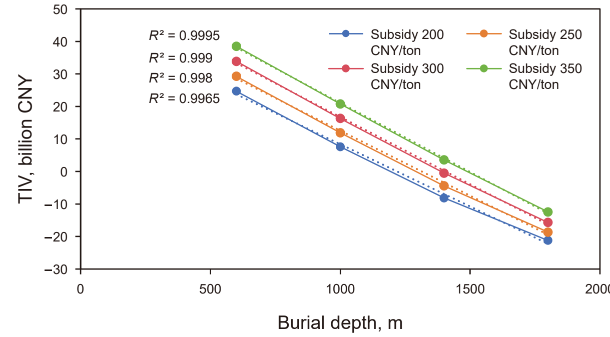

Fig. 6. The relationship between reservoir burial depth and TIV under different subsidy levels.

displacement ratios for oil fields in China where CCUS can be implemented is 3.38–6.43 (Li, 2019), with 90% of domestic CO_2-EOR technologies applied to low and ultra-low permeability reservoirs (Li et al., 2020). In such low permeability reservoirs, the oil displacement ratio is estimated to be 3 over a 15-year evaluation period (Wang et al., 2015). This paper sets the oil displacement ratio at 3.6, primarily based on the settings of the Qilu Petrochemical-Shengli Oilfield CCUS project, which aligns with the results from the literature review. As indicated in Fig. 7, the production and project investment value under different subsidy levels generally exhibit an approximate linear relationship.

4.1.2. Differentiated subsidy plan

Through quantitative analysis of the impact of the capture, transportation, enhanced oil recovery, and storage phases on the investment value of CO_2-EOR projects, key factors affecting project investment value have been identified: capture method, reservoir depth, and production. Among these, production is influenced by the oil displacement ratio and the volume of CO_2 injected. During preliminary categorization, it is necessary to define the range of oil displacement ratios before classifying the production per well. Table 3 outlines the ranges and values for these key factors.

Under different subsidy amounts, the boundary annual production per well (ECP) can be calculated (assuming gas drive takes effect within a year) as shown in Table 4. Similarly, boundary capture costs (ECC), boundary reservoir depths (ECD), and boundary annual production per well (ECP) can be determined. Conversely, these boundary values can also be used to grade subsidy targets. Projects that can proceed with CO_2-EOR development without government subsidies are classified as Category I, while projects requiring a subsidy of 100 CNY/ton per sequestered

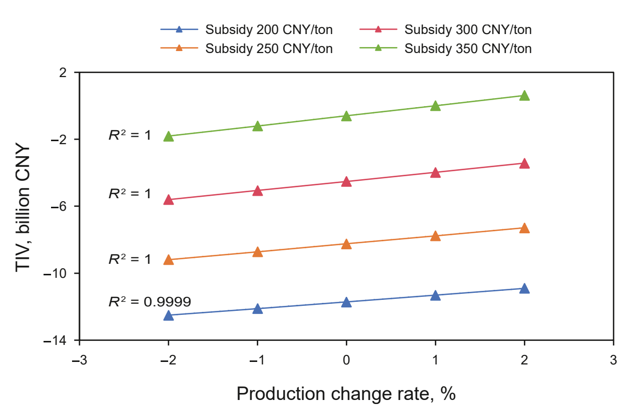

Fig. 7. The relationship between output and TIV under different subsidy levels.

Table 3
Classification of key factors.

Key factors	Ranges	Value
Capture method (CNY/ton)	Capture before combustion (100–180)	180
	Capture after combustion (230–310)	310
	Oxygen combustion capture (310–480)	480
Burial depth of the reservoir, m	Shallow [0, 2000)	2000
	Medium [2000, 3500)	3500
	Deep [3500, 4047)	4047
Substitution ratio of CO_2 to oil	Low [3.38, 3.6)	3.6
	High [3.6, 6.43)	6.43

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 payment, which is disbursed automatically. This fully transparent, automated process requires no manual intervention and enables rapid response to market fluctuations.

4.2. *Differential subsidy effect analysis*

In Section 4.1, we use national average data to design a differentiated subsidy scheme, while in Section 4.2, we select a case study of a typical region to validate and substantiate this scheme. This study employs a case analysis based on the data from the CCUS-EOR pilot project in the low-permeability oil reservoirs of the Caoshe-Taizhou Formation within the development block operated by Sinopec East China Petroleum's subsidiary. Given the comprehensive nature of the project data, selected sections of this oil field are used for the case study.

In terms of carbon emission sources, the project primarily relies on Sinopec's Nanjing Chemical Company, utilizing pre-combustion capture technology, with a capture scale of 100,000 tons/year, fully meeting the CO_2-EOR requirements of the project. The high-concentration CO_2 source of the Nanjing Chemical Company is located approximately 150 km from the adjacent oil field. The project employs a variety of transportation methods, including traditional liquid transport via tank trucks and tankers, as well as developing pipeline mid-pressure supercritical and dry ice solid phase among other transportation methods. The pilot project for the low-permeability oil reservoirs in the Caozhuang-Taizhou Formation commenced in 2005, and by 2021, the demonstration project included 14 CO_2-EOR development units. This case study selects data from a representative block, applies a differentiated subsidy scheme to grade the blocks, and calculates the subsidy budget for developing the project with a uniform subsidy under the same conditions. It compares the policy efficiency under uniform and differentiated subsidies and conducts scenario simulations on the case study.

Table 6 indicates that the block is of medium burial depth, all employing pre-combustion capture with oil exchange rates below 3.6. Combining the aforementioned transportation distance, modes of transport, capture method, and burial depth data, the project is classified. According to Table 7, the block is graded as

Table 5
CO_2-EOR project classification scheme with shallow reservoir burial depth and low oil exchange rate.

Capture method	ECP, ton	Project level
Capture before combustion	2738–3089	IV
Capture after combustion	3408–3968	IV
Oxygen combustion capture	5011–6323	IV
Capture before combustion	3089–3541	III
Capture after combustion	3968–4748	III
Oxygen combustion capture	6323–8564	III
Capture before combustion	3541–4150	II
Capture after combustion	4748–5910	II
Oxygen combustion capture	8564–13270	II
Capture before combustion	>4150	I
Capture after combustion	>5910	I
Oxygen combustion capture	>13,270	I

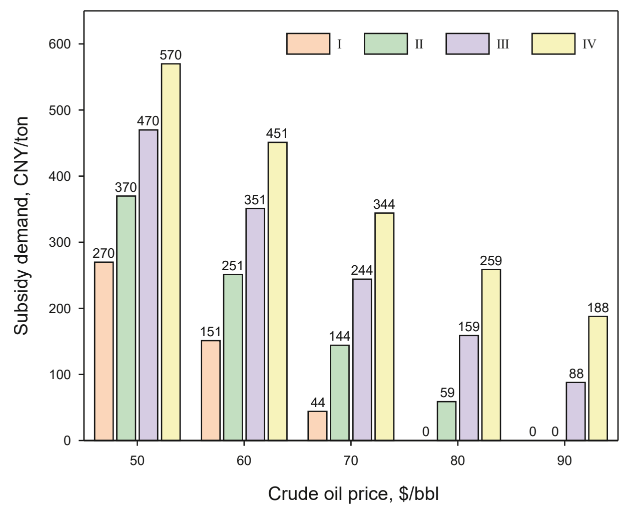

Fig. 8. Subsidy demand for projects at all levels under different oil prices.

Table 4
Edge case of production under different subsidy levels with shallow reservoir burial depth and low oil exchange rate.

Capture method	Edge case of production: single well annual production, ton			
	Subsidy 0, CNY/ton	Subsidy 100, CNY/ton	Subsidy 200, CNY/ton	Subsidy 300, CNY/ton
Capture before combustion	4150	3541	3089	2738
Capture after combustion	5910	4748	3968	3408
Oxygen combustion capture	13,270	8564	6323	5011

Table 6
Basic information about the block.

Basic parameters	Unit	Value
Reservoir type	/	Low permeability reservoir
Reservoir burial depth	m	2893
Number of oil wells	/	8
Single well production	ton	4996.30
Substitution ratio of CO_2 to oil	/	2.7
Transportation distance	km	150
Crude oil commodity rate	%	98
Crude oil price	$/bbl	75
Carbon price	CNY/ton	250
Production period	year	15

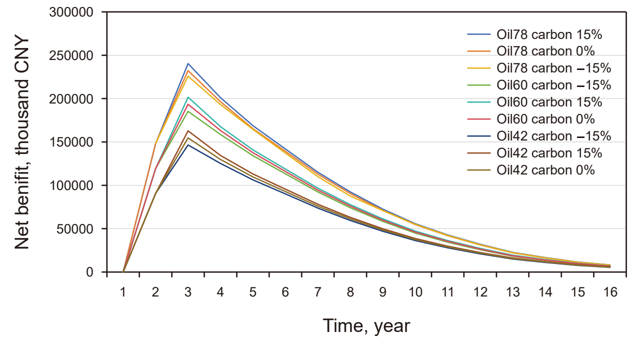

Fig. 9. Net benefit trends of CO_2-EOR projects under different scenarios.

Table 7
CO_2-EOR project classification scheme with medium reservoir burial depth and low oil exchange rate.

Capture method	ECP, ton	Project level
Capture before combustion	4352–4844	IV
Capture after combustion	5281–6023	IV
Oxygen combustion capture	7327–8836	IV
Capture before combustion	4884–5461	III
Capture after combustion	6023–7007	III
Oxygen combustion capture	8836–11129	III
Capture before combustion	5461–6258	II
Capture after combustion	7007–8376	II
Oxygen combustion capture	11,129–15030	II
Capture before combustion	>6258	I
Capture after combustion	>8376	I
Oxygen combustion capture	>15,030	I

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 ±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 development sequence under a differentiated subsidy grading, thus increasing the storage of carbon dioxide and the production of crude oil. The change in net benefits is primarily influenced by crude oil prices; when subsidy and carbon trading prices are fixed, the higher the crude oil price, the greater the increase in carbon dioxide storage and crude oil production. This aligns with the subsidy scheme shown in Fig. 8, where the subsidy amount is linked to crude oil price fluctuations. We acknowledge that actual source-sink distances in CO_2-EOR projects can vary from 10 (on-site EOR) to 200 km (off-site fields), and that distance significantly influences both pipeline and truck transport costs and thus TIV. Because this study employs a single representative distance, it underestimates TIV sensitivity to transport mode. Future work will collect project-level source-sink matching and distance data and introduce a distance-dependent transport-cost function to refine the model and fully capture how transport-mode differences affect investment value.

5. Conclusions and policy implications

This study employs a systems analysis approach to explore the roles and influencing factors of capture, transportation, oil recovery, and storage within the CO_2-EOR industrial chain. A system dynamics model was developed to assess subsidy requirements by capturing the feedback relationships among resources, production, and storage. The simulation analyses reveal several key findings that provide valuable insights for improving the efficiency of subsidy policies and advancing the development of CO_2-EOR demonstration projects.

While the choice of transportation mode is a notable cost component in the CCUS chain, our systems analysis reveals that its influence on subsidy requirements is secondary to the dominant effects of capture technology, reservoir depth, and oil recovery rates. This finding points to a crucial distinction for policy design: among these dominant factors, some represent unchangeable, 'innate' geological conditions (like reservoir depth), while others are optimizable, 'acquired' technical choices (like capture technology).

The significance of these 'acquired' choices is particularly evident in the capture segment, which constitutes the largest portion of project costs, typically 65%–85% (Yang et al., 2025). Additionally, our model integrates technology learning curves, projecting a decline in costs across all segments over time. While costs for each technology are indeed decreasing, the absolute cost of the capture segment consistently remains far higher than that of transportation. This ensures its dominance within the overall cost structure is preserved. Consequently, the wide variance in costs across different capture methods (a fact quantitatively demonstrated in detailed comparative studies) has a profound impact on project viability (Kheirinik et al., 2021). Based on this, our central finding is that the most effective subsidy framework is not one that focuses on a single element, but one that can comprehensively 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 economics are intrinsically linked to oil market dynamics, whether through economic modeling (Lin and Tan, 2021) or analysis of commercial contracts (Gao et al., 2022). Simulations indicate that projects requiring high subsidies (e.g., 300 CNY/ton) may no longer need financial support when crude oil prices exceed $80 per barrel, thereby demonstrating the importance of dynamically linking subsidy schemes to market conditions. Among the three key factors, reservoir burial depth is an immutable geological parameter, while capture methods and CO_2-EOR processes are variable and should be the primary focus of technical and economic research efforts. Advancing these processes could significantly reduce project costs and enhance feasibility.

Although the proposed grading scheme improves subsidy allocation efficiency, its applicability depends on baseline project parameters. For example, a project with a storage cost of 310 CNY/ton and an oil displacement rate of 3.6 benefits from a 12% reduction in subsidy requirements under the proposed scheme compared to uniform subsidy policies. However, changes in baseline parameters necessitate recalibration of subsidy intervals and amounts to maintain effectiveness. This need for project-specific data reinforces the scheme's suitability for the demonstration phase, where a case-by-case assessment is feasible. Additionally, while the grading scheme enhances fiscal efficiency, it does not account for the bargaining dynamics and profit-sharing arrangements among industry chain participants, which could impact the distribution of subsidies and the formation of development contracts.

In practice, policymakers should conduct comprehensive investigations of project-specific baseline parameters to accurately implement the proposed grading scheme, a process that is particularly well-suited for the limited number of projects in the demonstration phase. Linking subsidies dynamically to crude oil prices and project characteristics ensures resource efficiency while addressing the diverse needs of CO_2-EOR projects. This approach represents a significant refinement of existing policy instruments, such as Section 45Q tax credit, which typically offer a uniform incentive without differentiating by capture technology (Ren et al., 2022). Furthermore, targeted support for capture and EOR process optimization is critical to reducing costs and paving the way for future large-scale deployment. By integrating these considerations, the proposed differentiated subsidy framework offers a practical pathway to enhance fiscal efficiency and accelerate the successful implementation of key demonstration projects, thereby building the foundation for CCUS to contribute meaningfully to global carbon neutrality goals.

CRediT authorship contribution statement

Liang-Yu Xia: Writing – review & editing, Investigation, Conceptualization. **Yao Wu:** Writing – original draft, Software, Methodology. **Yue-Mei Zhang:** Supervision, Project administration, Data curation.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petsci.2025.11.040.

References

Agaton, C.B., 2021. Application of real options in carbon capture and storage literature: valuation techniques and research hotspots. Sci. Total Environ. 795, 148683. https://doi.org/10.1016/j.scitotenv.2021.148683.

Cai, B.F., Li, Q., Zhang, X., et al., 2021. Annual report on carbon dioxide capture, utilization, and storage (CCUS) in China (2021). Research on China's CCUS pathways. Institute of Environmental Planning of the Ministry of Ecology and Environment, Institute of Rock and Soil Mechanics. Chinese Academy of Sciences China Agenda 21 Management Center, pp. 16–65 (in Chinese).

Chen, W.H., 2019. Research on Carbon Capture and Storage Investment Decision-making for Coal-fired Power Plants Based on Emission Reduction. Doctoral Dissertation. China University of Geosciences, Beijing (in Chinese).

Dahowski, R.T., Davidson, C.L., Li, X.C., et al., 2012. A $70/t$CO_2$ greenhouse gas mitigation backstop for China's industrial and electric power sectors: insights from a comprehensive CCS cost curve. Int. J. Greenh. Gas Control 11, 73–85. https://doi.org/10.1016/j.ijggc.2012.07.024.

Edmonds, J., Nichols, C., Adamantiades, M., et al., 2020. Could congressionally mandated incentives lead to deployment of large-scale CO_2 capture, facilities for enhanced oil recovery CO_2 markets and geologic CO_2 storage? Energy Policy 146, 111775. https://doi.org/10.1016/j.enpol.2020.111775.

Fan, J.L., Xu, M., Yang, L., 2019. How can carbon capture utilization and storage be incentivized in China? A perspective based on the 45Q tax credit provisions. Energy Policy 132, 1229–1240. https://doi.org/10.1016/j.enpol.2019.07.010.

Gao, S., Hou, C.H., Zhao, L., 2022. On the economics of CO_2 contracts in the enhanced oil recovery industry. Energy Econ. 112, 106173. https://doi.org/10.1080/15140326.2022.2065064.

He, Y.F., Zhao, S.X., 2018. Influence factors and screening method of CO_2 huff & puff in tight oil reservoir based on multi index. Journal of Chongqing University of Science and Technology (Natural Science Edition) 20 (1), 40–44. https://doi.org/10.19406/j.cnki.cqkjxyxbzkb.2018.01.009 (in Chinese).

He, Y.F., Zhao, S.X., Ji, B.Y., et al., 2020. Screening method and potential evaluation for EOR by CO_2 flooding in sandstone reservoirs. Petroleum Geology and Recovery Efficiency 27 (1), 140–145. https://doi.org/10.13673/j.cnki.cn37-1359/te.2020.01.021 (in Chinese).

Kheirinik, M., Ahmed, S., Rahmanian, N., 2021. Comparative techno-economic analysis of carbon capture processes: pre-combustion, post-combustion, and oxy-fuel combustion operations. Sustainability 13 (24), 13567. https://doi.org/10.3390/su132413567.

Kwak, D.H., Kim, J.K., 2017. Techno-economic evaluation of CO_2 enhanced oil recovery (EOR) with the optimization of CO_2 supply. Int. J. Greenh. Gas Control 58, 169–184. https://doi.org/10.1016/j.ijggc.2017.01.002.

Lee, J.S., Chun, W., Roh, K., et al., 2023. Applying real options with reinforcement learning to assess commercial CCU deployment. J. CO_2 Util. 77, 102613. https://doi.org/10.1016/j.jcou.2023.102613.

Li, J.Q., 2019. Carbon Capture, Utilization and Storage Project decision-making Methods and their Application. Doctoral Dissertation. China University of Mining & Technology-Beijing (in Chinese).

Li, S.L., Sun, L., Chen, Z.H., et al., 2020. Further discussion on reservoir engineering concept and development mode of CO_2 flooding-EOR technology. Reservoir Evaluation and Development 10 (3), 1–14+141. https://doi.org/10.13809/j.cnki.cn32-1825/te.2020.03.001 (in Chinese).

Liang, D.P., Xu, C.L., Ma, D.H., 2012. The research on the model and stability of CCS based on the system dynamics. Journal of Management Sciences in China 15 (7), 36–50 (in Chinese).

Lin, B., Tan, Z., 2021. How much impact will low oil price and carbon trading mechanism have on the value of carbon capture utilization and storage (CCUS) project? Analysis based on real option method. J. Clean. Prod. 298, 126768. https://doi.org/10.1016/j.jclepro.2021.126768.

Liu, M.X., Liang, X., Lin, Q.G., et al., 2021. Key issues and countermeasures of CCUS projects linking carbon emission trading market under the target of carbon neutrality. Proceedings of the CSEE 41 (14), 4731–4739. https://doi.org/10.13334/j.0258-8013.pcsee.210544 (in Chinese).

Ma, N., 2020. Design and Optimization of the Differentiated Industrial Carbon Tax Policy. Doctoral Dissertation. China University of Geosciences, Beijing (in Chinese).

Mi, J.F., Ma, X.F., 2019. Development trend analysis of carbon capture, utilization and storage technology in China. Proceedings of the CSEE 39 (9), 2537–2544. https://doi.org/10.13334/j.0258-8013.pcsee.190375 (in Chinese).

Ozdemir, V., Liang, X., Lin, Q.G., Ma, X.F., 2018. Development trend analysis of carbon capture, utilization and storage technology in China. Proceedings of the CSEE 39 (9), 2537–2544. https://doi.org/10.13334/j.0258-8013.pcsee.190375 (in Chinese).

Proaño, L., Sarmiento, A.T., Figueredo, M., 2020. Techno-economic evaluation of indirect carbonation for CO_2 emissions capture in cement industry: a system dynamics approach. J. Clean. Prod. 263, 121457. https://doi.org/10.1016/j.jclepro.2020.121457.

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., et al., 2021. 2021 Domestic Carbon Price Mechanism Research Report. Shanghai Environmental Energy Exchange (in Chinese).
Zhao, Y.P., Zhao, H.F., Li, J., et al., 2018. Indoor experiment and field application of CO_2 flooding in ultra-low permeability oil reservoirs. Pet. Geol. Oilfield Dev. Daqing 37 (1), 128–133. https://doi.org/10.19597/J.ISSN.1000-3754.201706040 (in Chinese).