



**A Simulation-Based Data Envelopment Analysis Tool for Evaluating
Geological Carbon Storage Scenarios**

**Uma Ferramenta de Análise Envoltória de Dados Baseada em
Simulação para Avaliar Cenários de Armazenamento Geológico de
Carbono**

**Una Herramienta de Análisis Envoltura de Datos Basada en
Simulación para Evaluar Escenarios de Almacenamiento Geológico de
Carbono**

Peter Aanuoluwapo Omoyemi

Universidade Federal de Pernambuco – UFPE (peter.omoyemi@ufpe.br)

Walton Pereira Coutinho

Universidade Federal de Pernambuco – UFPE (walton.coutinho@ufpe.br)

Gustavo Charles Peixoto de Oliveira

Universidade Federal da Paraíba – UFPB (gustavo.oliveira@ci.ufpb.br)

Abstract

A combined approach of numerical simulation and Data Envelopment Analysis (DEA) is presented to analyze the operational efficiency of CO₂ storage in rock formations. Ten scenarios were simulated in the **UNISIM-II-D model**, which is representative of the Namorado Field of Campos Basin, were simulated using the CMG-GEM compositional simulator. Each case varied in rate of injection, number of wells, and well pattern, injecting 100 % CO₂ for 50 years and 150 years of shut-in on a post-injection observation. The DEA-CCR (CRS) model, implemented on Python (Pyomo), was used to find efficient cases that yield optimal conversion of injection inputs to storage outputs. Results show that only three of the scenarios realized complete efficiency under CRS, with



potential room for injection design and operational strategy enhancement. Two performance objectives were considered: maximizing storage index of CO₂ and minimizing mobile fraction of CO₂. The proposed framework demonstrates DEA as an open post-simulation tool for assessment that complements reservoir physics and enables sustainable decision-making for the optimization of CO₂ storage in Brazilian reservoirs. This DEA-type screening can guide follow-up, more-fidelity optimization (e.g., MINLP over well counts/rates) and facilitates pragmatic decision making for planning CO₂ storage under uncertainty.

Keywords: Geological Carbon Storage, Data Envelopment Analysis, Decarbonization, UNISIM-II-D Reservoir Model, Compositional Simulation.

Resumo

*Uma abordagem combinada de simulação numérica e Análise Envoltória de Dados (DEA) é apresentada para analisar a eficiência operacional do armazenamento de CO₂ em formações rochosas. Dez cenários foram simulados no modelo **UNISIM-II-D**, representativo do Campo de Namorado, na Bacia de Campos, utilizando o simulador composicional CMG-GEM. Cada caso variou em taxa de injeção, número de poços e configuração dos poços, com injeção de 100% de CO₂ por 50 anos e 150 anos de shut-in para observação pós-injeção. O modelo DEA-CCR (CRS), implementado em Python (Pyomo), foi utilizado para identificar os casos eficientes que resultam em conversão ótima dos insumos de injeção em resultados de armazenamento. Os resultados mostram que apenas três dos cenários alcançaram eficiência total sob CRS, indicando potencial para aprimoramento no projeto de injeção e na estratégia operacional. Foram considerados dois objetivos de desempenho: maximizar a eficiência de armazenamento de CO₂ e minimizar a fração móvel de CO₂. O arcabouço proposto demonstra a DEA como uma ferramenta aberta de avaliação pós-simulação que complementa a física do reservatório e possibilita uma tomada de decisão sustentável para a otimização do armazenamento de CO₂ em reservatórios brasileiros. Este tipo de triagem com DEA pode orientar otimizações subsequentes de maior fidelidade (por exemplo, MINLP sobre*



Anais do Simpósio Acadêmico de Engenharia de Produção (SAEPRO) da EEL-USP

IX SAEPRO – 25 e 26 de novembro de 2025

número e taxa de poços) e facilitar decisões pragmáticas para o planejamento do armazenamento de CO₂ sob incerteza.

Palavras-chave: Armazenamento geológico de carbono, Análise envoltória de dados, Descarbonização, Modelo de reservatório UNISIM-II-D, Simulação Composicional.

Resumen

*Se presenta un enfoque combinado de simulación numérica y Análisis Envoltorio de Datos (DEA) para analizar la eficiencia operativa del almacenamiento de CO₂ en formaciones rocosas. Se simularon diez escenarios en el modelo **UNISIM-II-D**, representativo del Campo Namorado en la Cuenca de Campos, utilizando el simulador composicional CMG-GEM. Cada caso varió en la tasa de inyección, el número de pozos y el patrón de pozo, con inyección de 100% de CO₂ durante 50 años y 150 años de shut-in para observación posterior a la inyección. El modelo DEA-CCR (CRS), implementado en Python (Pyomo), se empleó para identificar los casos eficientes que logran una conversión óptima de los insumos de inyección en resultados de almacenamiento. Los resultados muestran que solo tres escenarios alcanzaron eficiencia total bajo CRS, lo que sugiere un margen de mejora en el diseño de inyección y la estrategia operativa. Se consideraron dos objetivos de rendimiento: maximizar la eficiencia de almacenamiento de CO₂ y minimizar la fracción móvil de CO₂. El marco propuesto demuestra que la DEA es una herramienta abierta de evaluación post-simulación que complementa la física del yacimiento y permite una toma de decisiones sostenible para optimizar el almacenamiento de CO₂ en los reservorios brasileños. Este tipo de análisis basado en DEA puede orientar optimizaciones posteriores de mayor fidelidad (por ejemplo, MINLP sobre número y tasas de pozos) y facilitar decisiones pragmáticas para la planificación del almacenamiento de CO₂ bajo incertidumbre.*

Palabras clave: Almacenamiento geológico de carbono, Análisis envoltorio de datos, Descarbonización, Modelo de yacimiento UNISIM-II-D, Simulación composicional.

1. INTRODUCTION

The global push towards being carbon-neutral by 2050 has further strengthened the pursuit of technology with the potential to limit anthropogenic greenhouse gas emissions. Geological Carbon Storage (GCS) is among such pioneering and scalable options within the broader Carbon Capture, Utilization and Storage (CCUS) supply chain Silva; Santos; Oliveira, (2024), this technique captures carbon dioxide (CO₂) from industrial emissions, transports it through specialized infrastructure, and injects it into deep geological formations for permanent storage. While mammoth-sized GCS projects have operated in North America, Europe, and Australia, application of the same projects in Brazil is low with huge knowledge gaps related to injectivity, efficacy, and containment of local saline aquifers and matured reservoirs (Silva; Santos; Oliveira, 2024).

Pattern study of injection, CO₂ migration and trapping efficiency numerically under different operating conditions (Mirzaei-Paiaman; Carrasco-Jaim; Okuno, 2024); (Myshakin *et al.*, 2023). The process in this study was inspired by the integrated optimization workflow presented by Zou; Durlofsky, (2023) in "Integrated Framework for Constrained Optimization of Horizontal/Deviated Well Placement and Control for Geological CO₂ Storage." Their article presented a process that coupled reservoir simulation with optimization under different operating constraints. With this assumption, the present study employs the same simulation setup with the UNISIM-II-D reference model representing the Namorado Field in the Campos Basin of Brazil Correia *et al.* (2015), simulated using the CMG-GEM compositional simulator.

There were ten cases presented by altering injection rate, number of wells and well pattern while maintaining the same reservoir properties. In both cases, 100% CO₂ was injected over a 50-year period and shut-in for 150 years to monitor long-term containment and pressure stabilization. DEA was used as a post-simulation performance measurement technique in favor of the quantitative research Proudlove (2000). Two performance objectives were considered: optimally maximizing the efficiency of CO₂ storage and minimizing the proportion of mobile CO₂. With injection rate and number of wells as input variables and storage-related performance measures as outputs, DEA-CCR (CRS) was implemented with the help of Python (Pyomo) in order to determine efficient cases



that maximized the conversion of injection inputs into storage outcomes. This hybrid workflow bridges the gap between data-driven optimization and reservoir simulation Wang *et al.* (2023) and delivers an open and reproducible framework for CO₂ storage ranking and sustainable decision support in carbon management for Brazilian reservoirs.

2. THEORETICAL BACKGROUND

In the context of geological carbon sequestration, four distinct trapping mechanisms govern CO₂ immobilization: (1) Structural and Stratigraphic trapping, which relies on physical barriers and reservoir geometry; (2) Residual trapping, where CO₂ is immobilized in pore spaces due to capillary forces; (3) Solubility trapping, involving the dissolution of CO₂ into formation fluids; and (4) Mineral trapping, where CO₂ reacts chemically to form stable carbonate minerals (Akbarabadi; Piri, 2013). This study does not take mineral trapping into account because the CO₂ mineralization process takes place over geologically very long timescales, typically between thousands of years and millions of years. Chemical reactions for the formation of stable carbonate minerals take place too slowly in most subsurface environments to be observed to be significant within the timescale of CO₂ storage project. So mineral trapping is generally thought to be a long-term stabilization process and not one that significantly contributes to immobilization of CO₂ in the short or medium term. The optimization of CO₂ storage is the integration of reservoir simulation, well control, and performance assessment with physical and operating limitations. The theoretical context of this work is founded upon the study of Zou; Durlofsky, (2023), which formulated a multi-objective optimization framework for horizontal and deviated well placement and control in geologic CO₂ storage systems. The scheme has two main objectives: (i) minimization of the proportion of mobile CO₂ for enhanced long-term trapping and stability, and (ii) storage index maximization, which is the ratio of reservoir pore space actually filled by CO₂ within the footprint area of the plume.

The first objective function (f_1) computes the ratio of the mobile CO₂ mass in the entire system at the end of the last simulation time to the total injected CO₂ mass. Mathematically, it is expressed as:

$$f_1 = \frac{m_m}{m_t} \quad (1)$$

where m_m denotes the mobile (free-phase) CO₂ mass in kg.mol at the final simulation time T_f , and m_t is the total mass of CO₂ injected into the system. We take $T_f = 200$ years.

The second objective function (f_2) measures CO₂ storage index, calculated as the ratio between the pore volume containing CO₂ in the gas phase and the total pore volume within the storage footprint region D_{fr} :

$$f_2 = \frac{\sum_{i \in D_{sa}} V_i \phi_i S_i}{\sum_{j \in D_{fr}} V_j \phi_j} \quad (2)$$

where V_i and V_j denote the bulk volume, ϕ_i and ϕ_j are the porosities, and S_i the CO₂ gas saturation in grid block i within the storage aquifer domain D_{sa} . The objective is to maximize this ratio so as to identify well configurations that ensure efficient storage (Zou; Durlofsky, 2023).

To compare the relative efficiency of different injection situations, Data Envelopment Analysis (DEA) was employed. DEA is a linear programming, non-parametric method of estimating the relative efficiency of decision-making units (DMUs) against multiple inputs and outputs. Initially proposed by Charnes, Cooper, and Rhodes (1978), the DEA-CCR model makes an assumption of constant returns to scale (CRS), calculating the proportional correspondence between weighted outputs and inputs (Proudlove, 2000). In this study, all injection scenario simulations are a proxy for a DMU, where input parameters are injection rate and number of wells, and the outputs are CO₂ storage index



and mobile fraction of CO₂. Efficiency values range between 0 and 1, with unity representing that a scenario lies on the frontier of efficiency.

3. METHOD

This study integrates numerical reservoir simulation with Data Envelopment Analysis (DEA) to evaluate the efficiency of geological CO₂ storage conditions. The methodology consists of three phases: simulation setup, data extraction, and DEA application.

3.1. Simulation Setup

All the numerical simulations were done using the CMG-GEM compositional simulator in the UNISIM-II-D benchmark model, modeling the Namorado Field in Campos Basin, Brazil (Correia *et al.*, 2015). The UNISIM-II-D model was selected because its geo- and petrophysical data are available to the public, making it an open reproducible model for CO₂ injection and migration studies.

All ten cases were described with different injection rate (2000–100000 m³/day), number of injection wells (1–5), and well placement pattern, but with the same reservoir rock and fluid properties. In each case, 100% CO₂ was injected for 50 years followed by shut-in for 150 years to assess post-injection stabilization, pressure dissipation, and containment effectiveness (Luboń, 2020).

The composition model accounted for capillary trapping and phase behavior through the PR-EOS (Peng-Robinson equation of state). Residual and solubility trapping were implicitly represented through the gas saturation hysteresis and CO₂ solubility in brine.

3.1.1. Data Preparation

For every simulation, the following quantities were taken at the end of the 200-year run:

Injection rate (m³/day);

Number of wells;

CO₂ storage index (fraction);

Mobile CO₂ fraction (fraction).

These variables were organized into a dataset of ten various Decision-Making Units (DMUs) for the DEA model, as shown in **Table 1**.

Table 1 – Simulation scenarios with input and output variables

<i>Scenarios</i>	<i>InjectionRate(m³/day)</i>	<i>Number of Wells</i>	<i>Storage Index</i>	<i>Mobile CO₂</i>
S1	50000	3	0.143154	0.3991
S2	100000	3	0.142191	0.3991
S3	35000	3	0.142191	0.3703
S4	25000	3	0.142191	0.3224
S5	8000	3	0.142191	0.1633
S6	8000	4	0.142191	0.2299
S7	10000	5	0.142191	0.3241
S8	6000	5	0.142191	0.2716
S9	4000	5	0.142191	0.2167
S10	2000	4	0.142191	0.0895

Source: Prepared by authors (2025)

3.1.2. DEA Model Formulation

Each situation was evaluated as a Decision-Making Unit (DMU) in the input-oriented CCR model (constant returns to scale), having proportional efficiency for all units (Charnes et al., 2010). The model is to be used for minimizing the utilization of inputs with constant output levels. The DEA model were executed in Python with Pyomo and solved with GLPK solver, which simultaneously determines the optimal efficiency score θ and the optimal λ -weights for each scenario. Each DEA run corresponds to a single optimization problem evaluating one DMU at a time.

In Eq. (3), θ represents the objective function to be minimized, corresponding to the efficiency score of each Decision-Making Unit (DMU) under evaluation. The variable $\theta \in \mathbb{R}$ is bounded between 0 and 1 and expresses the proportional contraction applied to the input vector while maintaining output levels constant.

The set of coefficients $\lambda \in \mathbb{R}^n$ (for $j = 1, 2, \dots, n$) are intensity or peer weights that defines how much each DMU contributes to constructing a virtual composite unit, a weighted benchmark located on the efficiency frontier. These λ -weights are not assigned a priori; rather, they are decision variables computed internally by solving the linear programming (LP) problem. During optimization, the model selects λ -values that form a feasible combination of observed DMUs capable of producing at least the same outputs as DMU₀ with equal or fewer inputs. The set of optimal λ -weights therefore represents the reference peers that defines the efficiency boundary for each scenario.

The input parameters are denoted by $x_{ij} \in \mathbb{R}^m$, where $i = 1, \dots, m$ and $j = 1, \dots, n$, representing the injection rate and number of wells in each simulated scenario. Similarly, the output parameters are expressed as $y_{rj} \in \mathbb{R}^s$, where $r = 1, \dots, s$, corresponding to the CO₂ storage index and the mobile CO₂ fraction. Each DMU therefore represents a single simulation case, characterized by its input and output data values. The DEA model constructs a reference (or virtual) DMU as a convex combination of all real DMUs through the λ -weights.

The resulting Constant Returns to Scale (CRS) model, following the Charnes, Cooper and Rhodes (CCR) formulation, is expressed as:

$$\text{Minimize: } \theta \quad (3)$$

Subject to:

$$\sum_{j=1}^n \lambda_j x_{ij} \leq \theta x_{i0}, \quad \forall i = 1, \dots, m \quad (4)$$

$$\sum_{j=1}^n \lambda_j y_{rj} \geq y_{r0}, \quad \forall r = 1, \dots, s \quad (5)$$

$$\text{Non-negativity: } \lambda_j \geq 0, \quad \forall j = 1, \dots, n \quad (6)$$

Where $0 \leq \theta \leq 1$

Here, x_{i0} , and y_{r0} , denote the input and output parameters of the DMU being evaluated. Under CRS, efficiency is assumed independent of operational scale, implying that doubling all inputs should double all outputs.

The Variable Returns to Scale (VRS) model proposed by Banker; Charnes; Cooper, (1984) introduces a convexity constraint to account for scale efficiency. For this, an additional convexity constraint is introduced to the model:

$$\sum_{j=1}^n \lambda_j = 1 \quad (7)$$

In Eq. (7), the constraint ensures that the reference unit is a convex combination of existing DMUs and allows efficiency to vary with scale. This constraint was added so as to get the value of Scale efficiency which is CRS/VRS for each scenario. An efficiency value $\theta = 1$ indicates a relatively efficient scenario while $\theta < 1$ suggests inefficiency.

4. RESULTS

4.1. DEA Efficiency Scores

The outputs of both Constant Returns to Scale (CRS) as well as Variable Returns to Scale (VRS) models are presented in **Table 2** along with Scale Efficiency (SE = CRS/VRS).

Table 2 – DEA efficiency results for all scenarios

<i>Scenarios</i>	<i>CRS</i>	<i>VRS</i>	<i>SE</i>
S1	1.0000	1.0000	1.0000
S2	0.9934	1.0000	0.9934
S3	0.9957	1.0000	0.9957
S4	0.9973	1.0000	0.9973
S5	1.0000	1.0000	1.0000
S6	0.8125	0.8125	1.0000
S7	0.6500	0.6500	1.0000
S8	0.7222	0.7222	1.0000
S9	0.7647	0.7647	1.0000
S10	1.0000	1.0000	1.0000

Source: Prepared by authors (2025)

According to these results, three cases (S1, S5, S10) were relatively efficient (CRS = 1), indicating an optimal balance between injection effort and CO₂ retention. All the remaining cases were technically inefficient based on CRS but efficient based on VRS, showing that scale influences storage performance. It indicates that most of the scenarios exhibit high efficiency (> 0.7), confirming that DEA provides a robust ranking of operating performance.

5. DISCUSSIONS

From the results above, it indicates that the combination of reservoir simulation and DEA provides a quantitative method for analyzing and ranking CO₂ storage. In CRS, only scenarios S1, S5, and S10 were maximally efficient. More specifically, scenario S1, 50,000 m³/day and 3 wells, was the highest storage index (0.143154). Scenario S10, 2000m³/day and 4 wells, has the lowest mobile CO₂ fraction (0.0895) while Scenario S5, 8000m³/day and 3 wells, has a balance between its storage index (0.142191) and mobile CO₂ fraction (0.1633). This indicates that moderate injection rates with the presence of very few wells can offer maximum storage utilization of reservoir capacity with non-abnormal pressure buildup and excessive CO₂ mobility. This balance between storage performance and injection intensity makes a point that better trapping efficiency is not always correlated with higher rates or high numbers in well quantity. Instead, injection scheduling and well configuration must be optimized together to ensure that injected CO₂ is effectively trapped within the reservoir, minimizing the risk of plume migration and maintaining post-injection monitoring long-term containment. These findings carry meaningful implications for decision-makers involved in the early development of geological carbon storage (GCS) projects. An increase in storage index, that is, the proportion of injected CO₂ that remains securely stored, has the potential to accelerate the formation of effective carbon sinks, reducing the amount of gas that must be re-handled or re-injected over time. This directly contributes to lower long-term operational costs and shorter payback periods, once carbon pricing or credit markets become consolidated in Brazil.

The VRS model did not impose scale assumption, allowing most cases to reach full efficiency. This means that scale factors such as number of wells and injectivity distribution influence the observed performance. The unity values of Scale Efficiency (SE) of S6–S9 indicate that these cases are optimal in terms of technical scale but require enhanced proportional input distribution i.e., their inputs can be distributed among units or processes in some way, but with enhancements or adjustments so that the distribution is more effective. For companies contracted to deploy CO₂ storage as part of the wider



carbon capture, utilization, and storage (CCUS) value chain, such efficiency gains may increase return on investment (ROI) and improve the financial attractiveness of storage ventures.

Furthermore, applying data envelopment analysis (DEA) as a post-simulation assessment tool enables the comparison of multiple operational scenarios before implementation, allowing managers and engineers to prioritize configurations that maximize performance under resource constraints. This integrative approach bridges technical modeling with strategic decision-making, providing an adaptable and transparent framework for evaluating GCS efficiency within the Brazilian energy transition context.

Overall, DEA succeeded in linking physical simulation data and operational decision metrics. The methodology is transparent, reproducible, and scalable, providing a non-parametric optimization layer above deterministic reservoir simulations. This concurs with Zou; Durlofsky, (2023), who observed the importance of combining simulation and mathematical programming for CO₂ storage optimization.

6. FINAL CONSIDERATIONS

This study suggests the manner in which the integration of simulation results with data-led evaluation can enable more informed and sustainable decision-making in nascent GCS developments. By ranking the performance of different strategies, it is easier to determine alternatives that balance the environmental issues of large-scale carbon storage and economic needs.

While the analysis was based on test cases, the results emphasize the usefulness that systematic comparison tools like Data Envelope Analysis (DEA) can deliver at the preliminary planning stage. They help decision-makers to be able to predict which approaches will most probably lead to inexpensive, effective, and high-performance CO₂ storage.



More broadly, the findings identify the importance of GCS as part of Brazil's contribution to carbon emission reduction. Improvement in storage performance not only serves to achieve global climate targets but also allows Brazil to engage in early-stage carbon markets. As country policies evolve to enable carbon storage and capture, the integration of engineering models and strategic evaluation outlined here represents a valuable platform for ongoing analysis and use.

REFERENCES

AKBARABADI, M.; PIRI, M. Relative permeability hysteresis and capillary trapping characteristics of supercritical CO₂/brine systems: An experimental study at reservoir conditions. *Advances in Water Resources*, v. 52, p. 190–206, 2013. DOI: [10.1016/j.advwatres.2012.06.014](https://doi.org/10.1016/j.advwatres.2012.06.014)

BANKER, R. D.; CHARNES, A.; COOPER, W. W. Some models for estimating technical and scale inefficiencies in Data Envelopment Analysis. *Management Science*, v. 30, n. 9, p. 1078–1092, 1984. DOI: <https://doi.org/10.1287/mnsc.30.9.1078>

CORREIA, M.; HOHENDORFF, J.; GASPAR, A. T.; SCHIOZER, D. UNISIM-II-D: Benchmark Case Proposal Based on a Carbonate Reservoir. Paper presented at the **SPE Latin American and Caribbean Petroleum Engineering Conference, Quito, Ecuador**, November 2015. DOI: <https://doi.org/10.2118/177140-MS>

MSCHARNES, A.; COOPER, W. W.; RHODES, E. Measuring the efficiency of decision-making units. *European Journal of Operational Research*, v. 2, p. 429–444, 1978. DOI: [10.1016/0377-2217\(78\)90138-8](https://doi.org/10.1016/0377-2217(78)90138-8)

LUBOŃ, K. Influence of Injection Well Location on CO₂ Geological Storage Efficiency. *Energies*, v. 14, n. 24, p. 8604, 2021. DOI: [10.3390/en14248604](https://doi.org/10.3390/en14248604)



Anais do Simpósio Acadêmico de Engenharia
de Produção (SAEPRO) da EEL-USP

IX SAEPRO – 25 e 26 de novembro de 2025

MIRZAEI-PAIAMAN, A.; CARRASCO-JAIM, O. A.; OKUNO, R. Techno-economic-environmental study of CO₂ and aqueous formate solution injection for geologic carbon storage and enhanced oil recovery. *International Journal of Greenhouse Gas Control*, v. 138, p. 104257, 2024. DOI: [10.1016/j.ijggc.2024.104257](https://doi.org/10.1016/j.ijggc.2024.104257)

MYSHAKIN, E. M.; HAERI, F.; MOORE, J.; CRANDALL, D.; GOODMAN, A. L. Numerical Simulations of Carbon Dioxide Storage Efficiency in Heterogeneous Reservoir Models. *Geofluids*, v. 2023, Article ID 5089508, 16 p., 2023. DOI: [10.1155/2023/5089508](https://doi.org/10.1155/2023/5089508)

PROUDLOVE, N. Using Excel for Basic Data Envelopment Analysis. Manchester: **Manchester School of Management Working Papers**, 2000. ISBN 1 86615076 8. Available at: <https://www.researchgate.net/publication/255708004>.

SILVA, J. W. L.; SANTOS, M. D.; OLIVEIRA, G. P. Generalized functionals for qualification of geological carbon storage injection sites. *International Journal of Greenhouse Gas Control*, v. 135, p. 104167, 2024. DOI: [10.1016/j.ijggc.2024.104167](https://doi.org/10.1016/j.ijggc.2024.104167)

WANG, Y.; ZHANG, Z.; VUIK, C.; HAJIBEYGI, H. Simulation of CO₂ Storage Using a Parameterization Method for Essential Trapping Physics: FluidFlower Benchmark Study. *Transport in Porous Media*, v. 151, n. 5, p. 1053–1070, 2023. DOI: [10.1007/s11242-023-01987-5](https://doi.org/10.1007/s11242-023-01987-5)

ZOU, A.; DURLOFSKY, L. J. Integrated Framework for Constrained Optimization of Horizontal/Deviated Well Placement and Control for Geological CO₂ Storage. *SPE Journal*, v. 28, n. 5, p. 2462–2481, 2023. DOI: [10.2118/212228-PA](https://doi.org/10.2118/212228-PA)