

ECONOMIC FEASIBILITY OF CARBON SEQUESTRATION WITH ENHANCED GAS RECOVERY (CSEGR)

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ABSTRACT

Prior reservoir simulation and laboratory studies have suggested that injecting carbon dioxide into mature natural gas reservoirs for carbon sequestration with enhanced gas recovery (CSEGR) is technically feasible. Reservoir simulations show that the high density of carbon dioxide can be exploited to favor displacement of methane with limited gas mixing by injecting carbon dioxide in low regions of a reservoir while producing from higher regions in the reservoir. Economic sensitivity analysis of a prototypical CSEGR application at a large depleting gas field in California shows that the largest expense will be for carbon dioxide capture, purification, compression, and transport to the field. Other incremental costs for CSEGR include: (1) new or reconditioned wells for carbon dioxide injection, methane production, and monitoring; (2) carbon dioxide distribution within the field; and, (3) separation facilities to handle eventual carbon dioxide contamination of the methane. Economic feasibility is most sensitive to wellhead methane price, carbon dioxide supply costs, and the ratio of carbon dioxide injected to incremental methane produced. Our analysis suggests that CSEGR may be

economically feasible at carbon dioxide supply costs of up to \$4 to \$12/t (\$0.20 to \$0.63/Mcf).

Although this analysis is based on a particular gas field, the approach is general and can be applied to other gas fields. This economic analysis, along with reservoir simulation and laboratory studies that suggest the technical feasibility of CSEGR, demonstrates that CSEGR can be feasible and that a field pilot study of the process should be undertaken to test the concept further.

INTRODUCTION

Carbon dioxide (CO₂) injection into oil reservoirs for enhanced oil recovery (EOR) has been a proven technical and economic success for more than 20 years. Although the advanced technology of injecting carbon dioxide (CO₂) into mature natural gas (methane, CH₄) reservoirs for carbon sequestration with enhanced gas recovery (CSEGR) appears promising, it has not yet been tried in the field nor shown to be commercially feasible. The process of CSEGR is depicted in Figure 1 where we show the separation and compression of CO₂ from industrial and petroleum refining sources, injection into a mature natural gas reservoir, repressurization and enhanced production of CH₄, and the beneficial use of the CH₄ as a fuel. The mechanism of CSEGR is gas displacement and pressurization, as injected CO₂ moves through the pore space displacing CH₄ ahead of it [1]. This is in contrast to EOR which relies on miscibility of CO₂ with the oil phase, and enhanced recovery facilitated by the density and viscosity decrease of the oil-CO₂ mixture and corresponding greater mobility in the reservoir.

From the point of view of geologic carbon sequestration, depleted natural gas reservoirs are a promising target given their proven history of gas containment and production. The ultimate worldwide storage capacity of depleted natural gas reservoirs has been estimated at 800 Gt CO₂ (8 x

10^{14} kg CO₂) [2]. As for enhanced gas recovery, the average worldwide gas recovery factor is estimated to be approximately 75% [3], with roughly 30-40% of the gas in place left behind in water-drive gas reservoirs and approximately 10-20% left behind in depletion-drive reservoirs. Even 10% of the original gas in place in a depletion-drive reservoir can represent a large volume of currently unrecovered gas that makes potential incremental CH₄ production attractive when the alternative is field abandonment. In water-drive reservoirs where the potential additional CH₄ recovery potential is much higher, CO₂ injection will maintain reservoir pressure that will tend to keep water out of the reservoir. If CO₂ breakthrough to production wells occurs, separation of CO₂ from CH₄ can be carried out as a gas processing step with reinjection of the captured CO₂. Based on reservoir simulation and experimental studies, the process of CSEGR appears to be technically feasible. In particular, we have carried out numerical simulations of CO₂ injection into model natural gas reservoirs to study the processes of reservoir pressurization, gas displacement, and gas mixing [1,4]. Independent laboratory experiments of the displacement of CH₄ by supercritical CO₂ have further demonstrated the promise of CSEGR [5].

The purpose of this study is to investigate the economic feasibility of CSEGR. We selected the Rio Vista Gas Field in the Sacramento-San Joaquin Delta area of California (USA) for analysis. This gas field is typical of large onshore mature gas fields not associated with oil, and has the added feature of being near potentially large sources of CO₂ in the San Francisco Bay area. In our analysis, we first estimated the capital costs and operating costs for CO₂ acquisition and distribution, drilling or re-completing CO₂ injection and CH₄ production wells, gas purification and compression, and field design and monitoring. These costs are offset by the production of additional CH₄, the price of which will be variable depending on future market conditions. Although focused on a mature reservoir in

California, the approach is general and can be used at other gas fields with appropriate changes in model variables. We focus our analysis on the present-day circumstances in which CO₂ must be bought from a supplier and is therefore a significant cost of CSEGR. Before presenting the economic analysis, we show reservoir simulation results of the physical process of CSEGR for the Rio Vista scenario being considered.

RESERVOIR SIMULATION

A simplified numerical model based on the Rio Vista system [6] was developed for demonstrating the physical process of CSEGR. The reservoir is assumed to consist of 25 CO₂ injection wells, 16 CH₄ production wells, and 8 monitoring wells placed over the central part of the 16 km long by 7 km wide Rio Vista gas field. The well pattern and quarter five spot domain for simulation are shown schematically in Figure 2. Injection and production are assumed to be in the Domengine sandstone, the largest gas pool at Rio Vista. Note in Figure 2b that the CSEGR strategy we demonstrate involves injection of CO₂ into the lower regions of the thick reservoir while producing CH₄ from the upper regions. Injection of CO₂ is at a constant rate of 2.4 million t/year over the whole field, and uniformly distributed between the 25 injection wells (260 t/day per well). For comparison, this rate is approximately 57% of the CO₂ production rate of the nearby 680 MW gas-fired powerplant at Antioch, California. The simulation incorporates a total CH₄ production rate fixed at 750 t/year (150 MMMcf), or 48 t/day per well. This high production rate is nearly equal to the peak Rio Vista production in the 1940s, and was chosen simply to demonstrate CSEGR with a significant

enhancement in production over the current Rio Vista production which is approximately 10^7 Mcf/yr. Current production at Rio Vista represents the flattening tail of a production curve that declined by nearly one half from 1950 to 1960, and declined by over half again from 1960 to 1990. The idealized scenario simulated here allows approximately seven times more gas to be produced from the reservoir over 15 years than the current production projected over this same period [1]. Other properties of the model reservoir are presented in Table 1. Simulations are carried out using a new module for TOUGH2 [7] called EOS7C. This simulator calculates real-gas mixture properties in the ternary system $\text{H}_2\text{O}-\text{CO}_2-\text{CH}_4$ and models flow and transport of supercritical CO_2 , CH_4 , and water in gas and aqueous phases in three-dimensional model reservoirs.

We present in Figure 3 simulation results for the gas composition and density after 15 years of injection and production. Note that injecting CO_2 into the lower part of the reservoir while producing gas from the upper part of the reservoir exploits the large density contrast between CO_2 and CH_4 to delay CO_2 breakthrough and effectively fill the reservoir from the bottom up. To summarize the large number of process simulations we have carried out over the last few years, we can say that (1) the high density and viscosity of CO_2 favor CSEGR by limiting gas mixing, (2) that reservoir heterogeneity tends to accelerate breakthrough of CO_2 to production wells, but (3) that repressurization of the reservoir occurs faster than CO_2 breakthrough. An optimal strategy is to take advantage of the higher density of CO_2 and inject it into the lower portions of the reservoir to drive out the remaining lighter CH_4 , while minimizing mixing and contamination in the upper parts of the reservoir. Our simulations suggest that CSEGR is feasible from a process perspective in that the injection of CO_2 into depleted gas reservoirs can enhance CH_4 recovery, while simultaneously

sequestering large amounts of CO₂. In the following section, we analyze the economic feasibility of this particular CSEGR scenario.

ECONOMIC FEASIBILITY ANALYSIS

The economic feasibility of CSEGR depends on the incremental benefits of gas recovery relative to the incremental expenses of CSEGR. A key decision for evaluating CSEGR applications -- as well as for CO₂-enhanced oil recovery and coalbed methane projects – is proper timing: At what stage is CO₂ injection optimal? CSEGR technology may be applied at any stage in the life of a natural gas field, from initial discovery and development all the way to depletion and field abandonment. We believe that the optimal application of CSEGR is in mature (but not abandoned) natural gas fields where production is declining. We refer to such mature reservoirs that are still in production but that are becoming depleted as “depleting” reservoirs and focus our analysis on applying CSEGR at this stage in the life of the reservoir. A depleting gas field already has in place a working infrastructure of producing wells, gas gathering, treatment, compression, and transport facilities, plus the necessary regulatory approvals. In contrast, newly discovered fields lack infrastructure and their reservoir behavior is still poorly understood, making CO₂ injection more risky. Likewise, abandoned fields face large rehabilitation costs as well as regulatory hurdles. Our economic model assumes that CSEGR is applied to a depleting gas field, such as the Rio Vista field in the Sacramento Valley, the largest onshore gas field in California [6], estimated to contain an additional 3 Tcf of recoverable gas [8].

Incremental capital costs for CSEGR include CO₂ acquisition and transport via pipeline to the field, distribution of CO₂ within the field, injection wells, monitoring systems, CH₄ compression and

(eventually) CH₄/CO₂ separation facilities. A major expense today is the cost of acquiring CO₂, which may range from \$10/t from a relatively pure fertilizer or cement plant source up to \$50/t for a retrofitted power plant. We assumed that CO₂ is supplied at high purity and pressure to the pipeline terminus. We computed the maximum price that the field operator could afford to pay for CO₂ supply to break even under a 15% rate of return (pre-income taxes), under varying wellhead gas price and CO₂/CH₄ ratios. We assumed that the field operator would construct a new 50-km long pipeline and pipeline distribution network to transport CO₂ from the supply source to wells throughout the field. We assumed that existing shut-in or abandoned wells could be converted to dedicated CO₂ injection or monitoring wells at a cost of approximately one-third that of drilling new wells. Eventually, injected CO₂ mixes with CH₄ within the reservoir, requiring costly gas separation and conversion of the wellhead and flow lines to corrosion-resistant materials.

We estimated capital and operating costs for the CSEGR application based on current California gas production operations and experience at natural CO₂ production fields and EOR operations. The economic analysis is carried out with the same assumptions as the reservoir simulation presented above, with development and cost assumptions summarized in Tables 2 and 3. Standard royalty, severance, and other production taxes were subtracted from the cash flow.

While most of the variables in the model are generalized economic variables, some depend on the physical processes of CSEGR and can be estimated from reservoir simulation results. For example, the volumetric ratio of injected CO₂ to incrementally produced CH₄ depends on processes in the reservoir. Physically, this ratio represents the efficiency of EGR in terms of the displacement of CH₄ by CO₂; the closer the ratio is to unity, the more efficient is the gas recovery process. The degree to

which this ratio is greater than unity can reflect the combined effects of repressurization of the reservoir, dissolution of CO_2 into connate water, gas mixing, and reservoir geometry. Briefly, the CO_2 is denser than CH_4 and the change in density of CO_2 as pressure increases through the critical pressure of 73.8 bars is much larger than the change in density of CH_4 at typical reservoir temperatures. The result of this difference is that it takes more CO_2 to displace a given volume of CH_4 in a high-pressure reservoir. However, because deeper reservoirs tend to be at higher temperatures, the effects of higher pressure on CO_2 density are moderated. Furthermore, while repressurization and dissolution tend to make the ratio larger than unity, gas mixing decreases the ratio because the density of supercritical CO_2 decreases drastically upon mixing with small amounts of CH_4 which causes pressure increases with no additional injection whatsoever (e.g., [4]).

To capture expected variability in volume ratio, we tested the sensitivity of the result using volume ratio values of 1.5, 2.0, and 3.0 by varying the assumed incremental CH_4 production under a constant CO_2 injection rate. For reference, the volumetric ratio for the idealized case simulated above was approximately 2.0. Another physical property that can be estimated from simulation results is the gas composition, or mass fraction CH_4 in the produced gas. This property starts at unity in CSEGR, but declines as mixing occurs in the reservoir and CO_2 breaks through to the production wells. At 15 years in the scenario simulated above, the CH_4 mass fraction in the gas at the production well is approximately 0.80. For the purposes of the economic analysis presented here, we will assume that EGR is stopped (reservoir shut in) if the mass fraction of CH_4 drops below 0.5 at the production well. Carbon sequestration by CO_2 injection can continue for decades after the reservoir is shut in [1]. Following CSEGR, the CO_2 -filled reservoir can be used for gas storage with CO_2 serving as a very

effective cushion gas because of its large effective compressibility around its critical pressure and temperature [9].

RESULTS

The economic analysis shows that CSEGR may be economically feasible if the supply cost of CO₂ is low, if CO₂/CH₄ mixing is slow so there is little CO₂ breakthrough, and if there is a significant amount of CH₄ remaining in the reservoir to be recovered. Sensitivity analysis using the CSEGR economic model shows that the most critical parameters are wellhead natural gas price and the ratio of CO₂ injected to incremental CH₄ produced. The risk of natural gas price drop may be hedged, while capital costs may be estimated with reasonable certainty. Thus, the major remaining unknown economic factors are the volumetric CO₂/CH₄ ratio and the time to breakthrough. These key factors are likely to vary from field to field, based on reservoir architecture and field operation strategies, and can be forecasted using detailed reservoir simulation. However, field testing of CSEGR is needed to demonstrate empirically its feasibility and to clarify the influence of key economic variables.

Figure 4 shows the results of the sensitivity analysis. The base case (CO₂/CH₄ = 1.5 and wellhead CH₄ price = \$3.00/MMBtu ≈ \$3.00/Mcf) shows that CSEGR may be economic at CO₂ supply costs of under \$8/t (\$0.40/Mcf). This breakeven threshold rises to over \$15/t (\$0.79/Mcf) at a \$5/Mcf wellhead price. These CO₂ prices are only slightly below actual current CO₂ prices from geologic sources and low-cost gas processing plants in the Permian and Rocky Mountain basins of the western USA. However, capture, separation, and compression costs from power plants are far higher, perhaps \$50/t (\$3.00/Mcf). Under current technology, CSEGR would require a significant subsidy for CO₂ sequestration to be economic using flue gas CO₂ sources.

Two other sensitivity cases were run with less optimistic assumptions, using CO₂/CH₄ ratios of 2.0 and 3.0 (Figure 3). These scenarios represent fields with greater reservoir heterogeneity and/or less remaining CH₄ in place. Breakeven CO₂ supply costs for these less favorable reservoirs ranged from \$4 to \$6/t ((\$0.21 to \$0.31/Mcf) at a \$3/Mcf CH₄ wellhead price. This is likely to be sub-economic even using low-cost natural CO₂ field sources, which do not exist in California. However, advances in CSEGR injection, production, and field management technologies could reduce CO₂/CH₄ ratios and improve CSEGR economics. Furthermore, if future CO₂ markets involve effective payment for carbon sequestration, CO₂ may be free to the operator or even become a potential revenue stream making CSEGR even more attractive economically.

CONCLUSIONS

CSEGR may be economically feasible provided the volumetric ratio of CO₂ injected to incremental CH₄ produced is less than about three, depending on CO₂ supply costs and CH₄ wellhead prices. Many uncertainties remain in the evaluation of a new recovery and sequestration process, among which are uncertain monitoring requirements and uncertain CO₂ markets. For example, possible future CO₂ markets may involve payment to operators willing to accept CO₂ and inject it into the ground for carbon sequestration. In this case, CO₂ is no longer a cost but rather a revenue and the economics of CSEGR will be considerably more favorable. In any case, CSEGR will have to be evaluated on a field-by-field basis considering reservoir properties and conditions. The analysis in this study was based on an idealized model reservoir assuming homogeneous permeability and a single gas-bearing layer. In addition, the economic model was based on simulation results of a low-pressure reservoir, i.e., highly depleted and below the critical pressure of CO₂. For these reasons, the

results of our study must be considered tentative and subject to revision as more detailed reservoir simulations are carried out. Nevertheless, our results suggest that CSEGR will be feasible under certain conditions. Because both reservoir simulation and laboratory studies have also suggested that CSEGR is technically feasible, it is now time to consider seriously the development of a field pilot-study test of CSEGR.

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Tables

TABLE 1

PROPERTIES OF THE THREE-DIMENSIONAL QUARTER FIVE-SPOT DOMAIN

Property	Value	
Quarter five spot size	800 m x 800 m	160 acres
Reservoir thickness	50 m	160 feet
Porosity	0.30	0.30
Permeability (isotropic)	$1 \times 10^{-12} \text{ m}^2$	1 darcy
Residual liquid saturation	0.20	
<i>Relative permeability</i>		
Liquid	Immobile	
Gas	Equal to gas saturation.	
Molecular diffusivity in gas and liquid	$1.0 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$, $1.0 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$	
Reservoir temperature	75 C	167 F
Reservoir pressure at start of CSEGR	50 bars	725 psi
CO ₂ injection rate (per full well)	3 kg s^{-1}	260 t/day
CH ₄ production rate (per full well)	0.56 kg s^{-1}	48 t/day
Final reservoir pressure (after 15 years)	60 bars	870 psi

TABLE 2

DESIGN PARAMETERS FOR CSEGR APPLICATION AT A CALIFORNIA DEPLETING GAS FIELD(US\$ 2002)

Parameter	Value	
Reservoir Depth	1,500 m	4,921 feet
Reservoir Type	Sandstone, High Porosity & Permeability	
Total Field CO ₂ Storage Capacity	3.6 x 10 ⁷ t	0.7 Tcf
Total Field CO ₂ Injection Rate	6500 t/day	125 MMcfd
CO ₂ Injection Rate (per well)	260 t/day	5.0 MMcfd
CH ₄ Prod. Rate (Peak per well)	48 to 95 t/day	2.5 to 5.0 MMcfd
Wellhead Natural Gas Price	\$0.11 to 0.18/m ³	\$3.00 to \$5.00/Mcf
CO ₂ Injection Wells	25 wells	
CH ₄ Production Wells	16 wells	
Monitoring Wells	8 wells	
Project Duration	15 years	
Nominal CO ₂ Content at Production Wells	Years 1-5: 0%	
	Years 5-10: 5%	
	Years 10-15: 25%	

Mcf = 1 x 10³ ft³ = 28.3 m³. MMcf = 1 x 10⁶ ft³. Tcf = 1 x 10¹² ft³. t = tonne = 1 x 10³ kg.

TABLE 3

CAPITAL COSTS (US\$ 2002) FOR CSEGR APPLICATION AT A CALIFORNIA DEPLETING GAS FIELD

Cost Item	Unit Cost (x 1000 US\$)	Units	Total Cost (million US\$)
<u>Wells</u>			
CH ₄ Production Well: New Completion	\$390	4	1.56
CH ₄ Production Well: Workovers	\$40	12	0.48
CO ₂ Injection Well: New Completion	\$460	5	2.30
CO ₂ Injection Well: Converted CH ₄ Well	\$180	20	3.60
Monitoring Well: Converted CH ₄ Well	\$70	8	0.56
Total Well Costs			8.50
<u>Pipelines</u>			
CO ₂ Transport Pipeline (8-Inch Diameter)	\$125	50 km	6.25
CO ₂ Field Distribution Lines (2-Inch Diam)	\$30	10 km	0.30
Total CO₂ Pipeline & Distribution Costs			6.55
Total Capital Costs			15.05

Figure captions.

Figure 1. Schematic of CSEGR processes.

Figure 2. (a) Schematic of well pattern for CSEGR with well spacing of one mile (1.61 km). (b) Perspective view of quarter five-spot simulation domain.

Figure 3. (a) CO₂ mass fraction in the gas and (b) gas density after 15 years of injection into the lower part of the reservoir.

Figure 4. Results of sensitivity analysis showing actual breakeven CO₂ supply costs (no subsidy) for various CH₄ prices.

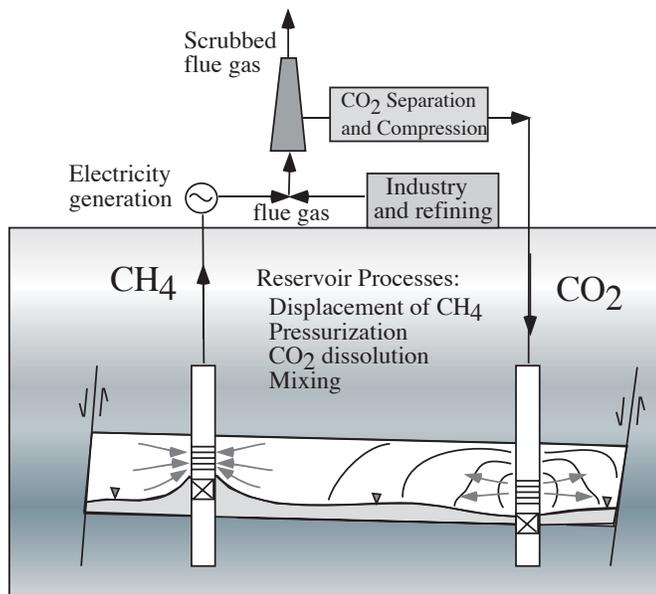


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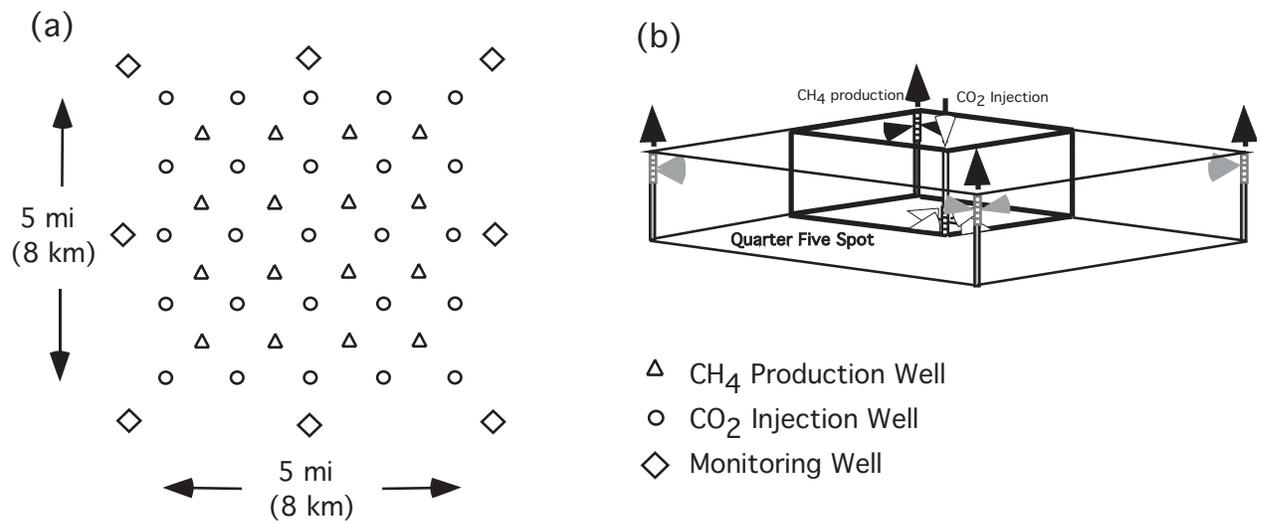


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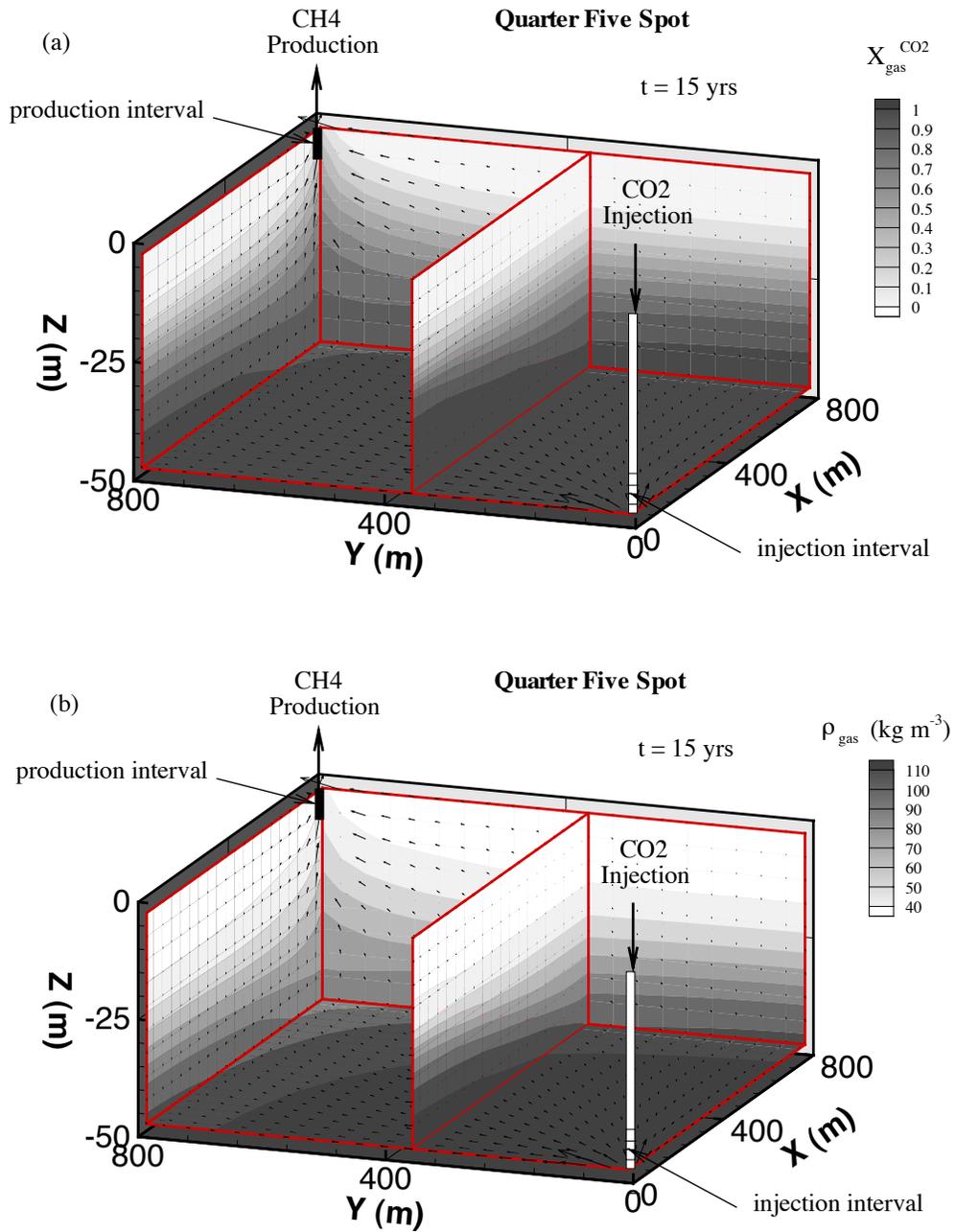


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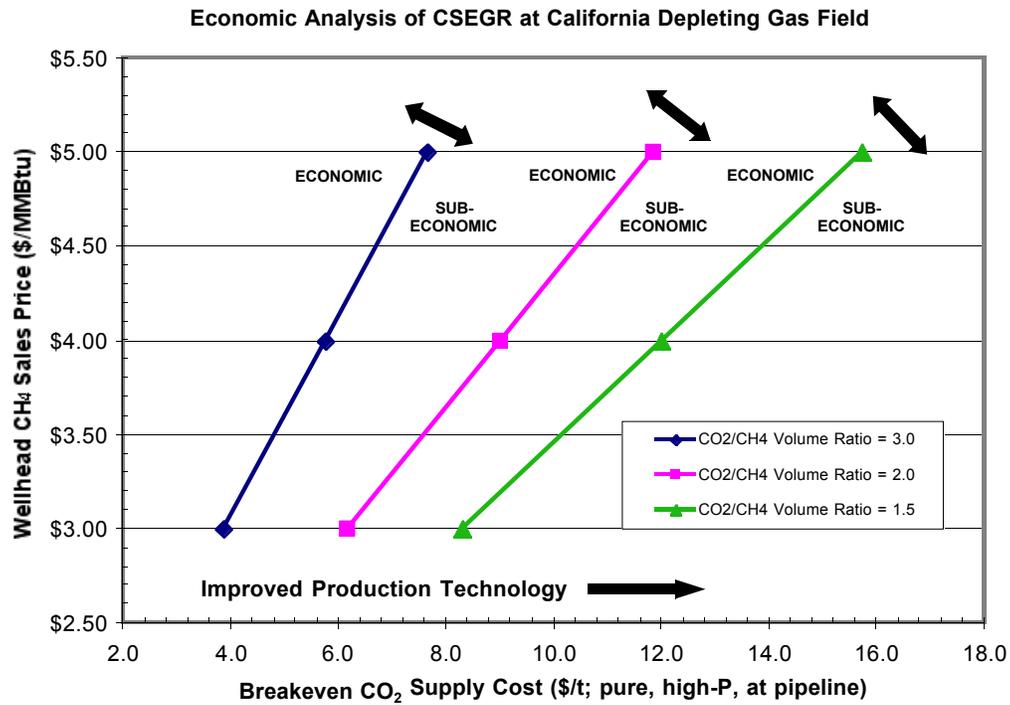


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