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Dynamic Policy Effects in Early-Stage Low-Rank Coalbed Methane Development: A System Dynamics Analysis of Representative Blocks in Xinjiang

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Abstract

Against the backdrop of ongoing efforts to increase natural gas reserves and production and advance the low-carbon energy transition, the importance of developing low-rank coalbed methane is becoming increasingly evident. However, its early-stage development faces challenges such as phased production evolution, long investment payback periods, and uncertainty regarding the effectiveness of policy incentives. We calibrate a system dynamics model for four blocks in Xinjiang to link well commissioning and production with annual accounting outcomes over 15 years. Separate scenarios test changes in CBM price, incremental-output subsidies, and taxes; technological accumulation and carbon revenue are examined as extensions. Without reinvestment, Baicheng has the highest cumulative output but a CNY 138 million after-tax accounting loss. A 10% CBM price increase makes the accounting sum positive while annual losses persist late in decline. In the hypothetical case allocating all subsidy receipts to new wells, Baicheng adds 28 wells at the baseline subsidy rate under the one-year funding lag and whole-well investment rule, while retaining a cumulative accounting loss. In the tax scenarios with 3% profit reinvestment, halving corporate income tax raises Baicheng's cumulative profit from CNY −143 million to CNY 14 million without changing its well count. These results distinguish immediate financial gains from subsequent investment responses and show why policy effects should be assessed by block and development stage.

Keywords: low-rank coalbed methane; early-stage development; system dynamics; dynamic policy effects; incremental-output subsidy

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1. Introduction

1.1. Research Background

The dual constraints of climate change and energy security are accelerating the global transition of energy systems from high-carbon fossil fuels to low-carbon and clean energy [1]. China has successively set carbon-peaking and carbon-neutrality targets and has made the construction of a clean, low-carbon, secure, and efficient new energy system an important task in advancing its energy revolution [2]. However, the energy transition is not a simple substitution of renewable energy for traditional fossil fuels, but a long-term process involving energy-supply stability, infrastructure compatibility, and techno-economic feasibility. In

this process, natural gas, because of its relatively low carbon intensity and strong system-balancing capability, serves as an important bridge between fossil-energy and renewable-energy systems, which is particularly relevant for a major fossil-energy-consuming country such as China [3]. In 2024, China's natural gas consumption was approximately 426.05 billion m^3 and is expected to peak at 590–600 billion m^3 around 2035 [3,4]. Continued growth in natural gas demand also creates greater demands for domestic supply diversification and security.

Coalbed methane is an important component of unconventional natural gas and has the dual strategic value of increasing natural gas supply and reducing greenhouse gas emissions. On the one hand, China's unconventional natural gas production exceeded 100 billion m^3 for the first time in 2024, accounting for 44.5% of total natural gas production and becoming an important driver of domestic natural gas reserve growth and production expansion [5]. On the other hand, CBM has the low-carbon characteristic of achieving emissions reductions through extraction itself: it can replace direct coal combustion and thereby lower end-use carbon emissions, while also avoiding uncontrolled methane releases. According to the IPCC Sixth Assessment Report, the 100-year global warming potential (GWP100) of fossil methane is approximately 27.9 times that of CO_2 [1]. Promoting large-scale CBM development is therefore not only an important pathway for strengthening domestic natural gas supply, but also a key means of coordinating energy transition with methane mitigation. Since the beginning of the 14th Five-Year Plan period, China's CBM industry has developed rapidly; production reached 13.8 billion m^3 in 2024, an increase of 17% year on year [5].

China shows marked spatial differences in CBM resources and development levels. Medium- and high-rank CBM in the Shanxi–Shaanxi–Inner Mongolia region has gradually entered large-scale development, whereas medium- and low-rank CBM in Xinjiang remains at a stage where exploration appraisal and early commercial development proceed in parallel. Xinjiang contains approximately 7.5 trillion m^3 of geological CBM resources at depths shallower than 2000 m, about one quarter of China's total CBM resources, and represents an important emerging area for CBM exploration and development following the Qinshui and Ordos basins [6].

Production in Xinjiang remains small relative to this resource base. The region produced more than 121 million m^3 of CBM in 2024 [7], while the development target set for 2025 was 2.5 billion m^3. Closing that gap requires progress across technical, market, and policy constraints. Low-rank reservoirs present difficulties for resource appraisal, stimulation, and stable production [6]. Overlapping coal and CBM mineral rights, limited long-distance pipeline capacity, and local demand conditions also restrict market access [8]. On the policy side, some firms have reported a decline in the subsidy received per cubic meter from about CNY 0.3 during the 13th Five-Year Plan to CNY 0.1 [9,10], raising questions about the strength of output-based incentives. Given geological risk, high initial investment, and long payback periods, the roles of price, subsidies, and taxes merit separate assessment at different development stages.

The issue for early-stage low-rank CBM development in Xinjiang is therefore how different instruments relate to a project's stage and its production and financial conditions. CBM price affects sales revenue; output-linked subsidies can offset some development costs once eligible production has been achieved; and tax relief affects retained earnings when a relevant tax base exists. The Xinjiang blocks differ in scale, baseline CBM price, and forecast production paths, providing contrasting cases in which to examine the channels and limits of individual instruments.

1.2. Literature Review

Research on CBM project economics and policy support has followed three broad lines: technical and economic evaluation of CBM and other unconventional gas projects; the design and assessment of price, subsidy, and tax measures; and applications of system dynamics and related methods to feedback among technology, investment, production, and policy.

1.2.1. Techno-Economic Evaluation of CBM and Unconventional Natural Gas Projects

Most studies use a discounted cash-flow framework and indicators such as net present value (NPV), internal rate of return (IRR), and payback period to evaluate how changes in price, production, investment, and cost affect the economic feasibility of unconventional natural gas projects [11–13]. Dai et al. [12] found that, when investment and cost are fixed, the wellhead gas price and production are the primary determinants of project NPV, with the gas-price sensitivity coefficient ranking first. Qin et al. [14] further argued at the industry level that building a large coal-measure gas industry requires both technological progress to raise per-well output and recovery and a gas-pricing mechanism that balances energy security with expected corporate returns. These studies identify key determinants of CBM economics and provide a basis for comparing development plans and investment decisions.

Research on the resources and development characteristics of low-rank CBM in Xinjiang has mainly focused on resource potential, reservoir conditions, and development adaptability. Li and Zhou [15] systematically analyzed the structural gap between Xinjiang's CBM resource advantage and limited capacity realization; Yu et al. [16] and Tang et al. [17] assessed low-rank CBM reservoir characteristics and exploration and development progress in the Junggar Basin; and Li et al. [18] emphasized the need for differentiated reservoir characterization and corresponding development strategies for deep coal seams. These studies are valuable for identifying key economic variables, but they mostly analyze period-by-period cash flow, pay limited attention to feedback among price, technology, production, and reinvestment, and cannot fully represent the cumulative effects of these variables over long development periods. This limitation motivates the use of system dynamics in the present study.

1.2.2. Design and Evaluation of Energy-Development Support Policies

Policies can alter returns through CBM prices, fiscal subsidies, and taxes. Regarding pricing mechanisms, studies generally treat gas prices as a core determinant of CBM project revenue and investment returns and emphasize that stable and reasonable price signals are important for increasing firms' willingness to invest and promoting large-scale industrial development [12,14].

Regarding fiscal subsidies, early studies mainly examined the incentive effects, fiscal costs, and marginal changes associated with output-based subsidy schemes [19,20]. Given the high investment risk and low commercialization level of low-rank CBM development, Fan and Xu [21] proposed a government–enterprise equilibrium mixed subsidy mechanism that combines direct subsidies and tax incentives; Fan et al. [22] developed a bilevel programming model for differentiated subsidies across multiple coal seams; and Fan et al. [23] further proposed a subsidy-allocation mechanism based on multi-stakeholder equilibrium. Regarding taxation, Acquah-Andoh et al. [24] analyzed tax incentives for CBM development under Indonesia's upstream petroleum fiscal framework, while Zhao et al. [25] systematically assessed the forms and economic consequences of oil and gas producer subsidies in OECD countries. China has established a relatively complete package of preferential taxes and fees, including value-added tax refunds after collection and resource-tax exemp-

tions for CBM extracted for coal-mine safety purposes [26], but comparisons of the annual effects of individual taxes under a common block-level production and accounting basis remain limited.

1.2.3. System Dynamics and Related Dynamic Methods in Energy Investment and Policy Evaluation

System dynamics describes long-term behavior through stocks, flows, and feedback loops and is useful for examining coupled variables, delays, and nonlinear responses. Wu et al. [27] applied it to technology, costs, subsidies, and competition in China's shale gas industry. Xiao et al. [28] modeled natural gas exploration, well construction, investment, technology, and policy, while Aslani et al. [29] studied renewable-energy policy and energy dependence in Finland.

Real options, Monte Carlo simulation, and simulation optimization have also been used to address uncertainty in energy investment. Liu et al. [30] combined real options with least-squares Monte Carlo simulation to study shale gas investment timing under market, technological, and environmental uncertainty. Daneshzand et al. [31] used simulation optimization to evaluate the phase-out of natural gas subsidies. These methods provide useful approaches to uncertainty, although relatively few analyses examine policy responses at the level of individual CBM development blocks.

System dynamics applications specific to CBM remain limited. Wei and Niu [32] combined grounded theory and system dynamics to examine how institutional support affects the CBM industry. At the block scale, however, CBM price, incremental-output subsidies, and individual taxes have seldom been compared under the same production and accounting conventions. Whether a change in profit is followed by additional wells and output depends on the investment rule and block parameters.

Taken together, technical and economic evaluation, policy analysis, and dynamic modeling have advanced understanding of CBM development, but their perspectives can be connected more closely. Economic evaluations identify key determinants of project returns, yet pay less attention to the relationship between changing production and annual accounting outcomes. Policy studies examine incentives, but the timing of individual instruments and differences across development stages and blocks warrant closer attention. Dynamic models can represent longer-term feedback, provided they distinguish direct financial changes from production responses conditional on subsequent investment. Linking block-level production paths, annual accounting, and stated transmission conditions can therefore improve the interpretation of policy scenarios for early-stage development.

1.3. Research Scope and Contributions

This study examines four representative Xinjiang blocks—Fukang No. 3, Fukang No. 8, Fukang No. 9, and Baicheng—using a common structure for production development and annual economic accounting. Block-specific parameters are calibrated to development-stage production forecasts, rather than observed historical production series. The resulting baselines support conditional comparisons of CBM price, incremental-output-subsidy, and tax scenarios under the stated production and accounting assumptions.

The contributions are threefold. First, the model links block-level production paths to annual profit and cumulative returns, showing when price, subsidy, and tax changes take effect. Second, the four blocks differ in scale, production profile, and economic conditions, allowing us to compare policy responses across blocks and development stages and to show why cumulative returns alone do not describe the full economic trajectory. Third, technological accumulation and carbon revenue are examined as model extensions to clarify

the feedback assumptions and evidence needed before their effects on output and profit can be inferred.

2. Materials and Methods

We developed a system dynamics model for policy analysis in early-stage low-rank CBM development. Its core represents production and annual economic accounting under individual CBM price, subsidy, and tax scenarios. Profit reinvestment, technological accumulation, and carbon revenue are switchable extensions used to examine responses under specified conditions.

2.1. Model Framework

System dynamics uses stocks, flows, and feedback loops to represent interactions and delays over time. It is suited to CBM development, where initial investment is substantial, production evolves over many years, and technical and economic factors can interact. The aim is to examine production and accounting responses in four Xinjiang cases using a structure that can be reparameterized for further study. When applied to other blocks, appropriate adjustments must be made in light of actual circumstances, such as local production and economic inputs, and compliance with the investment rules applicable to the project.

The model comprises a production module and an economic-accounting module. The production module determines active wells from planned well counts and commissioning schedules, then calculates annual CBM and marketable-gas output through well-group maturation, ramp-up, plateau, and two-stage decline. The accounting module calculates gas-sales revenue from marketable output and the baseline CBM price, adds eligible incremental-output subsidies, and deducts production and administrative expenses, depreciation, and taxes to obtain annual and cumulative after-tax accounting profit. Thus, the principal sequence runs from well numbers and commissioning through gas output to revenue, expenses, and profit.

Optional links test how profit or subsidy revenue can finance additional wells, how R&D can affect productive capacity, and how carbon revenue can enter operating revenue. They are activated only in specified structural sensitivity analyses. Figure 1 shows the model relationships; arrows indicate influence or computational dependence, with full equations in Supplementary Section S1.

2.2. Model Settings and Boundaries

The model was developed in Vensim PLE (version 10.4.0; Ventana Systems, Inc., Harvard, MA, USA) with a 15-year horizon and a one-year time step. Its boundary is upstream CBM development: well counts and commissioning, annual CBM and marketable-gas production, gas-sales and subsidy revenue, major production and administrative expenses, depreciation, taxes, and after-tax profit. Reservoir pressure, desorption, and fluid flow are not simulated explicitly, nor are downstream transmission, gas demand, or market-equilibrium feedback. The economic module uses annual accounting rather than complete project cash flows. It recognizes depreciation and annual expenses but does not represent all construction and drilling cash outflows, working-capital movements, or terminal value, and it applies no discounting. Cumulative after-tax accounting profit is the undiscounted sum of the modeled annual accounting balances. A positive sum is neither an estimate of NPV nor evidence that the project is financially feasible; discounting that profit series alone would not supply the missing investment cash flows.

Production parameters for each block were calibrated to a development-stage production forecast prepared from well tests, geological and reserve analyses, numerical simulation,

and empirical parameters. The same model structure was used for all four blocks, with block-specific inputs for planned wells, commissioning, single-well capacity, and production-curve parameters. Simulated annual output was compared with the corresponding reference forecast. Because the reference is a forecast rather than a continuous series of historical production measurements, this comparison evaluates calibration and case fit, not out-of-sample predictive validity. Where common economic parameters were unavailable, values from the block with the most complete records were applied consistently; other parameters reflect the characteristics of each block.

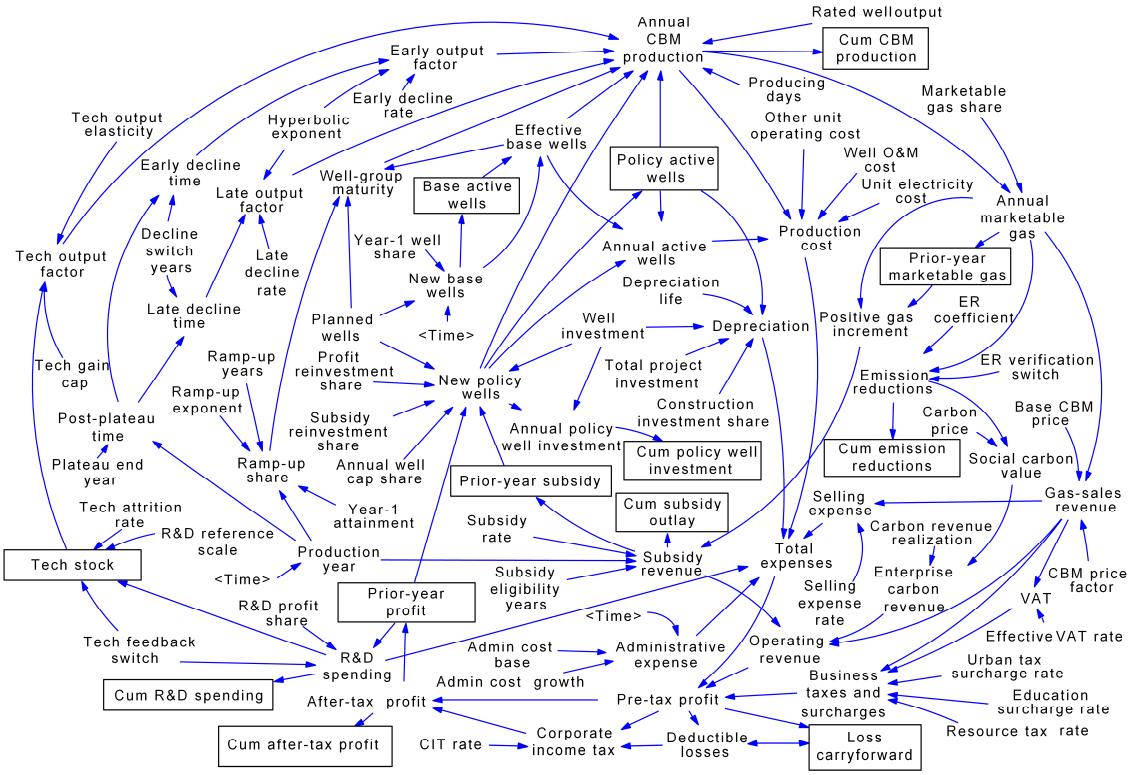


Figure 1. System dynamics model of investment and policy for CBM development. Arrows indicate dependencies among model variables, pointing from an input variable to the variable whose calculation or update uses that input.

2.3. Core Variables and Parameters

Model variables are classified by function as stocks, rates that directly change stocks, and auxiliary variables or parameters. Stocks relevant to the results include active baseline wells, active policy-funded wells, cumulative CBM production, prior-year profit and subsidy stocks, loss carryforwards, and cumulative after-tax accounting profit. Principal rates include newly commissioned baseline and policy wells, annual CBM and marketable-gas production, subsidy revenue, losses utilized, and after-tax profit. Gas-sales revenue, oil and gas production costs, total expenses, and taxes are annual accounting variables that affect subsequent decisions and stock changes through profit and related variables. Key auxiliary variables and parameters include planned wells, rated daily output per well, operating days, well-group maturity, first-year attainment, ramp-up duration and curvature, plateau end year, early- and late-stage decline rates, decline-switch year, hyperbolic exponent, marketable-gas ratio, baseline CBM price and price multiplier, subsidy rate, and major cost and tax parameters. Policy-funded new wells are counted as whole wells; in the baseline scenario, their annual upper limit is 5% of planned wells. Definitions, units, equations, parameter values, and initial conditions are given in Supplementary Section S1.

Production parameters are specified by block to represent differences in development scale, commissioning, and lifecycle production profiles. They include planned wells, the first-year commissioning share, rated daily output per well, operating days, first-year attainment, ramp-up duration and curvature, plateau end year, early- and late-stage decline rates, the decline-switch year, and the hyperbolic exponent. After the plateau, production passes through two decline stages. Let the capacity multiplier in stage $j(j = 1,2)$ be $f_j(\tau_j)$, where τ_j is the number of years elapsed in that stage. The functional form depends on the hyperbolic exponent b:

$$f_j(\tau_j) = \begin{cases} \exp(-D_j\tau_j), & b < 10^{-6} \\ (1 + bD_j\tau_j)^{-\frac{1}{b}}, & b \geq 10^{-6} \end{cases}, \quad j = 1,2 \tag{1}$$

Here, D_1 and D_2 are the early- and late-stage decline rates, respectively, and τ_1 and τ_2 are the years elapsed in the corresponding stages. The first stage lasts no longer than the specified decline-switch duration; subsequent years enter the second stage. The two multipliers are multiplied in the annual production equation. In the model, $b < 10^{-6}$ selects the exponential form. Table 1 lists the principal block parameters.

Table 1. Base parameter settings for the four blocks.

Parameter	Unit	Fukang No. 3	Fukang No. 8	Fukang No. 9	Baicheng
Planned wells	wells	30	106	220	780
Operating days	days/year	345	330	300	330
First-year commissioning share	%	100	100	100	61.54
Peak annual CBM production	10^8 m^3/year	0.32	1.43	1.62	6.99
First peak year	year	2	4	2	3
Ramp-up curvature	dimensionless	1	0.9	1	0.4
Plateau end year	year	12	5	12	6
Early-stage decline parameter	dimensionless	0.16	0.13	0.12	0.26
Late-stage decline parameter	dimensionless	0.16	0.11	0.12	0.13
Hyperbolic exponent	dimensionless	0	0	1	0
Total investment	CNY 10^8	2.30	12.28	14.08	57.24
Baseline CBM price (excluding tax)	CNY/m^3	1.95	1.95	1.95	1.56

2.4. Scenario Design

The scenarios vary the CBM price, incremental-output subsidy rate, and tax rates; Table 2 reports their levels and fixed structural settings. Calibration and the CBM price scenarios use the same baseline without feedback: profit and subsidy reinvestment shares, technological feedback, emission-reduction verification, and the carbon-revenue realization rate are all zero. Only the CBM price changes in the price group. Reinvestment shares describe assumed corporate funding allocations and are not compared as separate policy instruments.

Table 2. Individual policy scenarios and fixed settings within each group.

Scenario Group	Policy Levels	Profit Reinvestment Share	Subsidy Reinvestment Share	Within-Group Reference
CBM price	Baseline −20%, −10%, 0%, +10%, +20%	0	0	Baseline price; all feedbacks off
Subsidy rate	0, 0.1, 0.2, 0.302752, 0.4, 0.5 CNY/m^3	0	1	Baseline rate; subsidy reinvestment = 1
Taxes	VAT: 9%, 4.5%, 0%; resource tax: 1%, 0.5%, 0%; corporate income tax: 15%, 7.5%, 0%	0.03	0	Baseline rates; profit reinvestment = 0.03

In the subsidy and tax groups, prescribed shares of eligible subsidy revenue or positive after-tax profit enter the following year's new-well budget. The subsidy group fixes subsidy reinvestment at 1 and profit reinvestment at 0; the tax group fixes profit reinvestment at 3% and subsidy reinvestment at 0. Other feedbacks remain off. A subsidy share of 1 is a hypothetical full-allocation case in which all qualifying prior-year subsidy receipts enter the new-well budget. It is an upper bound on the assumed allocation share, not an estimate of company behavior or a bound on the well additions attainable under other financing arrangements. The 3% profit share is the midpoint of the tested sensitivity range. Subsidy and tax outcomes are compared only with their respective within-group references under the same reinvestment setting. Supplementary Section S3 compares alternative shares and explains the annual funding rule.

3. Calibration of Model Results

Production-curve parameters were calibrated to the development-stage reference forecasts for the four blocks. Calibration used the baseline without reinvestment, technological feedback, emission-reduction verification, or carbon-revenue realization. Table 3 compares 15-year cumulative CBM production from the model and reference curves and reports weighted absolute percentage error (WAPE) and root mean square error (RMSE) for the annual series.

Table 3. Calibration of baseline production curves for the four blocks.

Block	Reference (10^8 m^3)	Model (10^8 m^3)	Relative Error (%)	WAPE (%)	RMSE (10^8 m^3/Year)
Baicheng	58.63	58.22	−0.69	1.69	0.12
Fukang No. 3	4.40	4.39	−0.16	0.27	0.00 *
Fukang No. 8	13.23	13.15	−0.63	1.37	0.02
Fukang No. 9	22.67	22.67	0.01	0.08	0.00 *

* Values are rounded to two decimal places; an RMSE of 0.00 does not imply zero error.

Absolute relative errors in cumulative production are below 0.70% for all four blocks, and WAPE ranges from 0.08% to 1.69%. These statistics describe the fit to the development-stage reference forecasts used for calibration. They establish how closely the common structure reproduces those selected curves with block-specific parameters; they do not demonstrate accuracy against observed production. The fitted curves are retained as conditional production baselines for the policy scenarios, subject to the assumptions of the reference forecasts.

4. Simulation Results

CBM output and earnings evolve through commissioning, plateau production, and decline. Policy effects also depend on block conditions and the assumed flow of funds into subsequent investment. This section examines the price, subsidy, and tax groups using annual CBM production and after-tax accounting profit alongside 15-year cumulative production and economic indicators. Each group is compared with its own reference under the same reinvestment settings. Baicheng is shown in the main figures; annual results for the other blocks and full cumulative results are provided in Supplementary Sections S4 and S5.

4.1. Differences Between Production Scale and Cumulative Returns in the Baseline Scenario

Under the baseline without investment feedback, production scale and financial performance differ markedly across the four blocks (Table 4). Baicheng leads in 15-year cumulative CBM production (5.822 billion m^3) and gas-sales revenue (CNY 8.811 billion), yet it is the only block with a cumulative after-tax loss (CNY 138 million). Fukang No. 9 produces less (2.267 billion m^3) but earns the highest cumulative profit (CNY 1.624 billion). Fukang No. 3 and Fukang No. 8 produce 439 million and 1.315 billion m^3, respectively, and earn CNY 325 million and CNY 632 million. Higher cumulative output therefore does not necessarily translate into higher cumulative profit.

Table 4. Fifteen-year cumulative results for the four blocks under the baseline scenario.

Block	CBM Output (10^8 m^3)	Gas-Sales Revenue (CNY 10^8)	Subsidy Revenue (CNY 10^8)	Total Expenses (CNY 10^8)	Taxes Deducted from Profit (CNY 10^8)	After-Tax Accounting Profit (CNY 10^8)
Baicheng	58.22	88.11	2.05	86.73	4.80	−1.38
Fukang No. 3	4.39	8.57	0.10	4.68	0.74	3.25
Fukang No. 8	13.15	25.39	0.43	17.82	1.68	6.32
Fukang No. 9	22.67	44.21	0.49	24.75	3.71	16.24

Baicheng's large output does not yield a cumulative profit mainly because of its lower CBM price, the timing of production decline, and its expense burden. Its baseline price is below those of the other blocks, and its plateau ends earlier than that of Fukang No. 9. Under the model assumptions, depreciation continues on the specified investment base and administrative expenses rise over time. Once production declines, gas-sales revenue falls while some expenses do not fall in step. Baicheng's total expenses reach CNY 8.673 billion, leaving a cumulative loss after the relevant taxes despite its high production and sales. Fukang No. 9 has a lower output but a more favorable relation between revenue and expenses, resulting in the highest cumulative after-tax profit.

4.2. Profit Effects of CBM Price Changes Across Development Stages

Figure 2 shows annual after-tax profit for Baicheng at different CBM prices, and Table 5 reports cumulative profit for all four blocks. Cumulative profit rises with the CBM price in every block, but the magnitude differs. Baicheng shows the largest response: a 20% price reduction produces a CNY 1.661 billion cumulative loss, compared with a CNY 138 million loss at the baseline price; increases of 10% and 20% yield profits of CNY 617 million and CNY 1.371 billion, respectively. The three Fukang blocks remain cumulatively profitable at every tested price. The implications of a price change thus depend on each block's starting returns and production scale.

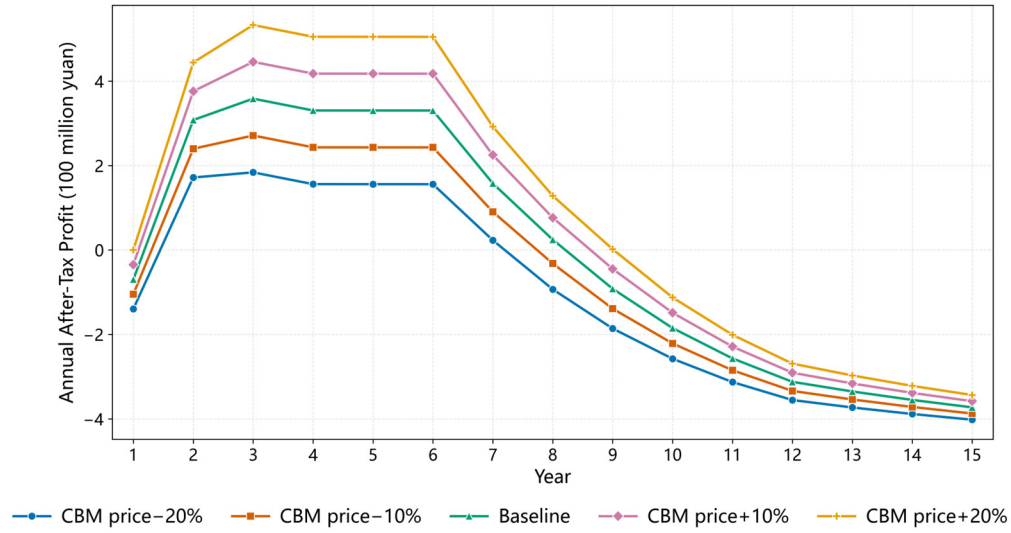


Figure 2. Annual after-tax accounting profit in Baicheng under different CBM prices.

Table 5. Fifteen-year cumulative after-tax accounting profit under different CBM prices in the four blocks.

Block	Cumulative CBM Output (10^8 m^3)	−20% (CNY 10^8)	−10% (CNY 10^8)	Baseline (CNY 10^8)	+10% (CNY 10^8)	+20% (CNY 10^8)
Baicheng	58.22	−16.61	−8.97	−1.38	6.17	13.71
Fukang No. 3	4.39	1.83	2.54	3.25	3.95	4.66
Fukang No. 8	13.15	2.00	4.17	6.32	8.45	10.57
Fukang No. 9	22.67	8.94	12.59	16.24	19.89	23.54

Annual profit reveals a clear development-stage pattern. Baicheng records annual losses from Year 9 at the baseline CBM price. A 10% price increase makes 15-year cumulative profit positive but does not eliminate losses late in the decline phase. Even with a 20% increase, annual losses persist from Years 10 to 15 and reach CNY 344 million in Year 15. The additional revenue from a higher price is proportional to the marketable gas sold in a given year, so it is greatest during ramp-up and plateau production. As output declines, that gain weakens while depreciation and administrative expenses do not decline proportionately. Some taxes and charges also depend on sales revenue, so the profit gain is not simply proportional to the price change.

CBM prices affect project returns primarily through gas-sales revenue, with the outcome shaped by block scale, development stage, and cost structure. A higher price can materially improve Baicheng's cumulative return without removing annual losses caused by later production decline. Profit reinvestment is disabled in this scenario group; the price change therefore leaves the planned wells and production path unchanged. The results measure the direct price effect under the same production conditions, rather than additional capacity induced by a price incentive. Price-policy assessment should consider both the cumulative gain and the timing of annual profits.

4.3. Stepwise Production Responses and Long-Term Profit Constraints Under Incremental-Output Subsidies

Figure 3 shows annual CBM production and after-tax profit in Baicheng under different subsidy rates; results for the other blocks are given in the Supplementary Material. Under the hypothetical subsidy-funded investment rule, capacity responds discretely and differs across

blocks. With all qualifying prior-year subsidy receipts allocated to new wells and no profit reinvestment, Baicheng adds 28 policy-induced wells at the baseline rate (approximately CNY 0.303/m^3). This well count is conditional on the assumed allocation and funding rule. Its 15-year cumulative production rises from 5.822 billion m^3 without a subsidy to 6.004 billion m^3. At CNY 0.5/m^3, the block adds 46 wells and produces 6.121 billion m^3. Fukang No. 3 receives subsidy revenue at the baseline rate without adding a well; it adds two only at CNY 0.5/m^3. Fukang No. 8 and Fukang No. 9 add one and seven wells, respectively, at the baseline rate. The same subsidy rate therefore need not produce the same capacity response.

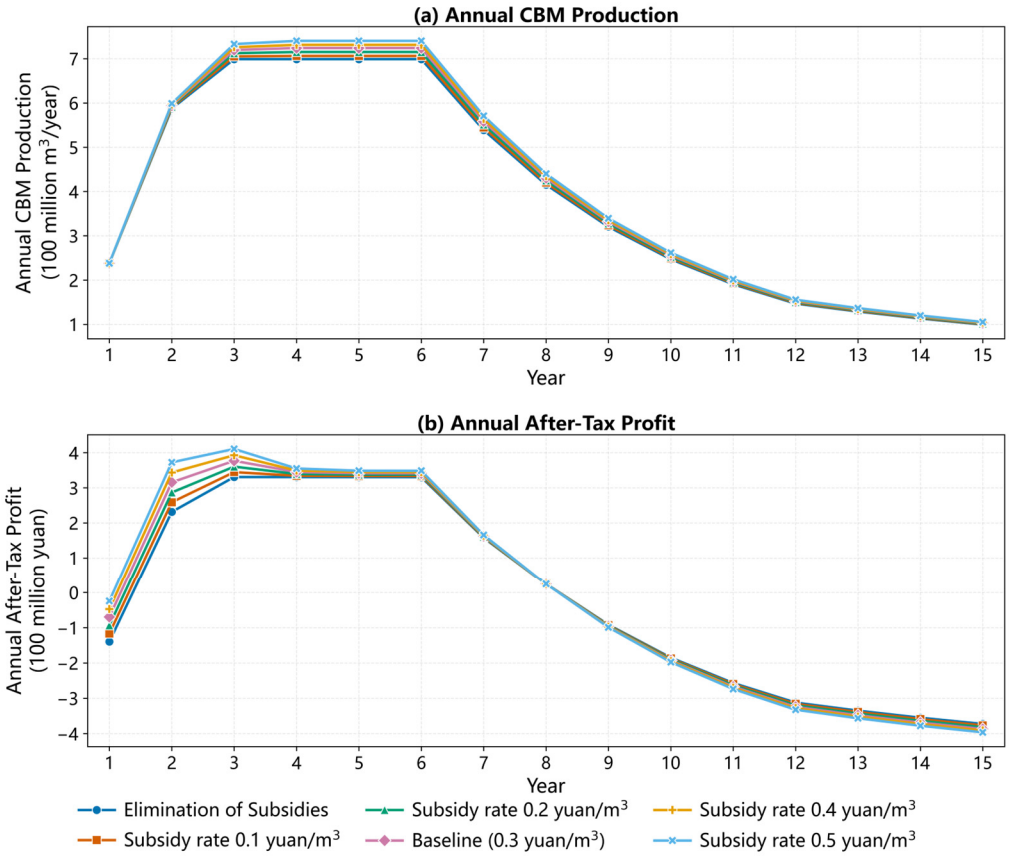


Figure 3. Annual CBM production and after-tax accounting profit in Baicheng under different subsidy rates.

The discontinuity arises from a one-year funding delay and the investment threshold for a whole well. Eligible additional output generates subsidy revenue in the current year, whereas subsidy funds retained from the previous year enter the new-well budget. If available funds are below the cost of one well, a higher subsidy improves current earnings without adding capacity. A new well and its output appear only after that threshold is crossed; policy-induced wells therefore begin production no earlier than Year 2. Differences in existing output, well investment, and well productivity affect when each block reaches the threshold. New wells also add production costs and depreciation, so additional output need not improve profit in the same proportion.

Subsidy effects also vary over the development cycle. In Baicheng at the baseline rate, subsidy receipts are concentrated in the first four years and policy-induced wells are added mainly in Years 2–4, when incremental-output support is strongest. Receipts then diminish as the project reaches plateau production and decline, while the costs and depreciation associated with new wells continue. Baicheng's 15-year cumulative after-tax loss improves

from CNY 312 million without the subsidy to CNY 147 million at the baseline rate, but remains a loss; even at CNY 0.5/m^3, the cumulative loss is CNY 32 million. Its annual profit is lower than in the no-subsidy case from Year 8 onward. Fukang No. 9 remains profitable each year under all subsidy rates, whereas Fukang No. 8 still incurs annual losses late in decline.

4.4. Uneven Profit Gains and Limited Production Responses to Tax Relief

Figure 4 shows annual after-tax profit for Baicheng under the tax scenarios; results for the other blocks appear in the Supplementary Material. Tax relief improves returns, but its size and timing differ by tax. Under the tested rates and accounting rules, corporate income tax relief generally has a larger effect on cumulative profit than relief from value-added or resource tax. With 3% profit reinvestment, Baicheng's 15-year cumulative profit is CNY −143 million at the baseline rates. Halving and eliminating corporate income tax raises it to CNY 14 million and CNY 171 million, respectively, while eliminating value-added tax or resource tax leaves losses of CNY 73 million and CNY 65 million. Corporate income tax relief acts in years with taxable income—principally Years 2–8 in Baicheng and Years 2–12 in Fukang No. 8 —and has no direct benefit after a block enters a loss-making period. Resource tax relief lowers an expense deducted in the profit calculation; value-added tax mainly changes profit through associated surcharges. Tax savings therefore need not equal profit gains, and improved cumulative profit does not eliminate annual losses late in decline.

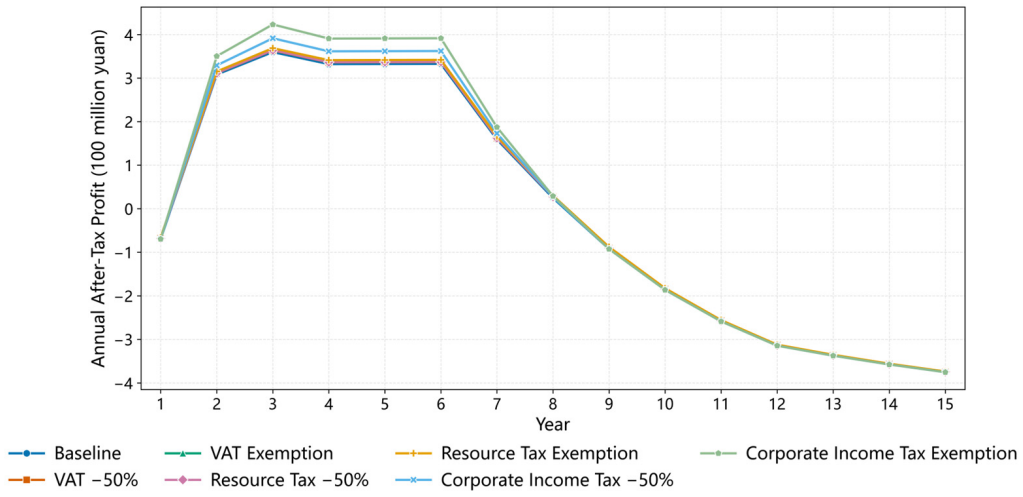


Figure 4. Annual after-tax accounting profit in Baicheng under different tax scenarios.

The additional profit from tax relief does not produce extra capacity in the tested scenarios. When 3% of after-tax profit enters the next-year new-well budget, Baicheng adds five policy-induced wells under every tax-rate setting, while the other three blocks add none. Production paths within each block consequently coincide across the tax settings. The extra retained profit does not cross the threshold for another whole well. Unlike incremental-output subsidies when sufficient funding is available, tax relief here changes profit without changing the number of wells. Its potential production effect depends on the reinvestment share and investment per well. The direct financial effect and any subsequent capacity effect should therefore be assessed separately, in light of each block's profitability and development stage.

4.5. Block Differences in Policy Transmission

The scenario results distinguish where each policy instrument enters the model and when a financial gain can increase capacity. A CBM price change directly alters revenue from

existing marketable production and, without reinvestment feedback, changes profit alone. An incremental-output subsidy raises current revenue and may finance new wells through retained receipts in the following year, but the response depends on the funding delay and the cost of a whole well. Tax relief reduces the tax burden and raises after-tax profit; at the tested 3% profit reinvestment share, it adds no wells beyond those in each block's tax-group reference. Higher policy-related earnings therefore do not necessarily expand capacity. This outcome depends on the prior-year funding base, the assumed reinvestment share, whole-well investment, and the absence of budget carryover and external finance. Different funding and investment arrangements could change the well count and timing of the production response.

Block economics and development stage further shape these effects. Despite its large cumulative output, Baicheng has a lower baseline CBM price, enters decline relatively early, and bears expenses that continue as sales fall. Higher prices and subsidies improve cumulative profit but do not remove late-stage annual losses. Fukang No. 3 cannot finance an additional well at lower subsidy rates, illustrating the importance of production scale and investment per well. Corporate income tax relief has its strongest direct effect in years with taxable income and weakens when losses begin. Policy evaluation should consequently examine cumulative returns, annual profit, and additional capacity together, with attention to block conditions and the stage of development.

5. Discussion

5.1. Aligning Incremental-Output Subsidies with Development Stage and Investment Needs

In the Baicheng subsidy scenarios, policy-funded wells add output, but even a higher subsidy rate does not make 15-year cumulative after-tax profit positive. On the accounting basis used here, additional gas supply and improved cumulative returns are not equivalent. An incremental-output subsidy ties public support to measurable increases in marketable gas. If it is also intended to ease financial pressure on developers, output, block returns, and fiscal spending need to be assessed separately rather than represented by a single indicator.

The investment effect of a subsidy depends on the sequence of funding needs and payments. Drilling and supporting facilities require expenditure before production, whereas an output-based subsidy can be received only after eligible incremental gas is produced. In a block with established production and sales and plans for further drilling, subsidy revenue may help finance later wells. In a pilot block with little marketable output, initial funding needs may arise well before subsidy receipts. The whole-well responses in our scenarios similarly suggest that both the amount and timing of support matter relative to firms' investment plans. Early pilot support or credit enhancement addresses initial funding needs more directly, although its suitability depends on project risk and how funds are used. Support for exploration appraisal and demonstration projects has been proposed for blocks that have not yet established stable marketable output [8]; its effectiveness still requires evaluation against subsequent project performance.

The instruments also enter at different points: a CBM price change affects sales of existing marketable gas; income tax relief operates mainly when taxable income exists; and an incremental-output subsidy can provide revenue when new gas is produced even before the firm becomes profitable. In policy simulations for unconventional gas, Liu et al. [19] found that output incentives may affect production plans. Fan et al. [22,23] examined differences among coal seams and the allocation of subsidies among stakeholders. Future evaluations could therefore consider the durability of added supply, payment timing, fiscal cost, and firms' actual investment plans alongside the subsidy rate when assessing suitability at different development stages.

5.2. Measuring Technological Accumulation and Adapting It to Block Conditions

The production increase in the technological-feedback extension follows from the prescribed relationship between accumulated technology and capacity (Supplementary Section S6). The engineering question is how knowledge and process improvements generated by R&D become measurable capacity changes in a particular seam and well group. R&D expenditure measures inputs, but does not directly measure accumulated technological capability or its production effect; identifying the productivity contribution of R&D capital has long been a methodological challenge [33]. In CBM development, effects should be linked to specific practices, such as well placement, reservoir stimulation, and drainage control, and assessed through attainment time, plateau performance, decline, and unit production cost [6].

Such measurement must account for block heterogeneity. Xinjiang CBM reservoirs vary substantially in coal rank, gas content, structure, and hydrology [6,16], and a study of Xinjiang wells found different drainage and productivity patterns across water-production levels [34]. The same R&D spending or field practice may therefore have different capacity effects in the four blocks. Future work could record when pilot well groups adopt specific technologies, together with completion and drainage settings and continuous gas, water, pressure, and cost data. Comparisons among wells of similar geological setting and age could then help identify effects at different stages of the production curve. For early-stage projects, assessments of technology support should emphasize reproducible field performance rather than R&D expenditure or short-term output alone.

Against the background of carbon neutrality, combining CO_2 capture with enhanced CBM recovery is another potential direction for technology investment. Displacement experiments on low-rank coal indicate potential gains in methane recovery, but swelling and permeability changes during CO_2 injection make field outcomes dependent on reservoir and operating conditions [35,36]. A block-level study further found that economic outcomes depend on the CBM price, injection design, and conditions for carbon revenue [37]. Firms may obtain additional gas-sales revenue, whereas any revenue from CO_2 storage must be assessed alongside capture, transport, injection, and monitoring costs and the relevant verification and trading rules. This physical production pathway should be evaluated separately from carbon-revenue accounting.

5.3. Measurement Requirements for Environmental Returns and Their Technological Feedback

Evaluation of low-rank CBM development should consider greenhouse gas emissions and their control alongside production and economic returns. With China's carbon-neutrality objectives, the expansion of its national carbon market and the development of voluntary emissions trading make potential emissions costs and revenue from verified reductions relevant to longer-term decisions [38,39]. Independently developed surface CBM projects, however, are not currently covered by the national carbon market's allowance-compliance system. Environmental revenue discussed here therefore remains conditional on applicable accounting and realization rules.

Reliable measurement is a prerequisite for analyzing environmental-return feedback. Chinese policy and standards for methane control and CBM emissions call for stronger monitoring, accounting, reporting, and verification capacity and monitoring of relevant surface-development facilities [40,41]. The extension in Supplementary Section S6.2 assumes that marketable CBM fully displaces coal while providing comparable energy services. Actual end users, displaced fuels, and utilization efficiencies have not been established for the four blocks, so the resulting reduction and carbon-revenue values remain exploratory. A project assessment would require consistent records of gas produced and used, methane venting and leakage, gathering and transmission, and fuel and electricity consumption.

Greenhouse gas intensity differs across natural gas supply chains [42], so output multiplied by a uniform factor cannot represent a block's actual environmental performance. With continuous, verifiable data, later models could distinguish emissions from production activities, reductions attributable to specific technologies, and their costs, and then determine whether environmental returns qualify for recognition under applicable rules.

Environmental policy and price signals may also redirect technology investment. If monitoring identifies leakage, venting, or operating energy use as major emissions sources, firms may invest in closed gathering systems, leak detection, or more efficient drainage. These measures may also change gas losses, operating costs, and production. Lack of emissions data and upfront finance has been identified as a barrier to methane mitigation [43]. Further analysis should therefore estimate, using block-level evidence, separate links from green technology investment and accumulated capability to capacity, emissions reduction, and economic outcomes. The value of environmental policy cannot be judged solely by whether revenue finances another well.

6. Conclusions and Policy Implications

We developed a system dynamics model for four representative low-rank CBM blocks in Xinjiang: Fukang No. 3, Fukang No. 8, Fukang No. 9, and Baicheng. Calibrated to development-stage production forecasts, the model links production, annual economic accounting, and subsequent investment under specified rules. Its 15-year price, subsidy, and tax comparisons are conditional on those forecasts, block parameters, and funding assumptions. The principal findings are as follows.

(1) Production scale and accounting outcomes need not move together, and a positive cumulative accounting sum can coexist with annual losses. Under the baseline without reinvestment, Baicheng has the highest 15-year cumulative production, 5.822 billion m^3, but a CNY 138 million cumulative after-tax accounting loss. A 10% CBM price increase makes the accounting sum positive without eliminating annual losses late in decline. These outcomes reflect the assumed CBM price, production lifecycle, and expense structure. They compare annual and cumulative accounting balances over the stated horizon and do not establish overall project feasibility.

(2) A funding delay and the investment threshold for a whole well jointly constrain the conversion of policy gains into capacity. CBM price changes mainly alter sales revenue on a fixed production path. Under the specified funding rule, incremental-output subsidies can add wells after the allocated prior-year receipts cross the whole-well threshold, producing a delayed and discrete response. In the hypothetical full-allocation case, Baicheng adds 28 policy-induced wells at the baseline subsidy rate but retains a cumulative after-tax accounting loss; the accounting sum also remains negative at CNY 0.5/m^3. In the tax scenarios with 3% profit reinvestment, halving corporate income tax raises Baicheng's cumulative profit from CNY −143 million to CNY 14 million without changing the well count within the group. Neither a profit gain nor a production increase alone establishes policy effectiveness.

(3) Policy effects differ across development stages and blocks, so their timing and persistence matter. A higher CBM price yields the largest revenue gain during ramp-up and plateau production and a smaller gain as sales decline. Incremental-output subsidy receipts are concentrated early, while costs and depreciation from the new wells continue later. Corporate income tax relief acts mainly in years with taxable income. Differences in production paths, profitability, and investment conditions also cause the same policy setting to generate different financial and production responses across blocks. Evaluation should therefore include annual earnings, cumulative profit, additional capacity, and development stage.

The findings have three policy implications.

(1) Match support to development stage and share early-development risk. For blocks still in exploration or pilot production without stable marketable output, demonstration support, risk compensation, and credit enhancement could address upfront funding constraints. For blocks with an established production base, incentives can be linked to additional marketable gas, well productivity, and investment needs. The timing of support should match the timing of expenditure, since a subsidy paid only after additional output is produced may not cover the risks of starting development.

(2) Broaden the assessment of incremental-output subsidies from volume alone to overall performance. Alongside additional output, evaluation should consider the persistence of production from new wells, unit production costs, and the use of public funds. For eligible projects, some support could be tied to verified technical improvements and production efficiency. Methane mitigation and other environmental measures should enter performance assessment only when reliable monitoring and verification data are available. This would help direct support toward sustained development efficiency as well as near-term output.

(3) Strengthen dynamic policy assessment at the block level. Price, subsidy, and tax changes should be evaluated separately for their effects on annual earnings, cumulative profit, and additional capacity, distinguishing immediate financial gains from subsequent investment responses. For blocks that enter decline early, price changes and continuing expenses deserve particular attention; where new investment is constrained, the funding share, well cost, and payment timing are decisive. Better project cash-flow, well-group production, and environmental data would support policies adapted to different development stages and resource conditions.

This study has several limitations. Production parameters are calibrated to development-stage forecasts, and performance against independent production observations remains untested. The sensitivity analyses describe local responses to selected parameters and stipulated reinvestment shares; they are not a probabilistic assessment of all uncertainty or a test of alternative investment structures. Some economic inputs are shared because the block records differ in completeness. The reported well counts and accounting-profit thresholds also depend on the one-year funding lag, whole-well investment, and the assumption that unused annual budget is not carried forward. External finance and company-specific drilling decisions are not modeled. These conditions limit the transfer of numerical results to other projects.

The model does not resolve reservoir and drainage differences well by well, individual well life and shut-in decisions, pipeline access, or demand changes. Annual accounting results do not establish full project feasibility; dated project cash flows and discounting are needed for NPV analysis. Technological and environmental extensions remain exploratory and require field evidence. Application to another block would require local production, cost, tax, financing, and investment data, examination of the relevant behavioral rules, and evaluation against independent observations. The four cases support analysis of policy transmission under stated conditions, rather than a statistically representative estimate for all Xinjiang CBM projects.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en19215221/s1, Supplementary Sections S1–S6 contain variable definitions and equations, sensitivity analyses, complete scenario results, and the technological and environmental extensions. Supplementary Material includes: Section S1 Model parameters and equations; Section S2 Sensitivity of key structural parameters; Section S3 Sensitivity to reinvestment assumptions; Section S4 Annual results for the other blocks under single-policy scenarios; Section S5 Cumulative results for baseline and single-policy scenarios; Section S6 Technological accumulation

and carbon-revenue feedback; Table S1. Baseline parameters and scenario switches; Table S2. State variables and their equations; Table S3. Named rates that directly change state variables; Table S4. Auxiliary variables and their equations; Table S5. Selection rationale and model implementation of the sensitivity parameters; Table S6. Change in 15-year cumulative gas production under production-structure perturbations (%); Table S7. Change in 15-year cumulative after-tax profit under cost-parameter perturbations (100 million CNY); Table S8. Sensitivity to the subsidy reinvestment share; Table S9. Sensitivity to the profit reinvestment share; Table S10. Fifteen-year cumulative production and economic indicators under the no-feedback baseline; Table S11. Fifteen-year cumulative economic results under CBM price scenarios; Table S12. Fifteen-year cumulative production and revenue under subsidy scenarios; Table S13. Fifteen-year cumulative costs, taxes, and profit under subsidy scenarios; Table S14. Fifteen-year cumulative taxes and after-tax profit under tax scenarios; Table S15. Fifteen-year cumulative production, R&D expense, and after-tax profit under technological feedback; Table S16. Fifteen-year cumulative outcomes under carbon-revenue and profit-reinvestment assumptions; Figure S1. Annual after-tax profit under CBM price scenarios, Fukang No. 3; Figure S2. Annual after-tax profit under CBM price scenarios, Fukang No. 8; Figure S3. Annual after-tax profit under CBM price scenarios, Fukang No. 9; Figure S4. Annual CBM production and after-tax profit under subsidy scenarios, Fukang No. 3; Figure S5. Annual CBM production and after-tax profit under subsidy scenarios, Fukang No. 8; Figure S6. Annual CBM production and after-tax profit under subsidy scenarios, Fukang No. 9; Figure S7. Annual after-tax profit under tax scenarios, Fukang No. 3; Figure S8. Annual after-tax profit under tax scenarios, Fukang No. 8; Figure S9. Annual after-tax profit under tax scenarios, Fukang No. 9.

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