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Techno-Economic Analysis of CO_2-Stimulated Geothermal Systems

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ABSTRACT

Enhanced Geothermal Systems (EGS) offer high energy potential and geographic flexibility but face challenges regarding initial capital expenditures and uncertain economic returns. This study investigates the techno-economic feasibility of CO_2-based EGS compared to traditional water-based systems using a scenario modeling approach. Twenty distinct scenarios were analyzed—anchored by a GEOPHIRES v2.0 water-based baseline—to evaluate capital investment, operational costs, and energy efficiency against variables such as soak times and Water-Alternating-Gas (WAG) ratios. Results indicate that while the superior thermodynamic properties of CO_2 enhance heat extraction, economic viability is heavily constrained by transportation and storage costs. However, optimized injection strategies can reduce expenses, while the 45Q tax incentive for carbon storage credits offers a secondary revenue stream. The study concludes that while CO_2-based systems present clear technical advantages, financial success is contingent upon regional carbon pricing infrastructure, effective CO_2 management, and the optimization of fluid interactions for thermal exchange.

1. INTRODUCTION

Geothermal energy offers a sustainable and dependable source of power by harnessing the Earth's natural heat (Rohit et al. 2023). Beyond electricity generation, geothermal systems present an opportunity to diversify the global energy mix and enhance power grid resilience in the face of growing energy demands. There is an increasing interest in technologies that provide long-term reliability and operational efficiency. One such emerging strategy involves using carbon dioxide (CO_2) to enhance geothermal heat recovery, while simultaneously leveraging geothermal reservoirs for CO_2 storage which have the potential to qualify for incentives such as the 45Q tax credit (Liu et al.,2026), (Rashid et al., 2020).

This dual-purpose approach, extracting geothermal energy while storing CO_2, has shown the potential to significantly improve the performance and economics of geothermal systems (Pruess, 2008). A key benefit is its contribution to meet the global increasing energy demands. These innovations build on geothermal intrinsic advantages, including its ability to provide stable baseload power, long operational lifespans, and minimal surface land requirements, positioning it as a vital component of future energy infrastructure.

Modern geothermal systems generally fall into two categories: open-loop and closed-loop designs. Closed-loop systems, which circulate a working fluid through sealed subsurface piping, offer greater site flexibility and lower contamination risk. The thermophysical properties of water, specifically its higher viscosity and limited thermal expansivity, impede efficient heat transfer and result in elevated pumping energy requirements (Wu et al., 2023). These challenges are amplified in low-permeability formations, where insufficient fluid-rock interaction diminishes system performance (Pruess, 2008).

In light of this, CO_2 has emerged as a promising alternative option for open-loop application. Its lower viscosity and higher expansivity enable more efficient heat extraction (Schifflechner et al., 2024), particularly in challenging geologic conditions with benefits such as the increase in conductivity, sweeping efficiency improvement, and heat exchange enhancement (Garcia et al., 2022). However, these benefits must be weighed against the higher costs associated with CO_2 sourcing, transportation, compression, injection, and recycling infrastructure (Liu, et al., 2022, 2023, 2024a, 2024b 2026a, 2026b). A critical economic assessment is needed to determine whether the performance improvements offered by CO_2 justify the additional expenses.

This study addresses that need by conducting a comprehensive economic analysis of CO_2-enhanced geothermal systems. It evaluates capital expenditure (CAPEX), operational expenditure (OPEX), and net present value (NPV) across various design scenarios. The analysis considers CO_2 utilization rates, replenishment needs, breakeven timeframes, and differences in cost structure between CO_2- and water-based systems. Furthermore, it incorporates potential revenue from power generation and carbon credits, including tax incentives, to assess long-term financial sustainability. By modeling multiple what-if scenarios and integrating real-world economic parameters, this research identifies cost-effective strategies for deploying CO_2-enhanced geothermal systems and contributes to the broader effort of advancing clean, economically viable, reliable, and secure energy solutions (Wei et al., 2021).

2. METHODOLOGY

To evaluate the economic performance of CO_2 based geothermal systems utilizing water as working fluid a case modeling approach was taken using GEOPHIRES v3.0(Liu et al., 2026), an open-access geothermal techno-economic simulation tool along with a custom post processing economic module. Twenty Case Scenarios were created to demonstrate the significant differences between different variables such as increased CO_2 prices or electricity volatility. The simulation process began by modeling a baseline closed-loop geothermal system using water (Case 1). System assumptions were drawn from GEOPHIRES defaults and adjusted to reflect a mid-size project. Building upon this baseline, Cases 2 through 20 replicated the system architecture using CO_2 as the working fluid, incorporating performance enhancements based on published data. These enhancements reflect improvements in thermal conductivity, heat exchange efficiency, sweep efficiency, and flow dynamics, resulting in projected energy recovery gains of 15% to 35% over the water-based system. Additional scenarios varied key economic drivers including CO_2 sourcing, transport, storage costs, and operational strategies such as water-alternating-gas (WAG) injection and Huff & Puff soak timing. (Heddle et al., 2003). While GEOPHIRES provides a robust simulation backbone, it does not natively model CO_2-specific logistics such as injection recycling, sourcing variability, or carbon storage incentives. To address this, the economic module was developed to augment the outputs to align with the desired CO_2-specific changes made. This module introduced three major variables:

- CO_2 Sourcing and Transport Costs: Calculated based on reservoir CO_2 losses and the volume required for replenishment. These costs were added to both capital expenditure (CAPEX) and operational expenditure (OPEX).

- Storage Revenue from 45Q tax credit: A portion of the injected CO_2 retained in the reservoir was monetized using the 45Q tax credit, treated as a secondary revenue stream alongside electricity sales.

- Financial Metrics: Core economic indicators such as Net Present Value (NPV), levelized cost of electricity (LCOE), breakeven year, and cumulative cash flow were recalculated to reflect these CO_2-specific cost and revenue elements.

2.1 Financial Calculations

Revenue was computed from net electricity generation and average electricity pricing, with sensitivity analyses conducted to account for market price volatility. NPV was calculated using a standard discounted cash flow model:

$$NPV = \sum_{t=0}^{T} \frac{R_t - C_t}{(1+r)^t}$$

where:

- R_t= annual revenue (electricity + 45Q credits)

- C_t= annual costs (including CO_2-related costs)

- r= discount rate

T= project lifetime The Breakeven Year refers to the earliest point in a project's life cycle when cumulative revenues match or exceed total expenditures. At this moment, the project has effectively paid off its investment and is beginning to generate net gains. It is an important measure of investment recovery speed and is often used alongside other financial metrics to assess risk and return potential.

The calculation is based on undiscounted cash flow, using the following equation:

$$\text{CumulativeCashFlow}_t = \sum_{i=0}^{t} (R_i - C_i)$$

Where:

- R_i: income received in year i (including electricity revenues and CO_2 storage credits)

- C_i: total expenses incurred in year i (e.g., upfront capital, O&M, and CO_2 logistics)

- t: specific project year being evaluated

- The breakeven year occurs at the smallest t where:

$$\text{Cumulative Cash Flow}_t \geq 0$$

2.2 Scenario design and summary

This study employs a comparative techno-economic modeling approach to evaluate the feasibility of substituting water with CO_2 as the working fluid in closed-loop geothermal systems. 20 simulated cases were developed to isolate and analyze the impact of various technical, operational, and market-driven parameters (Fu et al., 2022). Each scenario was constructed using consistent assumptions for plant lifetime (30 years), system configuration, and performance benchmarks, with variations applied systematically to test sensitivity and performance across five defined investigation groups.

- **Group 1: Baseline and Control (Cases 1–2):** Established reference conditions for both water (Case 1) and CO_2 (Case 2) systems using equivalent system configurations (Archer, 2020). Case 2 incorporates a 15% thermal performance uplift due to the improved thermophysical properties of CO_2 (Wu et al., 2023).

- **Group 2: CO_2 Injection Scaling (Cases 3–7):** Explored thermodynamic trade-offs by increasing CO_2 injection rates up to 2.5x baseline values. Recovery factors were varied to assess the marginal benefit of enhanced throughput against rising fluid costs and parasitic energy demands (Xu et al., 2024).

- **Group 3: Market and Supply Chain Tests (Cases 8–12):** Simulated the impact of external economic variables, including CO_2 storage efficiency (Case 8) (Wei et al., 2021), electricity price fluctuations (Cases 9–10), and CO_2 sourcing costs (Cases 11–12), to assess the system's vulnerability to market shifts and infrastructure constraints (Pruess, 2007), (Middleton & Bielicki, 2009).

- **Group 4: Cost Structure Sensitivity (Cases 13–14):** Adjusted CAPEX and OPEX assumptions by ±15% to capture the economic influence of construction cost overruns or technological learning curve benefits under fixed performance parameters (Liu et al., n.d.).

- **Group 5: Operational Optimization (Cases 15–20):** Focused on advanced fluid management strategies to maximize thermal recovery while reducing fluid consumption. This includes WAG schemes (Cases 15–17) with varied injection ratios (Heddle et al., 2003), and Huff-n-Puff cyclic injection methods (Cases 18–20) (Mansure et al., 2005) with soak durations of 6, 12, and 24 hours, respectively. (Xiao, 2023), (Yu, 2023).

All simulations were evaluated using Net Present Value (NPV), breakeven year, lifetime electricity generation, and Levelized Cost of Electricity (LCOE) to quantify economic performance. The integration of cash flow modeling, discounting mechanisms, and profit margin analyses allowed for a comparison of system-level profitability and investor readiness.

3. RESULTS

The results from the techno-economic analysis demonstrate a wide range of financial outcomes across the 20 modeled geothermal scenarios, driven by variations in working fluid type, CO_2 management strategies, capital costs, and operational configurations. These outcomes are evaluated primarily through metrics such as Net Present Value (NPV), total project costs, electricity generation, and breakeven year.

The baseline water-based system (Case 1) produced a modest yet positive NPV of approximately $34 million, establishing a reference for economic viability under conventional closed-loop operation. When CO_2 was introduced as the working fluid (Case 2), results showed only a minimal increase in revenue, with the NPV hovering just above breakeven. This suggests that the substitution of CO_2 alone does not yield substantial financial gains unless paired with system-level enhancements.

Cases 3 through 7, which explored the impact of increasing CO_2 injection volumes and energy recovery rates, resulted in significantly negative NPVs despite relatively high electricity generation. The steep decline in financial performance in these cases is attributed to the escalating costs of CO_2 sourcing, handling, and recycling infrastructure costs which outweighed the thermal benefits gained from higher fluid throughput. Case 6, while generating the most electricity across all scenarios, ranked among the worst in terms of financial return, underscoring that output quantity alone is not a sufficient driver of profitability.

Case 12 emerged as the least financially viable scenario, with an NPV of approximately –$114 million, due to the compounding effects of high CO_2 sourcing and storage costs. In contrast, Cases 13 and 14, which modeled reduced capital and operational expenditures, displayed marked improvements in financial metrics, validating the sensitivity of geothermal economics to cost structure optimization.

The most favorable outcomes were observed in Cases 15 through 20, which applied enhanced operational strategies such as WAG injection and Huff & Puff soak timing. These cases achieved the highest NPVs with Case 16 peaking at $205 million while also maintaining manageable cost profiles and earlier breakeven years. The alignment of high profit margins with optimized cash flow trajectories in these scenarios highlights the importance of efficient fluid management and process design in achieving long-term financial sustainability.

3.1 Cost-Revenue-Profit analysis

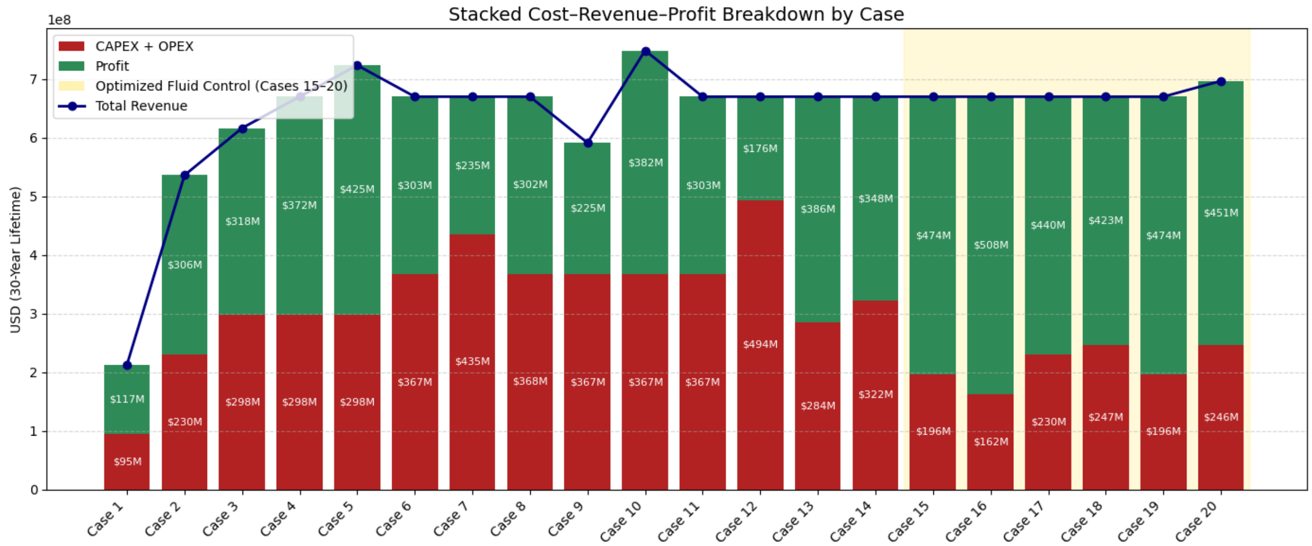

Figure 1: Stacked Cost-Revenue-Profit Breakdown by Case

Figure 1 presents a comparative analysis of Lifetime Profit and NPV across all 20 modeled geothermal scenarios. The stacked cost-revenue-profit chart offers a clear lens into the composition of project financials across all 20 scenarios, highlighting the importance of cost efficiency and cash flow timing in shaping overall viability.

- **Strong Revenue does not equal Strong Profitability**: Several scenarios, such as Cases 6 through 12, report total revenues near or above $670 million, yet yield relatively modest profits due to high CAPEX and OPEX burdens. Case 12, for example, sees over $494 million in lifetime costs, leaving only $176 million in profit, despite solid gross revenue. This disconnect underlines how cost intensity can erode financial returns, even when generation output is high.

- **Optimized Fluid Control Delivers Superior Margins**: The optimized cases (15–20), shaded in yellow, clearly outperform in terms of margin efficiency. Cases 15 and 16, for instance, both post high profit margins exceeding $450 million, despite having total revenues comparable to less efficient cases. This highlights how operational strategies such as WAG or Huff-n-Puff injection can enable better thermal performance with lower cost-to-output ratios.

- **Cost Discipline Outweighs Throughput:** While cases like Case 5 generate higher-than-average revenue and profit (~$425 million), they are still outpaced in net returns by cost-optimized or control-optimized cases. This reinforces the idea that revenue maximization does not guarantee investment-grade performance unless costs are tightly managed.

- **Role of CAPEX in Value Erosion**: The size of the red bars in Cases 6–12 reflects how large upfront investment requirements can lead to delayed profitability, which is later confirmed by their poor performance in the NPV and breakeven analyses. Cases 6 and 12 in particular are the worst of these scenarios in terms of CAPEX erosion. These cases serve as examples of nominal profit masking deeper economic inefficiencies.

While figure 1 presents a comparative analysis of Lifetime Profit and NPV across all modeled scenarios, it also expresses a critical financial distinction: while total profit captures operational success over the system's 30-year life, NPV reveals how effectively that profit translates into real, timely investment value when discounted over time. To address this, NPV is used in parallel with cumulative profit to evaluate the financial performance of each scenario from an investor's perspective.

The following comparison (Figure 2) visualizes how profit and NPV can diverge depending on capital intensity, payback speed, and incentive structures. In theory, high total profit should correlate with a strong NPV. However, differences in upfront costs, breakeven timing, and discounting effects can cause significant deviations between the two metrics. For instance, some cases may generate high nominal profits but suffer from delayed returns, weakening their NPV. Others may yield lower absolute profit but concentrate returns in earlier years, producing a more favorable discounted cash flow profile.

By mapping both metrics across all 20 modeled cases, this analysis reveals which scenarios offer not only strong revenue surpluses, but also timely, risk-adjusted financial returns. This joint examination helps differentiate between merely "profitable" projects and those that are truly financeable under commercial expectations.

3.2 Lifetime Profit vs NPV by Case

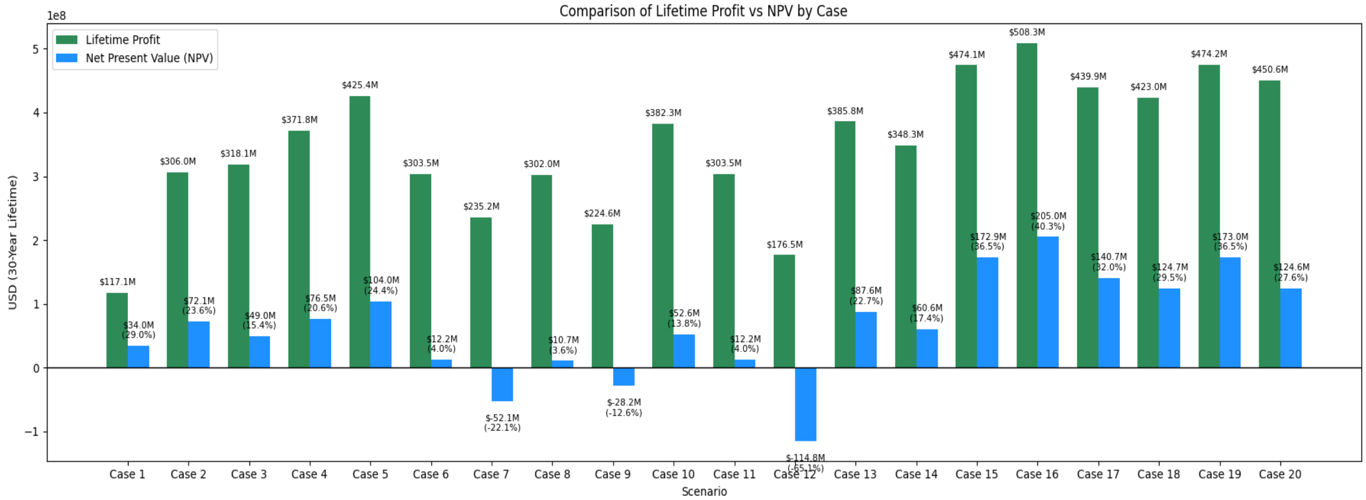

Figure 2: Comparison of Lifetime Profit vs NPV by Case

Figure 2 presents a comparative analysis of Lifetime Profit and Net Present Value (NPV) across all 20 modeled geothermal scenarios. Several key insights emerge from the comparison between the two variables.

- **Divergence in Profit vs. Value**: Although many scenarios report strong lifetime profits exceeding $300 million, their NPVs vary widely. For example, Case 5 demonstrates robust profitability but yields a much lower NPV than Cases 15 and 16. This suggests that profit generated later in the project lifecycle, especially under high upfront CAPEX, has diminished financial weight due to discounting.

- **Delayed Returns Diminish Value**: Cases 6–12 show relatively high total profits ($220M–$310M) yet severely underperform in terms of NPV. In Case 12, despite generating over $176 million in total profit, the NPV is deeply negative due to prolonged payback times and capital costs. This confirms that late-stage cash flow, though nominally significant, contributes far less to financial feasibility.

- **Optimized Cases Lead on Both Fronts**: The most favorable outcomes are observed in Cases 15 and 16, which not only post the highest profits (over $470M and $508M, respectively), but also deliver the strongest NPVs with over $170 million and $200 million. These cases align efficient cash flow timing, low breakeven years, and disciplined cost management, translating efficient operational performance into high investment appeal.

- **Financial vs. Operational Success**: This analysis demonstrates that high electricity generation or raw profit figures alone do not equate to favorable investment conditions. Financial success in geothermal development hinges on synchronizing cost structure, cash flow timing, and incentive leverage to maximize early returns.

These findings illustrate that NPV and Lifetime Profit must be evaluated in tandem to gain a superior understanding of the economic viability of a project. Scenarios that delay cash flow recovery or require excessive upfront capital may appear profitable on paper but often fail to meet investor thresholds without strategic optimizations.

3.3 NPV vs. Breakeven Time

As discussed below, Figure 3 reframes the economic results through a commercialization lens by plotting NPV against breakeven time, with threshold lines defining an "investment-grade" region (NPV ≥ $100M and breakeven ≤ 10 years). Several patterns emerge.

- **Optimized Cases Dominate the Investable Region:** Cases 15–20, which employ Water-Alternating-Gas and Huff-n-Puff operational strategies, cluster in the upper-left quadrant of the plot. These scenarios consistently meet or exceed both commercial thresholds, demonstrating that high returns and rapid capital recovery are achievable when CO_2 utilization is actively constrained through optimized fluid cycling. Case 16 lies furthest into the high-return/fast-payback zone, indicating that the combination of strong NPV and rapid capital recovery is achievable when CO_2 use is constrained through optimized project design. This finding aligns with the earlier cost–revenue profit figure, where these cases succeed not because they maximize gross revenue, but because they preserve margins by lowering cost intensity.

- **Positive NPV Alone Does Not Ensure Commercial Viability:** Several mid-range scenarios (e.g., Cases 2–5 and 13–14) exhibit positive NPVs but fall outside the ideal quadrant due to extended breakeven periods of 11–13 years. This reinforces the interpretation from the previous figure (Lifetime Profit vs NPV by Case): projects can generate substantial total profit over 30 years yet still underperform from an investment standpoint when capital recovery is delayed.

- **Unoptimized CO_2 Deployment Exhibits Failures:** The lower-right quadrant isolates scenarios characterized by slow payback and weak or negative NPV, including Cases 7, 9, and 12. Case 12 represents the most severe economic breakdown, combining the longest breakeven horizon with a deeply negative NPV. When viewed alongside the stacked cost–revenue–profit breakdown, these outcomes reflect excessive CAPEX and OPEX burdens that suppress liquidity and extend recovery beyond typical commercial tolerances.

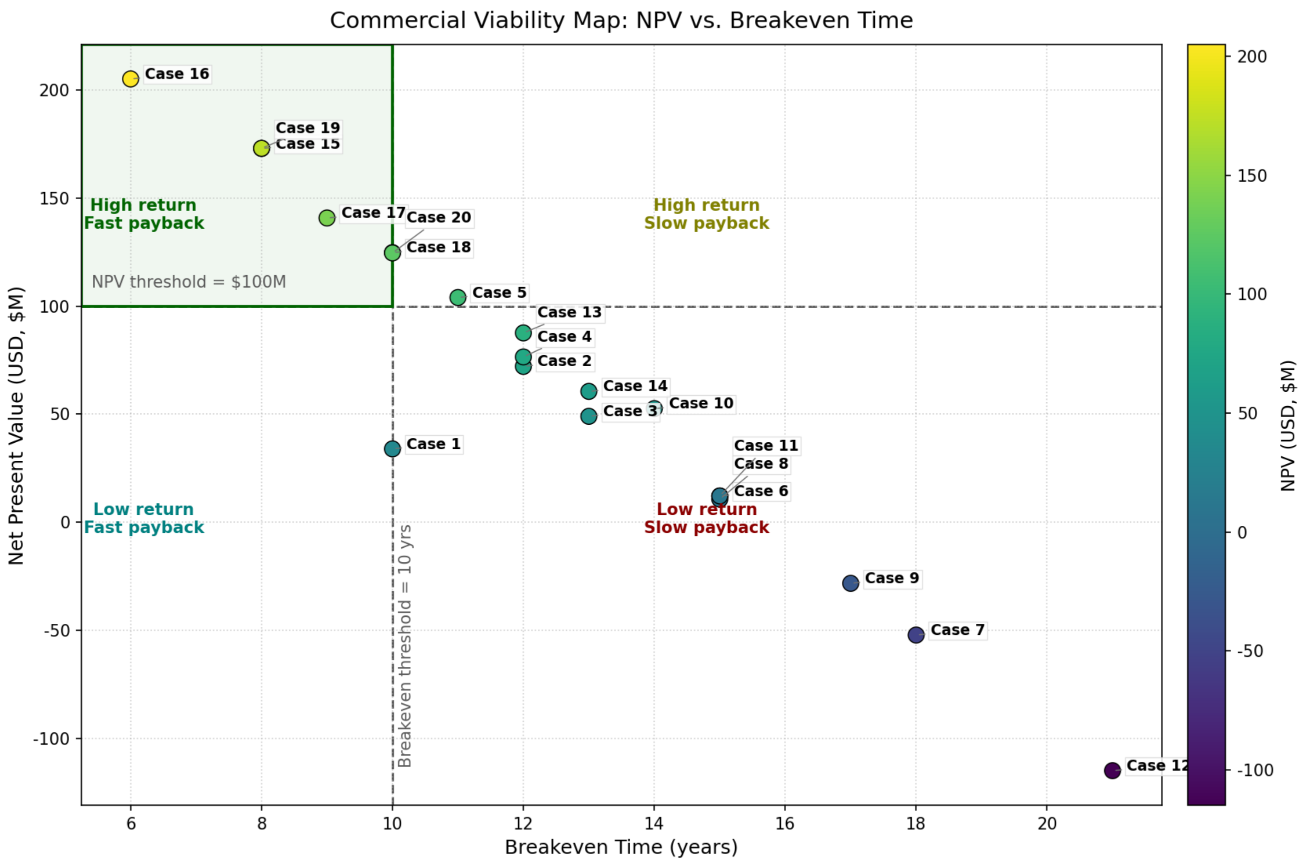

Figure 3: Commercial Viability Map: NPV vs. Breakeven Time

3. CONCLUSIONS AND FUTURE WORK

This study provides a techno-economic evaluation of carbon dioxide (CO_2) versus water as working fluids in next-generation geothermal systems, exploring 20 distinct scenarios that vary by fluid selection, injection strategy, capital intensity, and incentive structure. By integrating metrics such as Net Present Value (NPV), lifetime profit, breakeven year, cash flow, and levelized cost of electricity (LCOE), the analysis captures not only the financial magnitude of potential returns but also their timing and risk profile, key concerns investors, developers, and policymakers alike.

Key takeaways:

- CO_2 Substitution Alone is Insufficient: Simply replacing water with CO_2 (e.g., Case 2) yields only marginal improvements over the water baseline (Case 1), demonstrating that system-level redesign is required to gain the most value.

- Operational Strategy Drives Value: Cases employing WAG or Huff & Puff injection methods (e.g., Cases 15–20) achieved the highest NPVs, up to $205 million and the shortest breakeven times (as little as 6 years). This shows that fluid control strategies, and not necessarily through output maximization, can be the key to economic success.

- A commercialization screen separates cases. The NPV vs. breakeven viability map highlights an "investment-grade" region (NPV ≥ $100M and breakeven ≤ 10 years) that is predominantly occupied by the optimized operational cases. In contrast, high-consumption or poorly constrained CO_2 scenarios fall outside this region, reflecting payback horizons that are unlikely to meet commercial return requirements.

- Profit Timing Is Critical: While many scenarios reported high lifetime profits, their NPV margins varied dramatically. Using case 12 as an example again, it generated over $176 million in profit but had an NPV of –$114.8 million due to delayed returns and high upfront costs. This reinforces that early cash flow recovery is essential for financial feasibility.

- Cost Structure Sensitivity: The system's performance is highly sensitive to capital and operational costs. Cost-optimized cases (e.g., 13–14) outperformed several high-revenue scenarios, proving that profitability hinges more on cost control than gross output.

- Incentives Remain Crucial: The analysis showed that the Section 45Q tax credit plays a pivotal role in achieving positive NPVs, particularly in CO_2-based systems. Without it, breakeven timelines stretch and profitability erodes, especially in capital-intensive configurations.

- NPV Margin as a Decision Tool: Expressing NPV as a share of lifetime profit emerged as a valuable metric to distinguish financially investable scenarios from nominally profitable but economically inefficient ones. Margins above 30% consistently aligned with early breakeven and capital efficiency.

Ultimately, this study concludes that CO_2-based geothermal systems can dramatically outperform water-based systems, but only when coupled with optimized fluid management, disciplined cost structures, and supportive policy frameworks. Projects that ignore these dimensions may appear profitable in the long run but fail to meet the near-term investment thresholds necessary for deployment.

Future research should focus on pilot scale demonstrations that can confirm and refine model assumptions, mainly homing in on CO_2 storage integrity, subsurface behavior, and large expenditures. Advancing integrated simulation frameworks that can dynamically capture evolving cost structures, fluid losses, and complex operational strategies would significantly enhance the reliability of techno-economic assessments. Finally, more comprehensive environmental and geological risk assessments are critical to addressing overall concerns and supporting broader deployment of CO_2-enhanced geothermal systems.

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