|  |  |
| --- | --- |
| cetlogo ***CHEMICAL ENGINEERING TRANSACTIONS*** ***VOL. xxx, 2025*** | A publication ofaidiclogo_grande |
| The Italian Associationof Chemical EngineeringOnline at www.cetjournal.it |
| Guest Editors: David Bogle, Flavio Manenti, Piero SalatinoCopyright © 2025, AIDIC Servizi S.r.l.**ISBN** 979-12-81206-21-2; **ISSN** 2283-9216 |

“Are Microbes Going to Eat My Investment?”: An Economic Assessment of Microbial Activity in Underground Hydrogen Storage

Victoria Dimuro Duckwitza,\*, Nicola Paltrinieria, Khine Kyawb

a *Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, 7030 Trondheim, Norway*

b *NTNU Business School, Norwegian University of Science and Technology, 7030 Trondheim, Norway*

 victoria.d.duckwitz@ntnu.no

In the context of the energy transition and the growing need for energy security, underground hydrogen storage (UHS) emerges as a promising approach to address the intermittency of renewable energy sources and seasonal demand fluctuations. Despite the technical feasibility of UHS, microbial communities present in the subsurface pose potential problems, since these microbes can lead to hydrogen loss, impurity production, biocorrosion, among others, all of which involve economic and operational challenges. While many studies focus on technical viability, this study examines the economic impact of microbial activity. This paper presents an integrated techno-economic model that analyzes four microbial-activity and losses scenarios (Null, Low, Medium, High) into cash-flow forecasts for the three UHS options by comparing the levelised cost of storage (LCOS), net present value (NPV) and internal rate of return (IRR) for the different categories. Outcomes indicate that aquifers require additional purification systems, resulting in a more pronounced economic difference between scenarios. Salt caverns, due to their low microbial activity, lead to smaller economic impacts. In gas depleted fields, where hydrogen is expected to mix with residual native gases, separation units are already necessary regardless of microbial influence, therefore, the economic impact arises from the loss of hydrogen rather than the addition of equipment.

* 1. Introduction
		1. Energy-system context

Decarbonization, energy security, and affordability define today’s energy-sector "trilemma." Their simultaneous pursuit accelerates the deployment of renewable power and electrification, but it also magnifies the mismatch between variable generation and end-use demand, especially across different seasons and large-scale energy storage, therefore, becomes critical. Hydrogen emerges as a versatile energy carrier because surplus renewable electricity can be converted to H₂ and later reconverted to power or used directly in hard-to-abate sectors (IEA, 2023). Underground energy storage is widely regarded as a scalable long-duration option, already enhancing natural gas security. Preliminary technical studies indicate that these facilities can be repurposed for hydrogen with some adaptations (Yousefi et al., 2023). However, large-scale demonstrations for hydrogen are still rare, causing significant uncertainty regarding costs and operability.

Three geological settings dominate techno-economic screening for underground hydrogen storage (UHS):

Salt caverns (SC), artificial cavities formed in rock salt, offer low permeability to hydrogen, making them a suitable option for sealing. Depleted gas fields (DGF), existing hydrocarbon traps with established flow paths, secure caprock integrity, and a well-stocked network, are suitable for seasonal storage due to their larger pore volumes. Aquifers (Aq) are regionally extensive formations that share operational limits with DGFs, but there is less historical data; therefore, their sealing capacity and microbial inventory requieres closer scrutiny (Kruck & Crotogino, 2013).

* + 1. Microbial activity in subsurface H₂ storage

Injecting pure hydrogen creates an energy-rich niche for hydrogenotrophic microorganisms. Five metabolic groups dominate: sulfate-reducing bacteria (SRB), methanogenic archaea, homo-acetogenic bacteria, iron-reducing bacteria (IRB) and nitrate-reducing bacteria (NRB). Each pathway consumes H₂ and yields a specific product: H₂S, CH₄, acetate, Fe²⁺/FeS or N₂ (Hystories, 2023a) These products can degrade gas quality, corrode equipment or trigger clogging, among other undesired effects (Hystories, 2023b). Laboratory incubations report hydrogen losses from < 0.1 % per year in halite brines to > 30 % per year in sulfate-rich sandstones at 35 °C (Dopffel et al., 2021). Microbial growth is constrained by temperature, salinity, pH, nutrient availability, and electron-acceptor supply; therefore, robust classification is essential.

Microbial losses are not the only ones; hydrogen can also be lost via geochemical, physical and structural sinks. Geochemical reactions include carbonate dissolution, pyrite reduction and adsorption. There are also physical losses like diffusion through the seal or dissolution in brine. Structural losses from capillary and hysteretic trapping can happen several percent of hydrogen per cycle (Indro et al., 2024). Understanding these parallel processes is essential since economic studies concentrate on the net recoverable hydrogen.

Against this background, the present paper quantifies how microbial activity and other losses alters the cost competitiveness of the principal UHS types. An integrated techno-economic model couples the loss envelope, purification-train decision logic, and discounted cash-flow analysis to compute the levelized cost of storage (LCOS), net present value (NPV), and internal rate of return (IRR) under four microbial scenarios (Null–High).

* 1. Methodology
		1. Storage types and baseline designs

Three geological options are modeled: salt caverns (SC), depleted-gas fields (DGF), and aquifers (Aq). They provide the best combination of capacity and technical maturity; other underground options, such as depleted oil fields and mined cavities, were excluded due to higher risks of contamination and costs. All three baselines assume amount of hydrogen injected per year over a 30-year lifespan. The cushion gas requirement, well counts, and other technical storage site parameters follow HyStories' “mid-case” values (Hystories, 2023c). The boundaries span the injection to the delivery part downstream of purification; hydrogen production, long-distance transport and end-use are out of scope except where purity specifications must be met. The results provide an estimate of the microbial activity costs that investors could assign to future European UHS projects.

* + 1. Microbial-activity scenarios

Based on a review of various literature documents, this study adopts a four-tier envelope (Classes A–D) that filters first on temperature and salinity and then refines the score by sulfate, dissolved inorganic carbon, pH and nutrient status.

A quick data screen assigns any candidate reservoir to one of four microbial-risk bands:

* Thermal gate. Above ≈ 122 °C field is sterile (class A); between 90 – 122 °C only thermophiles survive and biological H₂ loss is negligible (class B) (Thaysen et al., 2023).
* Salinity gate. Below 90 °C, activity is throttled if brine salinity exceeds ≈ 100 g/L; such saline settings permit only slow halophilic sulfate-reducers or acetogens (class C), if the salinity exceeds ≈ 400 g/L, is again sterile (class A) (Hystories, 2023d).
* Active window. When both temperature is < 90 °C and salinity < 100 g/L, the full suite of hydrogenotrophs can flourish, giving the highest risk of H₂ consumption (class D).
* Modifiers. The preliminary score shifts up if sulfate (> 1.25 g/L) or dissolved inorganic carbon (> 5 mM) is abundant, and down if pH is extreme (< 4.5 or > 10) or nutrients are depleted (Hystories, 2023d).

These simple gates translate routine formation data (temperature, salinity, sulfate, pH) into an expected range of microbial hydrogen loss that can be fed directly into techno-economic models.

Salt caverns are hypersaline brines which drive Class C in the lower salinity cases; residual SRB can generate trace H₂S but annual H₂ loss would be low. Deep depleted gas fields with temperatures between 80–120 °C and sulfate depletion place DGFs on the A/B boundary; fields at 30–60 °C shift to C or D depending on salinity.

Aquifers in the range of 40–120 °C, moderate to high salinity and frequent sulfate > 0.5 g/L make many aquifers Class D, explaining higher biotic-loss risk (Dopffel et al., 2021).

* + 1. Quantification of losses

Since literature shows high variability of hydrogen losses, ranging from zero hydrogen consumption to significant losses >30 %, four cases for each of these storage types were set in an effort to cover this variability: Null (N) a baseline case with no losses used for comparison, low (L), medium (M) and high (H) losses. Storage sites with environmental conditions that categorize them as A and B are considered Null, while facilities classified as C and D can range from Low to High. The percentual annual lost assumed for each process and storage type are displayed in Table 1 and Table 2.

Table 1: Annual percentage of microbial activity losses assumed for each storage type and different cases low (L), medium (M) and high (H)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Process | DGF (L) | DGF (M) | DGF (H) | SC (L) | SC (M) | SC (H) | Aq (L) | Aq (M) | Aq (H) |
| Methanogenesis | < 0.1  | 3 | 15 | < 0.5 | 1 | 3 | < 0.1  | 4 | 15 |
| Acetogenesis | < 0.05 | 1 | 5 | < 0.2 | 1 | 2 | < 0.05 | 2 | 6 |
| Sulfate reduction | < 0.1 | 1 | 5 | < 0.5 | 3 | 8 | < 0.5 | 4 | 15 |
| Iron reduction | < 0.1 | 1 | 3 | 0 | 0 | 0 | < 0.1 | 1 | 5 |
| Denitrification | < 0.05 | 0.3 | 1 | 0 | 0 | 0 | < 0.05 | 0.5 | 2 |

Table 2: Annual percentage of other losses assumed for each storage type and different cases low (L), mid (M) and high (H)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Process | DGF (L) | DGF (M) | DGF (H) | SC (L) | SC (M) | SC (H) | Aq (L) | Aq (M) | Aq (H) |
| Geochemical losses | < 0.05 | 0,3 | 0,5 | 0,0 | 0,0 | 0,0 | < 0.1 | 0,5 | 1,0 |
| Physical losses | < 0.05 | 1 | 2 | 0,0 | 0,1 | 0,2 | < 0.4 | 1 | 2 |
| Structural losses | 1 | 3 | 5 | 0,0 | 0,0 | 0,0 | 3 | 5 | 10 |

All this information is used to calculate the withdrawal flow rate and composition, allowing for the selection, sizing, and quantification of the costs associated with purification equipment and the total hydrogen that can be exported after accounting for all losses to estimate yearly profits.

* + 1. Purification and tail-gas handling logic



*Figure 1: Hydrogen mixture path after withdrawal from UHS, main purification equipment*



*Figure 2: Tail gas from PSA unit, proposed handling options and outputs*

Microbial activity happens during the storage time, therefore the processes and equipment affected are going to be the ones after withdrawal. All withdrawal streams pass through a base train: coalescing filter → guard bed→ dehydration unit, to remove liquids, H₂O, and trace H₂S. If H₂S exceeds 20 ppm, an MDEA absorber is required before polishing with the guard bed. If overall H₂ purity after these treatments falls below 99.5%, a PSA unit is necessary. The gas is still at almost storage pressure when it arrives at the PSA, which requires lower values to function. Therefore, a turbo-expander is considered; this piece of equipment incurs capital expenditures but reduces electrical consumption or generates a new income stream by selling the electricity. PSA tail gas is the byproduct of the hydrogen that wasn’t recovered in the main stream (H₂ plus mostly CH₄). For the tail gas, three handling options are considered: grid injection, reinjection, or onsite power. For simplicity, the gas reinjection option is used in the calculation, which requires a compressor, thereby impacting both capital and operating expenses. Equipment performance assumptions (99.99 % H₂S removal in guard bed and MDEA, 98 % dryer efficiency, negligible pressure drop) come from vendor data collated, as well as compressors and expanders' efficiencies. A diagram of the process is depicted in Figure 1 and Figure 2. Together, these methodological blocks translate microbial activity into surface equipment, cash flows and, ultimately, economic impact for each UHS type.

* + 1. Techno-economic model

A discounted cash flow (DCF) framework is used to evaluate each site's scenario. Cash flow components are:

CAPEX: baseline subsurface and surface costs derived from the HyStories project equations plus extra surface equipment driven by microbial activity. Equipment costs are adjusted using the Capital Cost Scaling Methodology, where cost estimates are scaled from reference system configurations, Eq (1).

OPEX: fixed + variable; extra power to run PSA and tail-gas systems is scenario-dependent.

ABEX & residual value: plug-and-abandon costs plus cushion-gas sale after the life span of the site.

|  |  |
| --- | --- |
| $$SC=RC\*\left(\frac{SP}{RP}\right)^{exp}\*\frac{CEPCI\_{SY}}{CEPCI\_{RY}}$$ | (1) |

Where: Exp (Exponent) it takes into account the economies of scale, for which as equipment size increases, the cost per unit of capacity decreases. RC (Reference Cost) is the base cost of equipment. RP (Reference Parameter) is a key equipment specification strongly correlated with cost, used to scale estimates across different unit sizes. SP (Scaled Parameter) is a parameter of the same type as the reference parameter, specific to the process scale being evaluated. SC (Scaled Cost) is the estimated cost for the specific process being analyzed, adjusted from the reference cost. CEPCI (Chemical Engineering Plant Cost Index) will be used to ajust historical cost estimates by accounting for inflation and fluctuations in equipment, labor, and material costs over time. RY: Reference year. SY: Study year.

The net present value (NPV) is the algebraic sum of the levered free-cash-flow (FCF) for each year t as shown in Eq (2). A positive NPV indicates that the project earns more than its required return (Brealey et al., 2019).

|  |  |
| --- | --- |
| $$NPV=\sum\_{t=0}^{N}\frac{FCF\_{t}}{(1+WACC)^{t}}$$ | (2) |
| $$FCF\_{t}=Operating CF\pm Financing cash flows\pm Investment cash flows$$ | (3) |

Where: Investment cash flows are composed by the negative CAPEX in the construction years, any mid-life replacement CAPEX, the positive residual value (scrap-value plus cushion gas sale) in the final year and the negative ABEX also in the final year. Operating cash flows is the annual revenue from the storage tariff of hydrogen (and less relevant, the electricity sold from the turboexpander), minus the OPEX. Financing cash flows are the senior debt drawdown in year 0 and scheduled principal repayments thereafter, interest is treated as an expense in the operating section so it is not repeated here. (HyStories Project, 2023e)

The amount of hydrogen to export is calculated considering microbial losses, geochemical, physical and structural losses and the hydrogen that is reinjected as part of the tail gas in case a PSA unit was needed.

The Levelized Cost Of Storage (LCOS) is calculated with Eq (4):

|  |  |
| --- | --- |
| $$LCOS=\frac{\sum\_{}^{}(CAPEX\_{t}+OPEX\_{t}+ABEX\_{t})\*(1+WACC)^{-t}}{\sum\_{}^{}H\_{2} to export\_{t}\*(1+WACC)^{-t}}$$ | (4) |

While the Internal rate of return (IRR) is the discount rate that drives the same NPV to zero, in practice it is the project’s break-even yield (Brealey et al., 2019).

NPV, IRR and LCOS are discounted at the project WACC of 7.6%; WACC is built from 61.5 % senior debt, 38.5 % equity and market-aligned coupons, a corporate tax of 25.7% following standard project-finance practice (Penev et al., 2024).

The business model chosen for a UHS facility strongly affects its financial performance, revenue stability, and risk profile. In this case a tolling model was used, in which the storage operator acts as a infrastructure provider. The client delivers hydrogen, pays a fee for storage services, and retrieves the hydrogen later. Also, the allocation of the costs of hydrogen losses follows a model in which they are absorbed by the client who accepts that they will not recover 100% of the injected hydrogen.

* 1. Results and discussion

Table 3: Null case results presented as base case for each storage site (no microbial activity or losses)

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | DGF | Aq | SC |
| H2 export (kg/yr) | 41,122,874 | 46,922,974 | 46,816,331 |
| NPV (k€) | 263,647 k€ | 371,368 k€ | 385,900 k€ |
| IRR | 17.93% | 29.63% | 33.69% |
| LCOS (€/kg) | 2.45 € | 1.81 € | 1.67 € |

As shown in Table 3 in the absence of microbial activity or hydrogen losses (null case), SC demonstrates the most favorable economic performance among the three storage types, achieving the lowest LCOS at 1.67 €/kg, followed by Aq at 1.81 €/kg and DGF at 2.45 €/kg. This economic advantage is primarily attributed to higher hydrogen export volumes and lower purification requirements in aquifers and salt caverns. In contrast, DGF scenarios require PSA units to remove residual native gases, reducing net exportable hydrogen and raising purification costs. While repurposing existing infrastructure in DGF sites is technically feasible, it was excluded from this study to ensure conservative and generalizable assumptions, considering the facilities would be built from scratch. It is also important to note that the favorable LCOS of salt caverns partially reflects their operational model, which enables more than one full cycle per year for reaching the same injection amounts than porous media (SC: 2.2 cycles/year vs. DGF & Aq: 1 cycle/year), thus allowing higher use of the capacity installed and improved economic efficiency. The results below highlight only the variations from those base figures to maintain clarity in comparison, emphasizing how each case shifts in relation to different microbial activity scenarios.

Table 4: Variations considering microbial activity and losses (Null-High) within the depleted gas field

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Low-Null | Medium-Null | High-Null |
| Δ H2 export (kg/yr) | -420,070 | -2,923,749 | -10,126,414 |
| Δ NPV (k€) | -11,845 k€ | -41,684 k€ | -127,551 k€ |
| Δ IRR | -1.60% | -3.54% | -9.35% |
| Δ LCOS (€/kg) | 0.11 € | 0.27 € | 0.88 € |

Table 5: Variations considering microbial activity and losses (Null-High) within the aquifer.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Low-Null | Medium-Null | High-Null |
| Δ H2 export (kg/yr) | -1,295,390 | -8,374,705 | -19,810,745 |
| Δ NPV (k€) | -22,650 k€ | -134,531 k€ | -269,900 k€ |
| Δ IRR | -3.13% | -13.98% | -23.37% |
| Δ LCOS (€/kg) | 0.13 € | 0.81 € | 1.85 € |

Table 6: Variations considering microbial activity and losses (Null-High) within the salt cavern

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Low-Null | Medium-Null | High-Null |
| Δ H2 export (kg/yr) | -25,492 | -386,425 | -4,094,628 |
| Δ NPV (k€) | -6,790 k€ | -11,380 k€ | -82,665 k€ |
| Δ IRR | -2.16% | -2.58% | -11.61% |
| Δ LCOS (€/kg) | 0.07 € | 0.09 € | 0.51 € |

From Table 4 to Table 6 it can be seen that including microbial activity negatively impacts all three storage types economically. As biological activity increases from low to high levels, all scenarios exhibit lower hydrogen exports, decreasing NPV/IRR, and a higher levelized cost of storage are observed. Aquifers prove the most sensitive: while they offer strong baseline economics in the absence of microbial interference, medium and high microbial activity levels result in significant gas purity degradation, necessitating costly purification steps such as MDEA and PSA units. This leads to a sharp LCOS increase of up to +1.85 €/kg in the high case. Salt caverns, by contrast, demonstrate greater resilience; their LCOS remains relatively stable under low and medium microbial activity and only escalates under high microbial activity conditions when additional purification becomes necessary. Depleted gas fields present a unique case, as they require PSA treatment regardless of microbial activity due to the presence of native methane.

These findings highlight a critical economic vulnerability in UHS projects, particularly when microbial risks are not adequately mitigated. For all storage types, microbial hydrogen consumption and impurity generation not only diminish storage efficiency but also substantially reduce profitability. The sharp rise in LCOS, particularly in aquifers and depleted fields, highlights a systemic risk: if microbial impacts are underestimated, the economic viability of hydrogen storage projects could fail. This is particularly problematic for green hydrogen markets, which are already struggling with cost parity, and such vulnerabilities may stop investors or offtakers, ultimately slowing hydrogen adoption and jeopardizing broader decarbonization goals.

* 1. Conclusions

The modeling shows that microbial activity creates an uneven economic burden on underground hydrogen storage, light for salt caverns, moderate for depleted gas fields, heavy for saline aquifers. Lost hydrogen and extra purification equipment are the dominant drivers of economic degradation. A quick-look temperature–salinity screening can flag high-risk reservoirs early and guide site selection. Treating microbial activity as a design variable, supported by the right purification equipment, preserves the role of underground hydrogen storage as a robust pillar of a decarbonised energy system.

Nomenclature

LCOS – levelised cost of storage (€ kg⁻¹)

NPV – net present value (€)

IRR – internal rate of return (%)

WACC – weighted average cost of capital (%)

UHS – underground hydrogen storage

SC – salt cavern

DGF – depleted gas field

AQ – aquifer

CAPEX – capital expenditure

OPEX – operating expenditure

NPC – net present cost

ABEX – abandonment expenditure

PSA – pressure swing adsorption unit

MDEA – N-methyldiethanolamine absorber

SRB – sulfate-reducing bacteria

IRB – iron-reducing bacteria

NRB – nitrate-reducing bacteria

Yr – year

References

Brealey, R. A., Myers, S. C., & Allen, F. (2019). Principles of Corporate Finance (13th ed.). McGraw-Hill.

Dopffel, N., Jansen, S., & Gerritse, J. (2021). Microbial side effects of underground hydrogen storage – Knowledge gaps, risks and opportunities for successful implementation. International Journal of Hydrogen Energy, 46(12), 8594–8606. doi.org/doi.org/10.1016/j.ijhydene.2020.12.058

Hystories Project Consortium. (2023a). D3.2-0 – Changes in gas composition in micro habitat experiments as a result of microbial gas consumption. hystories.eu/publications-hystories/

Hystories Project Consortium. (2023b). D3.3-0 – Modelling of microbial H2 reactivity at lab and reservoir scale.

Hystories Project Consortium. (2023c). D7.1-1 – Conceptual design of salt cavern and porous media underground storage site.

Hystories Project Consortium. (2023d). D3.4-0 – Microbial risks and mitigation measures.

HyStories Project Consortium. (2023e). D8.1-1 – Joint Methodology for Individual EU Case Studies.

Indro, A. P., Sekar, L. K., Matey-Korley, G. V., Ikeokwu, C. C., & Okoroafor, E. R. (2024). A compilation of losses related to hydrogen storage in porous media: Implications for hydrogen recovery and productivity from saline aquifers. International Journal of Hydrogen Energy, 78, 1288–1305. doi.org/doi.org/10.1016/j.ijhydene.2024.06.365

International Energy Agency. (2023). Global Hydrogen Review 2023. www.iea.org/reports/global-hydrogen-review-2023

Kruck, O., & Crotogino, F. (2013). Benchmarking of Selected Storage Options (Issue Deliverable 3.3). arquivo.pt/wayback/20170622163935mp\_/http://hyunder.eu/wp-content/uploads/2016/01/D3.3\_Benchmarking-of-selected-storage-options.pdf

Penev, M., Gilbert, A., Rustagi, N., Kee, J., Koleva, M., & Chung, M. (2024). Capital Structure for Techno-Economic Analysis of Hydrogen Projects. doi.org/10.2172/2397248

Thaysen, E. M., Armitage, T., Slabon, L., Hassanpouryouzband, A., & Edlmann, K. (2023). Microbial risk assessment for underground hydrogen storage in porous rocks. Fuel, 352, 128852. doi.org/10.1016/j.fuel.2023.128852

Yousefi, S. H., Groenenberg, R., Koornneef, J., Juez-Larré, J., & Shahi, M. (2023). Techno-economic analysis of developing an underground hydrogen storage facility in depleted gas field: A Dutch case study. International Journal of Hydrogen Energy, 48(74), 28824–28842. doi.org/doi.org/10.1016/j.ijhydene.2023.04.090