

Supplementary file

Subsurface storage of CO₂, H₂ and natural gas: A review of site-selection criteria and decision-support approaches

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Appendix A: Case studies and applications

The following case studies illustrate how decision-support methods are applied in practice. Each case is presented using a consistent structure, including geological setting, decision-support methods applied, key outcomes, and lessons learned. The selected case studies are intended to represent different decision scales, storage contexts, and methodological approaches, rather than provide an exhaustive global survey.

Case 1: Gulf of Mexico - criteria-driven MCDM workflow for depleted reservoir CO₂ storage

Callas et al. (2022) present a scalable, criteria-driven workflow for screening and ranking depleted hydrocarbon reservoirs in the U.S. Gulf of Mexico for hub-scale CO₂ storage. The geological setting consists of mature offshore oil and gas reservoirs with large regional storage capacity, extensive existing infrastructure, and variable reservoir and seal characteristics.

The workflow begins with basin-scale screening of 1,317 fields using conservative technical and siting thresholds, including permeability, net thickness, seal presence, fault avoidance, and water depth constraints. This reduces the candidate pool by approximately 97%, leaving 31 fields that are grouped into ten geographic and stratigraphic clusters. These clusters are then evaluated using a weighted multi-criteria framework incorporating reservoir quality, seal redundancy, structural features, legacy well density, infrastructure proximity, and permitting context. Confidence factors are applied to account for data uncertainty, and an AHP-style interface enables weight adjustment and sensitivity analysis. For top-ranked clusters, rapid technical diagnostics, including Theis-based pressure estimates, caprock stability screening,

and statistical well-integrity risk models, are used to link ranking outcomes to physical feasibility.

The outcome is a prioritized set of candidate storage clusters, with Cluster 6 identified as the leading option due to favorable porosity, depth, multiple sealing units, and proximity to large CO₂ emission sources. The workflow demonstrates the ability to reduce a large regional inventory to a manageable shortlist while integrating both qualitative and quantitative criteria.

A lesson from this case is that combining transparent MCDM frameworks with rapid technical diagnostics enables efficient and auditable regional screening for CO₂ storage. However, results remain sensitive to threshold selection, data quality, and weighting assumptions, and must be followed by detailed site-specific characterization, dynamic simulation, and formal risk assessment before final investment decisions.

Case 2: Multi-criteria site selection of depleted gas fields for hydrogen storage in the United Kingdom

Harati et al. (2024) apply a criteria-driven, hybrid AHP-PROMETHEE workflow to rank 71 depleted gas fields across the United Kingdom for underground hydrogen storage. The study covers both offshore and onshore depleted reservoirs, including 61 offshore fields concentrated in the Southern North Sea, East Irish Sea, Central Graben, and Atlantic Margin, and 9 onshore fields located in the Cleveland, East Midlands, and Weald basins. Offshore assets dominate in capacity and deliverability, while onshore and near-shore fields offer potential advantages in cost and integration due to proximity to existing gas networks and emerging hydrogen infrastructure.

The approach integrates AHP for deriving expert-based weights and PROMETHEE for outranking-based ranking, enabling evaluation of trade-offs across eight criteria, including reservoir quality (porosity, permeability, net-to-gross), structural setting, hydrogen deliverability, working gas capacity, cushion-to-working ratio, and siting factors such as proximity to demand centers and renewable energy. Spatial analysis is performed using QGIS to quantify distances to hydrogen hubs and renewable resources. Prior to ranking, performance envelopes are assessed using hydrogen deliverability estimates calibrated against methane data from Hatfield Moors, accounting for hydrogen's lower density and viscosity.

The outcome is a ranked portfolio of candidate storage sites, with Cygnus identified as the leading option, followed by Hamilton, Saltfleetby, Corvette, and Hatfield Moors. High-performing sites are characterized by favorable reservoir quality, strong deliverability (often exceeding 100 million standard cubic meters per day), and large working capacities, although practical deployment is constrained by cushion-gas requirements, infrastructure availability, and economic considerations. The results also highlight trade-offs between offshore capacity and onshore accessibility, as well as the importance of proximity to renewable energy and hydrogen demand clusters.

A lesson from this case is that hybrid MCDM approaches can provide flexible and transparent decision-support tools for hydrogen storage planning, particularly when multiple competing criteria and uncertainties must be balanced. The ability to update AHP weights and PROMETHEE thresholds allows the framework to be iteratively refined as new data become available or policy priorities change, making it suitable for long-term, adaptive decision-making in emerging hydrogen systems.

Case 3: GIS-Based site selection of underground NG storage using fuzzy AHP-OWA in Iran

Sabzevari and Delavar (2017) develop a nationwide, spatially explicit framework to identify promising underground NG storage sites across Iran by combining expert judgment with geospatial data. The study operates at a national scale and does not focus on specific reservoir types, but rather on spatial patterns of demand, infrastructure, and accessibility that govern early-stage storage feasibility. This reflects a planning context where subsurface data are limited, and site selection is driven initially by surface and network considerations.

The framework integrates Fuzzy AHP to derive expert-based weights and quantifier-guided Ordered Weighted Averaging within a GIS environment to aggregate spatial layers. Ten experts perform pairwise comparisons of six criteria (gas consumption, population density, distance to production centers, pipelines, transport networks, and temperature) using linguistic judgments represented as triangular fuzzy numbers. These are defuzzified into a consistent weight set, with demand-related factors (gas consumption and population density) receiving the highest importance. The weighted criteria are then translated into standardized raster layers and combined using quantifier-guided Ordered Weighted Averaging, allowing planners to explore different risk attitudes through adjustable aggregation strategies ranging from opportunistic (OR-like) to conservative (AND-like) decision rules.

The outcome is a set of national suitability maps identifying consistent high-potential regions in the northeast, west, and Tehran-Alborz corridor, where demand aligns with infrastructure. Validation against ten existing underground gas storage facilities and feedback from thirty experts shows that the model reproduces real-world siting patterns, particularly under conservative aggregation settings. The results also demonstrate that suitability rankings

are sensitive to risk preferences, highlighting the importance of flexible aggregation logic in planning.

A lesson from this case is that GIS-based fuzzy MCDM frameworks are highly effective for early-stage, large-scale screening when subsurface data are sparse. By explicitly incorporating uncertainty and stakeholder preferences, the approach provides transparent and adaptable decision support, although it remains limited to preliminary screening and must be followed by detailed geological characterization and simulation-based evaluation. The framework is transferable to other regions and can be extended to CO₂ or hydrogen storage planning, particularly in contexts where rapid, policy-driven site identification is required.

Cross-case insights

Taken together, these studies show that decision-support workflows are increasingly tailored to scale and data availability. The Gulf of Mexico case illustrates a staged regional screening process strengthened by quick-look technical diagnostics. The UK case shows how hybrid MCDM methods can support hydrogen storage ranking under competing technical and infrastructure priorities. The Iran case highlights the value of GIS-based fuzzy screening where national-scale planning must proceed before high-resolution subsurface data are available.

Across all three cases, several common themes emerge: transparency in criteria and weights, explicit treatment of uncertainty, sensitivity to data quality, and the importance of aligning method complexity with decision scale. These studies also show that no single method is sufficient on its own; rather, robust site selection generally depends on combining structured ranking, spatial screening, and, where needed, physics-based validation.

In addition to the detailed cases presented above, similar approaches have been applied in a range of other settings, further illustrating the general applicability of integrated decision-support workflows. For example, GIS-MCDM approaches have been used for CO₂ storage screening in China and Australia (Bradshaw et al., 2004; Chen et al., 2009; Cai et al., 2017; Feitz et al., 2017), while reservoir simulation-based evaluation has been applied to saline aquifers in the North Sea (Chadwick et al., 2008). Hydrogen storage studies in Germany and the United States have also explored combined geological and techno-economic screening frameworks, particularly for salt caverns and depleted reservoirs (Minougou et al., 2023). These additional applications, although not discussed in detail here, support the broader relevance of the framework across different gases, geological settings, and regulatory environments. Across these cases, common elements include the use of staged evaluation, integration of multiple criteria, and increasing reliance on simulation and uncertainty analysis at later stages. These shared features reinforce the value of a unified framework for comparing site-selection approaches across different contexts.

Appendix B: Supplementary tables

Table S1. Representative engineering cases illustrating storage behavior, operational constraints across CO₂, H₂, and NG storage systems.

Project	Gas	Formation	Status / Maturity	Representative conditions	Key references
Teesside Hydrogen Storage Caverns (UK)	H ₂ (>95%-99.9%)	Bedded salt caverns in Permian Boulby Halite	Operating; Commercial	Depth: 350-400 m; Pressure: 15-50 bar; Temperature: 15-20 °C; Combined cavern volume: 70,000-95,000 m ³ ;	Cagluyan et al., 2020; Heinemann et al., 2021; Williams et al., 2022

				Cushion gas: 20%-30%; High- frequency industrial cycling	
Clemens Dome Hydrogen Storage Project (USA)	H ₂ (>95%- 99.9%)	Salt cavern in Gulf Coast salt dome	Operating; Commercial	Depth: 850 m; Pressure: 70-135 bar; Temperature: 40- 45 °C; Cavern volume: 580,000 m ³ ; Working capacity: 2,500 tH ₂ ; Cushion gas: 30%-35%; High-frequency cycling	Delshad et al., 2021; Ibrahim et al., 2025; Panfilov, 2016
Moss Bluff Hydrogen Storage Facility (USA)	H ₂ (>95%- 99.9%)	Salt cavern in Gulf Coast salt dome	Operating; Commercial	Depth: 790-850 m; Pressure: 55- 152 bar; Temperature: 42- 46 °C; Cavern volume: 566,000 m ³ ; Working capacity: 3,500 t H ₂ ; Cushion gas: 30%-35%; High- frequency cycling	Hematpur et al., 2023; Ibrahim et al., 2025; Liebscher et al., 2016; Seyed Ghafouri et al., 2026
Rough Gas Storage Facility (UK)	NG (current); proposed H ₂ storage	Depleted Rotliegende sandstone reservoir (Southern North Sea)	Operating for NG; H ₂ evaluation/trans ition studies ongoing	Storage capacity: 54 bcf NG; Restarted operation in 2022; Offshore depleted reservoir	Heinemann et al., 2025; Jutila et al., 2024; O' Shea, 2022

Spindletop Hydrogen Storage Caverns (USA)	H ₂ (>95%-99.9%)	Salt cavern in Gulf Coast salt dome	Operating; Commercial	Depth: 850-1,500 m; Pressure: up to 150 bar; Temperature: 45-55 °C; Cavern volume: 600,000 m ³ ; Cushion gas: 30%-35%; High-frequency cycling	Jahanbakhsh et al., 2024; Minougou et al., 2023
Underground Sun Storage / USS 2030 (Austria)	H ₂ -NG blends; progressing toward pure H ₂	Depleted gas reservoir / porous sandstone	Active demonstration; pre-commercial	Depth: 1,000-1,050 m; Pressure: 65-80 bar; Temperature: 40 °C; Working gas capacity: 1.2 million m ³ / 4.2 GWh; Cushion gas: 60%; Seasonal cycling	Madirisha and Ikotun, 2024; Malki et al., 2024; Wang et al., 2026
HyStock (Netherlands)	H ₂	Salt caverns in Zechstein salt dome	Under development; large-scale demonstration / planned commercial storage	Depth: 1,200 m; Pressure: planned high-pressure operation, up to 150-180 bar; Temperature: 45-50 °C; Planned capacity: 5,000-6,000 t H ₂ per cavern; Cushion gas: 30%-35%; Designed for rapid cycling and grid balancing	Qian et al., 2025; Wang et al., 2026

Diadema UHS Project (Argentina)	H ₂ /CH ₄ blend (~10% H ₂)	Depleted porous sandstone reservoir	Demonstration / Pilot; active since ~2008	Depth: 815 m; H ₂ concentration: 10%; Pressure: NR; Capacity: NR	Burtonshaw et al., 2024; Perez et al., 2016; Zivar et al., 2021
Kiel-Gaarden Cavern (Germany)	Historical town gas (~60-65% H ₂ with CH ₄ , CO, CO ₂); later NG	Salt cavern in Permian/Zechstein salt dome	Closed / decommissioned; Commercial	Depth: 1,330 m; Pressure: 45-100 bar; Temperature: 50-55 °C; Cavern volume: 32,000-37,000 m ³ ; Cushion gas: 25%-33%; Moderate-to-high frequency peak-shaving operation	Malki et al., 2024; Qian et al., 2025
Lille Torup Underground Gas Storage (Denmark)	NG (current); proposed H ₂ conversion	Salt caverns	Operating; Commercial	Operating since 1987; High-pressure salt cavern storage (65-180 bar reported); Existing NG infrastructure under evaluation for H ₂ conversion	Garcia et al., 2024
Sleipner CO ₂ Storage Project (Norway)	CO ₂	Offshore saline aquifer (Utsira Formation)	Operating; Commercial (1996-present)	Depth: 800-1,000 m; Pressure: 100-110 bar; Temperature: 29-41 °C; Injection: 1 Mt CO ₂ /yr; Continuous injection; High-purity CO ₂ (>98%)	Cavanagh and Haszeldine, 2014; Eiken et al., 2011; Furre et al., 2017; Zhang et al., 2022

Ketzin Pilot Site (Germany)	CO ₂ (historical NG site; used as analogue for H ₂ simulations)	Deep saline aquifer (Upper Triassic Stuttgart Formation; heterogeneous fluvial sandstone)	Closed; Pilot / research-scale (CO ₂ injection: 2008-2013)	Depth: 630-650 m; Pressure: 62 bar baseline, up to 68-78 bar during injection (<85 bar cap); Temperature: 33-35 °C (CO ₂ injected at 40°C); Capacity: 67.3 kt CO ₂ injected; Non-cyclic operation	Liebscher et al., 2013; Martens et al., 2012; Möller et al., 2014; Prevedel et al., 2014
Beynes Underground Gas Storage Facility (France)	Historical town gas (50%-60% H ₂ with CH ₄ , CO, CO ₂); currently NG	Saline aquifer (Lower Cretaceous sandstone)	Operating as NG storage; historical H ₂ -rich storage phase closed; Commercial	Depth: 430 m; Pressure: 35-45 bar; Temperature: 25-27 °C; High cushion gas (50%-60%); Seasonal injection-withdrawal cycling	Hou et al., 2026; Panfilov, 2010; Ranchou-Peyruse, 2024; Wang et al., 2026; Wei et al., 2026
Weyburn-Midale CO ₂ Monitoring and Storage Project (Canada)	CO ₂	Depleted oil reservoir / carbonate reservoir with CO ₂ -EOR	Operating; Commercial with research-demonstration component	Depth: 1,400-1,500 m; Pressure: 140-150 bar; Temperature: 60-63 °C; >40 Mt CO ₂ injected; CO ₂ purity 96%; semi-cyclic CO ₂ recycling during EOR	Preston et al., 2005; Verdon et al., 2011; Whittaker et al., 2011; Zhou et al., 2005

In Salah CO ₂ Storage Project (Algeria)	CO ₂	Deep saline aquifer adjacent to producing gas reservoir (Tournaisian sandstone)	Injection suspended/closed; large-scale industrial demonstration	Depth: 1,800-1,900 m; Pressure: 175 bar initial, 210-240 bar during injection; Temperature: 90-95 °C; 3.8 Mt CO ₂ injected; Non-cyclic injection	Ringrose et al., 2013; Rutqvist et al., 2010; Stork et al., 2015; White et al., 2014
Quest CCS Project (Canada)	CO ₂	Deep saline aquifer (Basal Cambrian Sands)	Operating; Commercial	Depth: 2,000-2,300 m; Pressure: 200 bar initial; Temperature: 60 °C; Injection: 1-1.2 Mt CO ₂ /yr; >10 Mt CO ₂ stored; CO ₂ purity: >95%-99%; Non-cyclic injection	Brown et al., 2023; Smith et al., 2022; Tawiah et al., 2020
Illinois Basin-Decatur Project (USA)	CO ₂	Deep saline aquifer (Mount Simon Sandstone; Eau Claire shale seal)	Post-injection monitoring; large-scale demonstration	Depth: 2,130-2,150 m; Pressure: 200 bar baseline; Temperature: 50 °C; 1 Mt CO ₂ injected; CO ₂ purity: >99%; Non-cyclic injection	Bauer et al., 2016; Bondarenko et al., 2025; Finley, 2014
Snøhvit CCS (Norway)	CO ₂	Offshore deep saline aquifers (Tubåen and Stø formations)	Operating; Commercial	Injection since 2008; Depth: 2,300-2,700 m; Supercritical CO ₂	Chiaramonte et al., 2015; Li et al., 2024; Shi et al., 2013; Trémosa et al.,

Lobodice Underground Gas Storage Facility (Czech Republic)	Historical town gas (~54% H ₂ with CH ₄ , CO, CO ₂); currently NG	Saline aquifer / porous sandstone	Operating as NG storage; historical H ₂ -rich phase closed; Commercial	Depth: 400-500 m; Pressure: 40 bar; Temperature: 25-45 °C; Cushion gas: 50%-60%; Seasonal cycling	Buriánková et al., 2022; Kopal et al., 2016; Tremosa et al., 2023
Tuz Gölü Underground Natural Gas Storage Facility (Turkey)	NG	Salt caverns in thick salt dome	Operating and expanding; Commercial	Depth: 1,100-1,500 m; Pressure: up to 205-210 bar; Temperature: 53-55 °C; Caverns: 630,000-750,000 m ³ each; Cushion gas: 33%; Seasonal peak-shaving and high withdrawal rates	Akter Önal and Çelebi, 2024; Meray, 2019

Table S2. Cross-gas interpretation of key storage criteria (Zhong et al., 2024).

Criterion	Role in CO ₂ storage	Role in H ₂ storage	Role in NG storage	Implication for site selection
Permeability	Controls injectivity and plume migration	Controls mixing, fingering, and loss pathways	Controls deliverability and withdrawal rates	Same parameter, but stricter heterogeneity constraints for H ₂
Pressure	Governs containment limits and caprock integrity	Influences recovery efficiency and	Governs cycling performance and withdrawal decline	Pressure limits are critical across all gases but for different reasons

			compression requirements	
Depth	Enables supercritical conditions and higher storage efficiency	Limited density benefit; influences pressure and cushion gas requirements	Influences capacity and operating pressure range	Minimum depth critical for CO ₂ ; less restrictive for H ₂ /NG
Porosity	Determines storage capacity and residual trapping	Influences mixing volume and recovery efficiency	Determines working gas capacity	Capacity vs recovery trade-off differs by gas
Heterogeneity	Influences plume migration and trapping efficiency	Strongly affects fingering, bypassing, and losses	Affects sweep efficiency and deliverability	Most critical for H ₂ due to mobility effects
Seal integrity	Critical for long-term containment	Critical for preventing losses and reactions	Important for pressure containment and safety	Highest containment risk sensitivity for CO ₂ and H ₂
Fluid interactions	CO ₂ -brine reactions enhance trapping (e.g., dissolution, mineralization)	Mixing, microbial activity, and potential reactions affect recovery	Limited compositional change under typical conditions	Strongest uncertainty and risk for H ₂ systems

Table S3. Comparative overview of regulatory frameworks relevant to subsurface gas storage (Tarkowski et al., 2025).

Region	Primary framework	Main coverage	Key strengths	Key gaps
United States	EPA UIC Class VI Program	CO ₂ geological storage	Detailed requirements for site characterization, permitting, monitoring, well integrity,	Limited direct guidance for underground H ₂ storage and hydrogen-specific operational risks

and post-closure
stewardship

European Union	Directive 2009/31/EC	CO ₂ geological storage	Comprehensive lifecycle regulation covering permitting, monitoring, environmental protection, liability transfer, and site closure	Regulatory framework primarily designed for CCS; limited explicit extension to H ₂ storage
Canada/Australia	Provincial/state-level CCS and petroleum-resource frameworks	CO ₂ and natural gas storage	Flexible integration with existing petroleum, groundwater, and subsurface-resource regulations	Fragmented implementation across jurisdictions; H ₂ -specific technical and liability frameworks still evolving
Global/general	Adapted underground natural gas storage standards	Natural gas and emerging H ₂ storage	Extensive operational experience with cyclic gas injection, withdrawal, and infrastructure management	Insufficient treatment of H ₂ -specific risks including diffusivity, microbial activity, geochemical reactions, material compatibility, gas mixing, and purity management

Table S4. Comparison between decision-making methods

Method	Aggregation logic	Strengths	Limitations	Example studies
AHP	Compensatory weighting / pairwise comparison	Adaptable; simple math; hierarchical structure improves focus/transparency	Interdependencies among criteria can distort results; many decision-makers complicate	Lewandowska-Śmierzchalska et al., 2024

TOPSIS	Compensatory distance-to-ideal	Uses full information; yields clear ranking; criteria need not be independent	weighting; relies on experience-based judgments Euclidean-distance basis ignores sign; attributes must be monotonic	Khamehchi et al., 2013
PROMETHEE	Partial/Full outranking	Supports group decisions; handles qualitative & quantitative data; can incorporate uncertain/fuzzy info	Objective structuring not explicit; depends on decision-maker weights; relatively complex (expert-oriented)	Harati et al., 2024
VIKOR	Compromise solution / regret minimization	Balances overall utility and worst-case regret; useful for compromise solutions under conflicting criteria	Sensitive to weight and normalization choices; assumes decision-maker preference for compromise	Tomić et al., 2019
ELECTRE	Non-compensatory outranking	Non-compensatory outranking; suitable for safety-critical decisions where poor performance cannot be offset	Requires threshold definition; can be complex to parameterize and interpret	Deveci et al., 2015
Fuzzy MCDM	Uncertainty/linguistic extension	Handles ambiguity via fuzzy sets; better captures expert preferences; mixes qualitative & quantitative inputs	Requires fuzzy-logic expertise; results sensitive to membership functions; heavier computation	Acar et al., 2024

Table S5. Relative importance and maturity of simulation capabilities across subsurface gas storage applications.

Simulation capability	CO ₂ storage	H ₂ storage	NG storage	Representative tools
Multiphase flow modeling	Widely applied	Widely applied	Widely applied	CMG GEM, TOUGH2, Eclipse
Geomechanical coupling	Critical for pressure management and fault stability	Moderate but increasing importance	Important for cyclic integrity and stress evolution	FLAC3D, COMSOL
Reactive transport modeling	Widely applied	Emerging application	Limited application	TOUGHREACT, PFLOTRAN
Microbial and biogeochemical coupling	Limited application	Emerging and increasingly important	Rare	Custom research workflows
Cyclic operational modeling	Rare	Critical	Critical	CMG GEM, Eclipse
Uncertainty and sensitivity analysis	Widely applied	Emerging application	Widely applied	CMOST, MRST

“Widely applied” refers to methods that are routinely incorporated into current storage evaluation workflows and have established use across studies or projects. “Emerging” indicates active but not yet mature or standardized applications, while “limited” or “rare” refers to niche or infrequently applied approaches in current subsurface storage practice.

Table S6. Machine learning applications in subsurface storage site selection and evaluation (Jayabal et al., 2025).

Task	Typical ML methods	Typical datasets	Purpose	Current limitations
Preliminary spatial screening and classification	Random Forest, SVM, neural networks, gradient boosting	GIS layers, fault maps, depth, thickness, porosity, permeability, seal/caprock indicators, infrastructure and environmental layers	Support early ranking or classification of candidate regions using geological, spatial, and infrastructure datasets	Sensitive to data quality, spatial bias, small training datasets, and expert-derived labels

Surrogate modeling and rapid performance prediction	Neural networks, Gaussian processes, Fourier neural operators, reduced-order models	Reservoir simulation outputs, pressure/saturation fields, plume extent, injection rates, well controls, petrophysical realizations	Approximate simulation outputs such as plume migration, pressure buildup, injectivity, or trapping behavior	Limited extrapolation beyond training simulations; requires high-quality physics-based datasets
Uncertainty quantification and sensitivity analysis	Bayesian models, ensemble methods, ANN surrogates, Monte Carlo workflows	Prior distributions, uncertain geological/petrophysical parameters, simulation ensembles, operational scenarios, pressure/capacity/recovery outputs	Evaluate uncertainty propagation, parameter sensitivity, and robustness of storage predictions	Requires careful validation; uncertainty estimates may reflect simulator assumptions rather than field reality
Monitoring, forecasting, and anomaly detection	Time-series models, autoencoders, CNN/LSTM models, anomaly detectors	Pressure and temperature records, seismic/4D seismic data, microseismicity, DTS/DAS, geochemical samples, production/injection histories	Detect leakage signals, pressure deviations, fracture risk, or unexpected operational behavior	Depends strongly on monitoring-data availability, sensor quality, noise handling, and interpretability
Physics-informed and connectivity-aware modeling	PINNs, graph neural networks, hybrid physics-ML models	Governing equations, boundary/initial conditions, well connectivity, fault/fracture networks, grid-based simulation data, pressure/saturation fields	Improve physical consistency and represent spatial connectivity, faults, fractures, and well interactions	Mostly research-stage; requires further field validation and storage-specific adaptation

Appendix C: MCDM

AHP

The AHP is a structured MCDM method that combines qualitative judgments and quantitative data through hierarchical decomposition and pairwise comparisons (Saaty, 1987). It is well suited to subsurface storage siting because it reflects how experts naturally break decisions into geological, operational, economic, and risk-related components (Sabzevari and Delavar, 2017). Weights are derived from comparison matrices, and internal consistency checks help identify contradictory judgments. In practice, many studies report the consistency ration (CR) and apply a threshold (often $CR < 0.1$) as a quality check on elicited preference (Kumar et al., 2017).

In subsurface storage studies, AHP has been widely used to screen aquifers, depleted reservoirs, and salt structures, producing ranked shortlists or criterion weights that can also be used in complementary methods such as TOPSIS or PROMETHEE (Lewandowska-Śmierzchalska et al., 2024; Llamas and Cienfuegos, 2012; Uliasz-Misiak et al., 2021). Its main advantage is that it allows measured data and expert knowledge to be combined without forcing all criteria onto a single physical scale (Mardani et al., 2015).

AHP's limitations are well known. It assumes independence among criteria, although geological and operational factors are often coupled. Results can be sensitive to expert bias, rank reversal may occur, and the number of pairwise comparisons grows rapidly with the number of criteria (Acar et al., 2024; Malczewski, 1999). These limitations motivate careful hierarchy design, structured elicitation, and, where needed, fuzzy-AHP variants.

TOPSIS

TOPSIS ranks alternatives according to their distance from an ideal solution and a worst-case solution after normalization and weighting (Chakraborty, 2022). In subsurface

storage, this logic reflects the need to balance competing objectives such as capacity, injectivity, containment, cost, and accessibility.

Its main strengths are computational efficiency, transparency, and scalability, which make it attractive for basin- and regional-scale screening (Khomehchi et al., 2013; Zhang et al., 2017). TOPSIS is often combined with AHP-derived weights, using AHP for elicitation and TOPSIS for ranking (Chakraborty, 2022).

Because TOPSIS is fully compensatory, strong performance in one criterion can offset weak performance in another. This is acceptable for early-stage prioritization but may be problematic when safety-critical criteria are involved. For this reason, many studies apply hard geological or regulatory filters before using TOPSIS or adopt fuzzy-TOPSIS variants when uncertainty is high (Ma et al., 2024). Results are sensitive to normalization, weighting, and distance metrics, so sensitivity analysis is essential.

PROMETHEE

PROMETHEE is an outranking method that compares alternatives pairwise across multiple criteria and aggregates the results into an interpretable ranking (Behzadian et al., 2010). Unlike additive methods, it does not assume full compensation, making it useful when poor performance on safety-critical criteria should not be offset by strengths elsewhere (Kumar et al., 2017).

Its defining feature is the use of criterion-specific preference functions and thresholds that distinguish insignificant differences from meaningful ones. These thresholds can reflect measurement uncertainty, model error, or regulatory limits, which are particularly valuable in subsurface applications where petrophysical, structural, and cost uncertainties can obscure real

differences between sites. PROMETHEE's flow-based outputs and GAIA visualization also help communicate trade-offs and the influence of weights (Behzadian et al., 2010).

Published applications show its flexibility in both CO₂ and hydrogen storage studies, where it has been used to rank geological options, test sensitivity to thresholds and weights, and encode threshold-like safety logic while remaining auditable (Harati et al., 2024; Tomić et al., 2019). As with all MCDM approaches, PROMETHEE results depend on modeling choices, particularly the selection of weights and preference-function parameters. These choices should be grounded in data quality, measurement uncertainty, and safety requirements, and evaluated through systematic sensitivity analysis.

Compared with AHP, PROMETHEE replaces hierarchical consistency checks with explicit modeling of preference intensities; compared with distance-based methods such as TOPSIS, it avoids reliance on internal ideal points and offers a more natural representation of threshold behavior, at the cost of additional parameterization and the need to justify preference-function selection.

Fuzzy MCDM

Fuzzy MCDM extends classical MCDM methods to cases where data are sparse, uncertain, or expressed linguistically rather than numerically. In early-stage subsurface screening, expert judgments such as “moderate permeability” or “high seal integrity” are common, and fuzzy numbers allow such vagueness to be represented explicitly (Çetin Demirel et al., 2017).

In the storage literature, fuzzy extensions are most often applied to AHP and TOPSIS, preserving their basic structure while allowing linguistic inputs and partial uncertainty

propagation. These methods are useful when data is incomplete, when legacy fields are poorly characterized, or when multiple stakeholders provide qualitative input.

Their usefulness depends on how linguistic terms are mapped to membership functions, how opinions are aggregated, and how defuzzification is performed. These choices should therefore be documented clearly and tested through sensitivity analysis (Narayanamoorthy et al., 2019). Where reliable quantitative data are available, classical MCDM with sensitivity analysis is often sufficient (Durbach and Stewart, 2012).

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