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Review

Global Geological CO_2 Storage: A Comparative Review of Project Experience, Economics, and Long-Term Stewardship

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Abstract

Quantitative comparisons of geological CO_2 storage projects often compare quantities, assets, operation period, and legal obligations that relate to different services. This critical integrative review analyzes nineteen selected geological CO_2 storage projects in the United States, Canada, Norway, continental Europe, Africa, Australia, Japan, China, Germany, and Iceland. The review uses explicit project-level inclusion criteria, a claim-based hierarchy of sources, and qualitative coding for physical setting, quantity basis, development architecture, economic description, and stewardship. Its contribution is an applied framework for project comparison based on the classification of evidentiary claims into five decision categories instead of a universal ranking of projects. The comparison reveals that design capacity, contracted capacity, actual injection, cumulative stored mass, and research campaign volume cannot be compared without records of operation and consistent definitions. Project experience also demonstrates the differences between subsurface dynamics and economic implications: pressure response affects development choice, monitoring quality affects evidentiary requirements for conformance and closure, and infrastructure ownership affects interpretation of disclosed expenditures. A storage-only economic comparison is possible only when the asset boundary, quantity boundary, reporting date, project maturity, and allocation of responsibility are explicitly defined. Financial assurance, post-injection stewardship, and transfer of responsibility in North America, Norway, continental Europe, and Australia are also jurisdiction-dependent and permit-dependent. The contribution of the review is a qualitative project comparison framework for the selection of analogous projects and the identification of needs for new appraisals, cost allocation, contract evidentiary support, or verification of closure requirements. The review does not evaluate project costs, estimate annual rate from cumulative injection, or provide representative global census.

Keywords: geological CO_2 storage; saline aquifer; depleted reservoir; site screening; techno-economic review; stewardship; financial assurance; project comparability

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1. Introduction

Geological storage is a terminal containment technology in the carbon capture and storage value chain. Capture technology determines the availability and composition of the stream, and transport determines how the stream reaches the storage interface, but the subsurface system determines the sustainable injection rate, pressure response, plume size, well design, monitoring design, closure evidence, and operator responsibility duration [1–5]. For this reason, geological storage performance cannot be quantified properly using a single annual nameplate. Projects with equal nameplate capacity may require a different number

of wells, different pressure management strategies, and a different contingency capacity due to differences in connected pore volume, permeability architecture, completion design, boundaries, geomechanical limitations, and operating conditions [5–11].

Public comparisons are also vulnerable to semantic confusion. A quantified entity may stand for capacity for capturing carbon dioxide, throughput in the pipelines, service under contract, permissible injection, maximum injection rate, measured yearly injection, a limited demonstration period, and cumulative mass stored. These entities serve different purposes and should not be compared directly. Research expenditures for monitoring differ from operational investments for CO_2 injection, just as planned storage capacity differs from actual stored mass. Similar confusion can arise when financial metrics are compared without clearly defined boundaries and objectives. The published expenditure may be associated with a subsurface reservoir, a transport-and-storage network, or an overall capture and storage system. Tariffs, subsidies, taxation incentives, loans, equity investment, refundable insurance, and the face value of a financial instrument are not equivalent to the cost of the resource [12,13].

The problem, thus, is not the absence of project examples but the absence of criteria that would establish what sort of evidence could respond to which inquiry. Early projects offer valuable insights into plume migration, pressure changes, well performance, monitorability, infrastructure reuse, and closure planning [7–9]. But, due to the dissimilarities of these projects in objectives and governance, universal ranking becomes nonsensical. A project could be a good analogue for the issue of pressure management but a bad analogue for the issue of well cost; a research facility could help in designing monitoring without dictating a commercial minimum; and network services could provide information on contract structure without disclosing the cost of storage alone.

This study solves this problem through a selection of worldwide cases, maintaining an exclusive focus on storage only. Transport and capture are mentioned only where it is necessary to identify and subtract/include their part in the reported value of the project. This review poses three related questions: What observations are compatible in their definitions? How do the physics of behavior and screening affect development and economics? How does the issue of stewardship and responsibility affect life cycle exposure? The paper does not perform estimations of the levelized cost of storage, simulation modeling, or normalization of incompatible information. Its novelty is the application of one framework of comparability to physical, economic, and stewardship evidence and the illustration of the decision to which each project is a suitable analogue or not.

First, this paper will formulate the transparent design of a critical integrative review and an evidence hierarchy. Then, it will relate storage screening to project experience, apply the framework of five classes of comparability to nineteen projects, and conduct a comparison of Canada and the United States. The following parts of the paper will address a comparison of the economic architectures of projects and specific stewardship arrangements of projects. The concluding discussion will contain the findings proven by the evidence, conjectures based on the evidence, and the evidence needed for quantitative techno-economic research in the future.

2. Review Design and Analytical Framework

2.1. Critical Integrative Review Design

An integrative review may involve empirical, technical, regulatory, and conceptual literature, provided that the decisions of searching, evaluating, and synthesizing are made explicit [5]. Since the unit of analysis in this study is a storage project rather than a homogeneous experiment, the design will be a critical, case-oriented kind of an integrative review, not a systematic or meta-review [5,6]. The goal is analytical transfer: storage project

evidence is analyzed for its suitability to make a certain screening, engineering, economic, or stewardship decision.

The starting pool of cases came from the project corpus built for this manuscript. To make the selection auditable, all cases were rescreened using the same eligibility criteria, with an evidence cutoff of 12 September 2026. A project qualified when it had four features: geological storage activity identified, storage medium and project purpose specified, evidence relevant to at least one review domain, and value as a unique geographic, geological, operating, or commercial archetype. Projects with enhanced oil recovery (EOR)-led developments were disqualified because changes in oil and gas production shift the goal and financing model. Also disqualified were capture-only announcements, projects without storage concept identified, duplicate phases with undifferentiated evidence, and claims substantiated by secondary statements that could not be found in the source documentation. Nineteen projects qualified in the final set. This set is deliberately diversified and is neither a random sample nor a full-world inventory.

The evidence searches matched the exact name of projects with the words geological storage, injection, monitoring, annual report, capacity, cost, funding, closure, permit, liability, and financial assurance. Current or source-dated project information was searched in the project portal and regulator website. The peer-reviewed scientific literature was searched for the interpretation of subsurface pressure, geomechanics, trapping, and monitoring. Citation searches back from the major technical study or report complemented exact-name searches. Table 1 documents the evidence search families, the purpose of selection, and the exclusion criteria. The search does not reconstruct records considered during the earlier manuscript development stage. Thereby, no exhaustive search claim as in the PRISMA framework is made here.

Table 1. Documented search and selection procedure for the critical integrative review.

Search Family	Typical Terms	Purpose	Retention Rule
Project identity	Exact project name + storage + injection + annual report	Confirm medium, status, scale, and date	Retain the most authoritative dated source for each field.
Physical behavior	Project name + pressure, injectivity, plume, geomechanics, monitoring	Identify observed mechanisms and design changes	Retain peer-reviewed or formal technical evidence linked to the project.
Economic architecture	Project name + cost, investment, tariff, funding, ownership	Identify scope and commercial structure	Retain only when the asset or service boundary can be described.
Stewardship	Project or jurisdiction + closure, post-injection, transfer, liability, assurance	Identify duties and transfer conditions	Prefer current regulation, government records, permits, or formal closure plans.
Cross-checking	Project name + milestone date or status	Resolve changing project status	Keep source-dated descriptions; do not merge incompatible periods.

The authority of the evidence depended on the individual claim. Legal obligations and compliance were determined on the basis of legislation, regulations, permits and governmental records. Subsurface interpretation was based on peer-reviewed project studies and technical reports from operators or joint ventures. Official announcements from operators or joint ventures were accepted as evidence for project milestones, ownership, design and commercial architecture, but not as independent evidence of sustained performance and containment. A source could therefore be authoritative evidence for one claim but weak for another. Conflicting claims were kept in the evidence record by the date and definition.

The data were classified deductively into five domains: project identity and maturity; geological and development setting; quantity definition and period of observation; economic boundary and commercial architecture; and stewardship or allocation of responsibilities. In each domain, observations were separated from the interpretation and decision-making to which the evidence was potentially applicable. Classification created the comparison classes used in Section 2.3. This was a single-author synthesis; there is no evidence extraction duplication or interviewer agreement statistic here. The project database in Appendix A provides the principal sources, the domains validated and limitations so that the reader can distinguish between the traceable evidence and the conditional interpretation.

2.2. Storage-Site Screening and Decision Gates

The storage screening is a process of gate-by-gate non-compensable selection followed by comparative assessment. Minimum technical functionality is containment, capacity, injectivity, and monitorability, in line with the established storage guidance and standards [7,8]. However, the economic development also requires legal access, permit pathway, specification-compliant gas stream, and feasible allocation of responsibilities. A positive economic scenario cannot make up for an unproved leakage path, insufficient pressure margin or lack of legal authority.

The value of a screening criterion emerges only when its evidence, scale and decision consequence become clear. A regional map identifies the formation, but it takes the well and seismic data to appraise a storage complex. Static pore volume is not a rate commitment. Completion-scale permeability alone does not determine injectivity since it depends on pressure differential, relative permeability, skin, boundary support, heterogeneity and well interference. Dynamic capacity is thus a development consequence rather than a single geological constant [14–17].

No universal cutoff criteria are provided in the framework. Depth, porosity, permeability, caprock thickness, distance to faults, and pressure margin should all be judged against the project timing, fluid composition, regulations and uncertainty. In Table 2, the criterion is applied to the specific project evidence. The project examples do not order projects; they provide insight into how a screening conclusion alters the decision at hand.

Table 2. Applied storage screening domains and their decision consequences.

Domain	Evidence Required	Gate or Decision	Project Illustration
Containment	Seal continuity, faults, legacy wells, geomechanics, credible pathways	Reject, redesign, or proceed to dynamic appraisal	In Salah shows why deformation and pressure require coupled interpretation rather than a simple pass/fail label [18–20].
Injectivity	Completion-scale tests, pressure differential, fluid mobility, well condition	Select completion and feasible rate range	Illinois and Quest provide industrial saline context, but their rates are not transferable without local tests [21–26].
Pressure management	Connected volume, boundaries, interference, fracture constraints	Define rate, wells, alternate interval, or brine response	Snøhvit required a change in injection interval after pressure response [27–30].
Capacity maturity	Static and dynamic estimates with confidence and development status	Match storage inventory to schedule and contingency	Porthos contracted design capacity is a future service envelope, not observed injection [31,32].

Table 2. *Cont.*

Domain	Evidence Required	Gate or Decision	Project Illustration
Well integrity	Construction history, materials, conversions, legacy penetrations	Accept new build, qualify reuse, remediate, or abandon	Porthos illustrates that reused gas wells require inspection, conversion, and long-term preservation [32].
Monitorability	Baseline, signal detectability, survey access, attribution, model update	Define Measurement, Monitoring, and Verification (MMV) program and closure evidence	Aquistore, Otway, Tomakomai, and Ketzin provide monitoring evidence but not a universal commercial minimum [33–36].
Legal access	Pore-space rights, storage permit, surface access, custody point	Hold until authority and rights are documented	US Class VI, Alberta, Norway, EU, and Australian systems allocate duties differently [37–40].
Commercial interface	Stream specification, delivery profile, capacity booking, outage allocation	Define service and responsibility boundary	Northern Lights and Porthos show how network interfaces differ from integrated projects [41–44].

2.3. Comparability Framework

The unit of comparison is a defined project or phase. The storage service commences when the custody transfer point for a specification-conforming CO_2 stream is achieved. At the opposite end of the project lifecycle, the expenditure incurred due to storage ends with project closure and post-injection management. Capture and common long-distance transportation are excluded from the cost boundary related to storage alone. They are addressed only when a published figure combines them with storage or when a network interface affects storage risk.

In advance of using the project evidence for comparison, six questions are asked. Is the set of physical storage mechanisms similar enough to answer the question? Is the reported quantity similar both in meaning and observation period? Are the asset and ownership boundaries aligned? Is the project maturity similar? Does the source of the information provide evidence to support the desired inference? Are stewardship responsibilities assigned to comparable parties and time spans? Failure on any question does not render the project irrelevant, but it limits the application to one particular module only.

The outcome of the assessment is a five-class decision system, as illustrated in Figure 1. In Table 3 and Figure 2, directly comparable evidence aligns the variables, boundaries, dates, and purpose. Conditionally comparable evidence may be used following explicit adjustment or candidate-specific validation. Mechanism-only evidence informs the physical or monitoring process but not the economic magnitude. Commercial-only evidence informs the ownership, contracting, or funding but not the reservoir performance. Unsuitable evidence fails the criteria for a particular decision. The classification is qualitative and purpose-specific: the same project may belong to different classes for different purposes.

Table 3. Qualitative classes used to determine whether project evidence can support a specified comparison.

Class	Meaning	Permitted Use	Prohibited Interpretation
Direct	Definition, period, boundary, maturity, and mechanism align.	Like-for-like qualitative comparison; quantitative reuse only if data are complete.	Assuming comparability beyond the audited fields.

Table 3. *Cont.*

Class	Meaning	Permitted Use	Prohibited Interpretation
Conditional	Relevant evidence exists but one or more differences require verification.	Scenario, prior range, or design alternative with explicit condition.	Treating the condition as already satisfied.
Mechanism only	The case demonstrates a physical, operational, or monitoring mechanism.	Identify causal pathways and contingencies.	Transfer project rate, cost, or safety outcome.
Commercial only	The case demonstrates ownership, network, tariff, support, or risk allocation.	Compare business architecture and interfaces.	Infer subsurface performance or storage-only cost.
Unsuitable	The evidence does not answer the stated question.	Document exclusion and seek other evidence.	Imputation, ranking, or silent substitution.

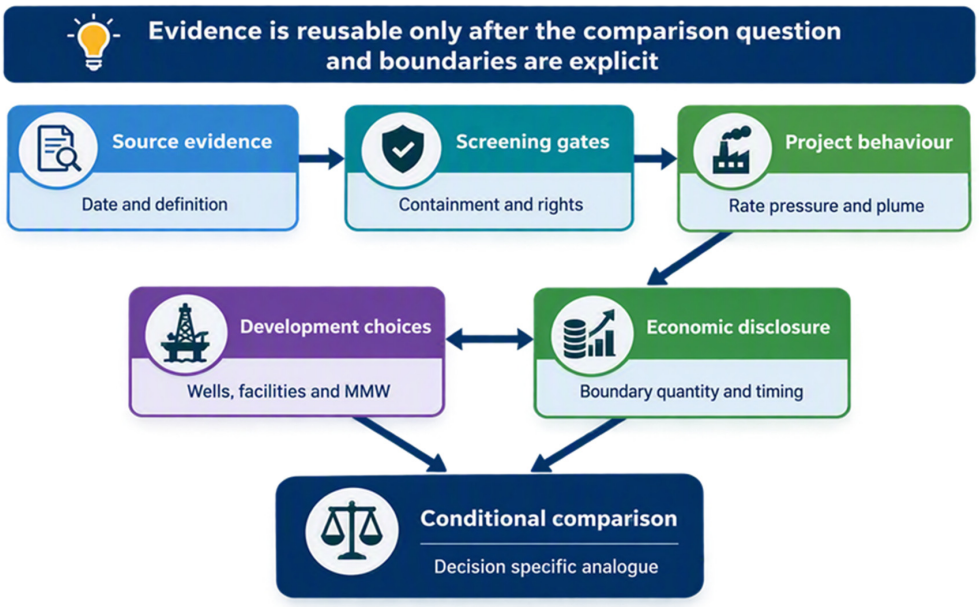


Figure 1. Applied evidence-to-comparison framework.

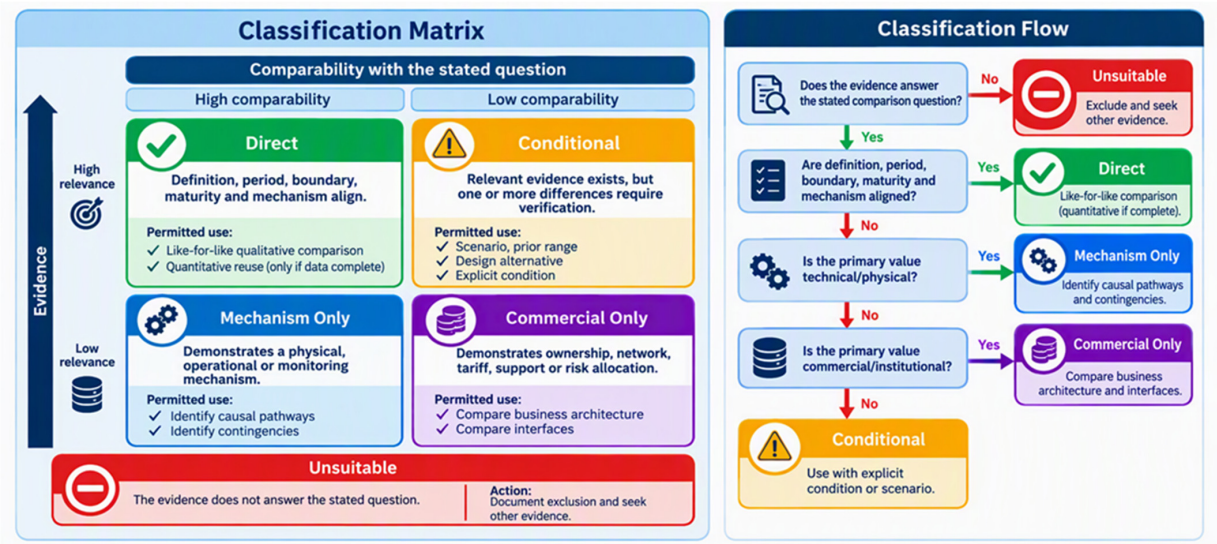


Figure 2. Framework for classifying geological CO_2 storage evidence.

3. Comparative Project Evidence

3.1. Selected Worldwide Project Landscape

The final set of cases was selected to represent a range of project characteristics across several dimensions. These include different storage settings (saline sandstone formations, depleted oil and gas reservoirs, and reactive basalt formations), project locations (onshore and offshore developments), and project configurations (integrated industrial projects, third-party transport and storage networks, and research or demonstration projects). The information about status and quantity basis is taken from dated references and is presented in Table 4. It is not a synchronous operating census. Design capacity, contracted capacity, injection, mass balance, and demonstration target are evidence of independent classes.

Table 4. Selected geological CO_2 storage projects and definition-aware parameters.

Project	Country	Medium	Source-Dated Status	Quantity and Basis	Depth	Ref.
Illinois Basin-Decatur	USA	Saline sandstone	Completed research injection	About 1 Mt cumulative; finite campaign	About 2100 m	[18]
Illinois Industrial CCS	USA	Saline sandstone	Commercial project described by DOE	Up to about 1 Mt/y design	About 2100 m	[19]
Red Trail Energy	USA	Saline sandstone	Injection initiated in 2022 source	Annual value not normalized	Not consistently disclosed	[20]
Quest	Canada	Saline sandstone	Operating in 2026 source	At least 1 Mt/y design	More than 2000 m	[21–23]
Aquistore	Canada	Saline sandstone	Research and monitoring site	0.73 Mt/y original design	3150–3350 m	[24,25]
Sleipner	Norway	Saline sandstone	Operating in government source	About 1 Mt/y maximum	About 800–1000 m	[26]
Snøhvit	Norway	Saline sandstone	Operating storage associated with LNG	About 0.7 Mt/y normal maximum	About 2600 m	[26–28]
Northern Lights phase 1	Norway	Saline sandstone	Operating; first storage August 2025	1.5 Mt/y transport-storage capacity	2600 m below seabed	[29,30]
Porthos	Netherlands	Depleted gas fields	Under construction; earliest H2 2027	2.5 Mt/y contracted design; about 37 Mt planned	3000–4000 m	[31,32]
Ravenna phase 1	Italy	Depleted gas field	Injection commenced September 2024	About 0.025 Mt/y phase design	About 3000 m	[33]
Greensand Future	Denmark	Depleted oil field	Start targeted 2025–2026 in source	0.4 Mt/y initial design	About 1800 m	[34]
Ketzin	Germany	Saline sandstone	Closed research site	About 0.067 Mt cumulative	About 630–650 m	[45]

Table 4. *Cont.*

Project	Country	Medium	Source-Dated Status	Quantity and Basis	Depth	Ref.
Carbfix2	Iceland	Reactive basalt	Operating process development	About 0.012 Mt/y reported	Site-specific	[46]
In Salah	Algeria	Saline sandstone	Injection ended	About 3.8 Mt cumulative	About 1800 m	[35,36]
Gorgon	Australia	Saline formation	Operating; injection since August 2019	3.3–4.0 Mt/y design; more than 11 Mt by July 2025	More than 2000 m	[37–39]
Moomba	Australia	Depleted reservoirs	Operating since 2024	Up to 1.7 Mt/y phase 1; more than 1 Mt by July 2025	Project-specific	[39]
Otway	Australia	Saline and depleted gas	Operating research center	Episodic tests; more than 0.1 Mt cumulative	About 1500–2000 m	[41–43]
Tomakomai	Japan	Two saline units	Post-injection monitoring	0.1 Mt/y demonstration target; 0.3 Mt cumulative	About 1100 and 2400 m	[44]
Shenhua Ordos	China	Deep saline formations	Demonstration completed	0.1 Mt/y pilot design	Deep multilayer setting	[46]

The sample is intentionally chosen to emphasize projects with technical or regulatory accessible data. This causes evidence selection bias: matured projects and publicly supported demonstrations are easier to examine than commercial projects with restricted information. Presence in Table 4 is associated with evidence availability and archetype representation rather than distribution of a technology in a particular geographical area. Absence in the table does not mean that the country does not have any storage activity.

3.2. Applied Project Comparability

In Table 5, the framework is applied to all nineteen projects. The table does not define the best project among them. For each project, the table gives a principal module where the project gives valuable information and a condition that prevents wholesale transfer. This makes it possible to check analogue selection: a reviewer can disagree with the classification and find the specific evidence that should change it.

Table 5. Applied comparability of the selected projects. Classification refers to the principal use in this review.

Project	Strongest Technical Use	Economic Architecture	Class	Principal Condition
Illinois Basin-Decatur	Saline injection and monitoring	Research budget not commercial	Mechanism only	Finite campaign and research purpose
Illinois Industrial CCS	Industrial saline development	Integrated source–storage context	Conditional	Design capacity needs operating-period evidence

Table 5. *Cont.*

Project	Strongest Technical Use	Economic Architecture	Class	Principal Condition
Red Trail Energy	Onshore saline operation	Integrated ethanol project	Conditional	Limited public completion and cost detail
Illinois Basin-Decatur	Saline injection and monitoring	Research budget not commercial	Mechanism only	Finite campaign and research purpose
Illinois Industrial CCS	Industrial saline development	Integrated source–storage context	Conditional	Design capacity needs operating-period evidence
Red Trail Energy	Onshore saline operation	Integrated ethanol project	Conditional	Limited public completion and cost detail
Quest	Onshore saline operation and MMV	Integrated full-chain funding	Conditional	Storage cost requires allocation from capture and pipeline
Aquistore	Deep saline monitoring	Research economics	Mechanism only	Research intensity is not commercial minimum
Sleipner	Long-duration offshore saline storage	Dedicated but field-linked structure	Conditional	Offshore setting and source integration limit cost transfer
Snøhvit	Pressure response and interval contingency	Integrated LNG-associated project	Mechanism only	Specific connected volume and facility context
Northern Lights	Offshore third-party storage service	Shipping–terminal–pipeline–storage network	Commercial only	Transport and storage are bundled
Porthos	Depleted-field reuse and staged injection	Open access transportation and storage (T&S) infrastructure	Commercial only	Construction-stage service, not observed utilization
Ravenna	Depleted-field and infrastructure reuse	Early phased industrial service	Conditional	Small phase 1 scale and operator announcement
Greensand Future	Cross-border offshore chain and depleted field	Planned scalable service	Commercial only	Source reports target rather than sustained operation
Ketzin	Shallow research injection and closure	Research economics	Mechanism only	Scale and purpose differ from commercial projects
Carbfix2	Dissolved-phase basalt mineralization	Distinct conditioning and water system	Mechanism only	Trapping and injection architecture differ
In Salah	Geomechanics and pressure interpretation	Integrated gas-processing context	Mechanism only	Injection ended and deformation is site-specific
Gorgon	High-rate saline development and monitoring	CCS embedded in LNG development	Conditional	Published economics are not storage-only
Moomba	Depleted-field multiwell operation	Integrated gas-processing project	Conditional	Operator-reported cost spans the chain
Otway	Monitoring, testing, and model validation	Research economics	Mechanism only	Episodic experiments are not commercial utilization

Table 5. *Cont.*

Project	Strongest Technical Use	Economic Architecture	Class	Principal Condition
Tomakomai	Two-reservoir demonstration and post-injection monitoring	Government-supported demonstration	Mechanism only	Target scale and research purpose
Shenhua Ordos	Deep multilayer saline pilot	Demonstration economics	Mechanism only	Limited consistent public operating and cost detail

No two cases are comparable in all domains. Even the two Illinois projects that have the same formation and location differ in purpose, period of operation and quantity basis. Therefore, the strongest comparison can be performed only module by module. Saline projects give information on pressure and plume behavior under similar geology; depleted-field projects inform reuse and pressure evolution; network projects can inform capacity booking and interface risks; and research projects can inform detection limits of monitoring and closing evidence.

3.3. Cross-Project Technical Mechanisms

The pressure behavior gives a clear link between subsurface behavior and development economics. The Snøhvit project shows that pressure response requires a different geological interval if behavior of pressure deviates from expectations [22,23]. The In Salah project informs why deformation, pressure, and faults require geomechanics analysis [30,31]. These projects do not provide generic pressure-cost multipliers. They indicate contingencies that need testing at another site: lower rate, different completion, more volume, brine management or redesign of the injection system.

Near-well injectivity and regional pressure accumulation have to be distinguished. Additional or enhanced injectors will decrease near-well pressure drop for a given injection rate, but increasing the number of wells in the same pressure-limited connected volume may not address regional pressure build-up [14]. The economic implications depend on the mechanism. Additional injectors will change drilling and completion requirements; a new interval will affect appraisal and well design; brine production will increase the number of wells, handling, treatment, and disposal; a reduced commitment will affect infrastructure usage and revenue risk.

The monitoring projects represent another type of evidence. Aquistore, Otway, Tomakomai, and Ketzin illustrate how baseline data, seismic imaging, pressure data, well data, and post-injection monitoring data add to the interpretation [47–51]. Their significance is not that all commercial facilities need to duplicate the same effort. They serve to show that monitoring design depends on the signal expected, geological setting, accessibility, pathway model, and decision threshold. Lack of detected leakage can only be interpreted in the context of monitoring coverage and performance.

Storage mechanisms are a clear comparability barrier if they change the physical service. Dissolved phase injection in reactive basalt by Carbfix2 is an example; it changes the conditioning, water consumption, injection process, and expected trapping mechanism [46]. It is an important case for mineralization and monitoring studies, but not as an analogue for free-phase injection in saline sandstone. Projects based on depleted fields require special attention to pressure management and depletion, thermal effects, legacy wells and infrastructure conditions.

The commercial maturity is an important factor affecting the evidence base. Northern Lights has demonstrated first storage and achieved a fully booked first-phase capacity, but

reaching an initial milestone is not the same as having years of operational experience [24]. Porthos is currently under construction, and its operation is expected to start in the second half of 2027 at the earliest [32]. These are valuable examples for networks and reuse facility designs, but the design capacity should not be used as observed reservoir deliverability.

3.4. Canada and United States Benchmark

Canada and the United States present a meaningful targeted comparison as shown in Table 6. They share similar features such as industrial saline storage projects, publicly available technical documents, and mature oil and gas regulatory systems, while responsibility and financing frameworks are different. Comparison is not a ranking between two countries; it is the identification of issues where federal, provincial/state, and project-specific data and analysis are needed.

Table 6. Focused qualitative comparison of Canadian and United States storage evidence [53–57].

Dimension	United States Examples	Canadian Examples	Comparative Interpretation
Project purposes	IBDP research; IICS and Red Trail industrial	Quest industrial; Aquistore research	Research and commercial quantities must remain separate in both countries.
Primary storage evidence	DOE and project reports; permit-specific records	Provincial annual reports, knowledge sharing, and research publications	Source availability differs by project rather than simply by country.
Regulatory architecture	Federal Class VI or approved primacy program	Provincial regimes; Alberta framework for Quest	The controlling permit and jurisdiction must be identified.
Post-injection care	Class VI plan, monitoring, non-endangerment, and site closure	Project and provincial closure requirements	A default US period is not a universal transfer date; Canadian treatment is province-specific.
Financial assurance	Approved instruments cover specified Class VI activities	Project agreements, closure duties, and applicable stewardship mechanisms	Instrument face value, paid fee, restricted cash, and physical work are different economic objects.
Economic evidence	Integrated industrial support and project-specific incentives	Quest received substantial federal and Alberta support	Public support affects investor exposure but does not define storage-only resource cost.

The Illinois projects highlight the differences between a finite research effort and a commercial industrial project in the same regional formation [18,19]. Red Trail is a project operating under North Dakota primacy, while federal Class VI regulations provide the reference for well construction, operations, financial accountability, post-injection management, and site closure [20,48–50]. The permit and primacy jurisdiction govern this operation. A statement that the project is in the United States does not provide a uniform liability outcome.

Quest combines capture, pipeline, and saline storage and has exceptionally well-documented public outreach [21–23]. Aquistore offers deep saline storage monitoring information in Saskatchewan, but it is run as a research project [24,25]. Alberta's site closure and post-closure stewardship planning process might provide a possible way forward to provincial liability if all the required conditions are met [52]. This contrasts with the operator post-injection management and release upon director approval of non-endangerment

and site closure within the federal Class VI approach. Both systems must not be equated to any preconceived monitoring period.

4. Qualitative Techno-Economic Comparison

4.1. Storage-Only Boundary and Evidence Requirements

The storage-only economic evaluation starts with the asset boundary, the ownership boundary, the quantity boundary, and the time boundary. Activities contributing to storage may include screening, appraising, injectors and observation wells, storage-side compression or pumping, metering, integrity management, monitoring, site closure, corrective actions, and post-injection management. Common pipelines, terminals, ships, platforms, and utilities have to be allocated. The physical storage service can start at custody transfer, but the expenditures on storage start earlier and may extend much beyond the end of injection.

The quantity denominator is just as important even if no unit cost is calculated. Contractually accepted, metered injection, reported capture, and stored mass can vary because of stream specifications, outages, boundaries of the measurement, and timing of verification. Thus, tariff per accepted tonne of CO_2 is not necessarily comparable with cost per injected tonne or with cost of a full chain per tonne captured. Project announcements linking capital expenditure to capacity do not show utilization.

Six fields have been used to evaluate economic evidence: the object reported; the assets included; the date and currency of the report; the maturity of the project; the associated quantity basis; and the treatment of site closure or other long-term responsibilities. Where one of the fields has not been provided, the data were kept to show the architecture or financing of the project. This analysis intentionally does not escalate, convert currency, divide, or calculate any unit cost by the author.

4.2. Project Economic Evidence

Table 7 shows the economic significance of selected disclosures. The table contains monetary observations only where they provide boundary information. It does not sort projects on the basis of cost. The Quest project offers a unique publicly disclosed allocation revealing that the storage was a relatively minor part of the original integrated capital structure, though the data is project- and date-specific [28]. Porthos reveals an infrastructure investment for a shared transport and storage service and separate European support [31]. The Northern Lights service project reports significant Norwegian support for phase 1 and European support for phase 2, but its service covers ships, terminal, pipeline, and offshore storage [29].

Table 7. Qualitative economic evidence from selected projects. No values are normalized or converted.

Project	Published Observation	Included Boundary	Funding or Model	Permitted Inference	Ref.
Quest	C$790 million original capital presentation; C$40 million identified as storage in 2015 presentation	Capture, pipeline, and storage shown separately in an integrated project	Federal and Alberta grants; integrated ownership	Project-specific historical allocation; not a general storage benchmark	[23]
Northern Lights phase 1	Government support reported at about 80% of phase 1 cost	Ships, receiving terminal, pipeline, subsea facilities, wells, and storage service	Norwegian support; capacity fully booked	Commercial network evidence; storage-only expenditure not disclosed	[29]

Table 7. *Cont.*

Project	Published Observation	Included Boundary	Funding or Model	Permitted Inference	Ref.
Northern Lights phase 2	EU grant of €131 million reported	Expansion of transport and storage capacity and shared infrastructure	EU Connecting Europe Facility support	Funding and expansion evidence; not subsurface unit cost	[29]
Porthos	€1.3 billion infrastructure investment announced at FID	Shared onshore and offshore transport plus depleted-field storage	€102 million EU infrastructure grant; customer SDE++ support described	T&S architecture and funding evidence; no storage-only allocation	[31,32]
Gorgon	Storage expenditure embedded in a major LNG development	Integrated capture and saline injection system	Project and regulatory commitments	Technical-development analogue; economic boundary remains integrated	[37–39]
Moomba	Operator-reported cost claim below US$30/t repeated by government source	Separation, capture, dehydration, compression, transport, and four injection wells	Integrated gas-processing project	Full-chain claim; unsuitable as subsurface storage-only cost	[39]
Ravenna phase 1	Competitive-service statement without auditable storage component cost	Capture, reused pipelines, platform, well, and depleted-field storage	Joint-venture phased development	Architecture evidence; monetary comparison unsupported	[33]
Research sites	Research and demonstration budgets vary by scientific objective	Injection plus extensive testing and monitoring	Public and research funding	Inform value of information and monitoring design, not commercial unit cost	[18,24,41–45]

The comparisons reveal another issue: the difference between public support and physical cost. Public funding reduced the exposure of private funding to the risk of labor, equipment, energy, wells, monitoring, and closure costs incurred by the Quest project, but it did not eliminate them [23]. Customer support under the Dutch framework represents the commercial feasibility of the entire chain of capture, transport and storage, while the infrastructure grant represents common infrastructure [31,32]. The observations have implications for bankability and risk allocation, but not storage cost evaluation.

Moomba presents yet another challenge. Geoscience Australia reports an operator's cost claim below US$30 per tonne while describing a project covering operations including separation, capture, dehydration, compression, transport, and injection [39]. This disclosure is valuable evidence of the integrated project proposition, but it cannot be used as a subsurface storage-only benchmark. This is also true for the Gorgon project, which involves an injection system within a large-scale LNG development project [37–39].

4.3. Development and Commercial Architectures

The cases highlight four storage architectures. The integrated source-to-storage projects such as the Quest, Gorgon, Moomba, and Illinois industrial projects integrate the operations of capture, transport, and injection into one industrial project. The integration reduces interface uncertainty, but in published sources it often obscures the cost of storage and may tie the availability of storage to one source facility.

The field-linked storage projects at Sleipner and Snøhvit have a long operating history, but remain linked to offshore facilities and source conditions. They offer good technical

insight, but not necessarily a third-party storage operation. Research and demonstration projects form the third architecture of projects, whose primary value is the research outcome. Their monitoring intensity, injection scheduling, redundancy and cost reflect their experimental nature.

Network projects like Northern Lights and Porthos give us a fourth architecture. In network projects, there is separation between emitters and a transport and storage service that shares its capacity. There is also capacity booking, custody transfer, specification, ship/pipeline interface, expansion, and distribution of interruption risk [29,31,32]. High design capacity does not mean high utilization. If emitters come late or deliver intermittently, shared resources can be available, but their utilization will be low. On the other hand, full-capacity utilization does not mean injection. Thus, network economics require both reservoir deliverability and customers' ramp-up.

The architectures are not stages in a maturity process. Each architecture addresses a specific coordination problem. The integration architecture internalizes interfaces but may disguise the economics of components. Network architecture enhances access and diversification but generates contracts and utilization requirements. Research site architecture offers high-value proof, but no cost baseline for commercial cases. An analogy would have to match the question with the right architecture.

4.4. From Screening Outcome to Economic Consequence

The proper techno-economic analysis needs to consider the economic implications of engineering decisions rather than project names. Limited injectivity might lead to changes in completion design, drilling pattern, or committed flow rates. Pressure limitations in the region will call for a new depth, wider development, the production of brine, or reduced flowrates. Existing wells might need acquisition, diagnostics, remediation, conversion, monitoring and abandonment. Offshore access will influence intervention and monitoring logistics. Each mechanism influences a particular activity and timing.

The monitoring costs need to depend on the monitoring and decision objectives. Surveys done for mapping plume migration, the system for detecting the leakage path, and the monitoring program for providing closure assurance will have different monitoring frequencies and coverage. Research programs indicate methods that might be useful in commercial design, which should be risk-based and location-specific. Similarly, stewardship cannot be represented by adding one generic percentage to the capital cost. It includes activities, instruments, and responses that happen at different times and conditions.

Uncertainty also needs to stay linked to this set of mechanisms. The downside scenario is not a higher cost but a logical physical and economic scenario, such as limited sustainable injection leading to more wells and late acceptance by the customers, or slow pressure stabilization affecting monitoring time and assurance time. Future quantitative analysis can only evaluate such scenarios after identifying underlying decisions, probabilities, and contractual consequences.

5. Stewardship and Long-Term Responsibility

5.1. Stewardship as an Evidence and Funding Sequence

The evidence gathering starts before the injection. Baseline conditions, definitions of the area of review or storage complex, monitoring plans, corrective action plans, financial responsibility, and closure criteria will define what evidence needs to be gathered during the operation stage. Then comes injection, where a model is updated by metered mass, pressure, plume observations, well integrity information, and environmental monitoring. After ceasing the operation, the operator plugs or converts the wells if necessary, performs monitoring and corrective actions, and proves the conditions of closure or transfer.

Transferring responsibility does not mean transferring all liabilities at once. The legal result will differentiate responsibilities from regulatory duties, civil liability, ownership of stored CO_2, pore-space rights, financial responsibility, indemnity, and government stewardship. It is thus important to analyze the statute, permit, contract, and closure decision independently. Table 8 gives the relationship between some of the projects and jurisdictional mechanisms currently in place without providing legal advice.

Table 8. Comparison of CCS projects, closure evidence requirements, and long-term responsibility mechanisms.

Project Group	Controlling Framework	Evidence Before Closure	Long-Term Mechanism	Critical Caution
Illinois and other Class VI cases	US federal Class VI or authorized primacy program	PISC plan, plume and pressure monitoring, non-endangerment demonstration, approved closure	Operator maintains required responsibility until regulatory release; state law may add mechanisms	Do not describe the 50-year default as automatic liability transfer [48–50].
Red Trail Energy	North Dakota primacy	State-administered Class VI permit obligations and project-specific plans	State authority administers the federal-equivalent program	Primacy changes administrator, not the need to inspect the permit [20].
Quest	Alberta framework and project agreements	MMV, abandonment, reclamation, closure evidence	Potential Crown responsibility after closure conditions; stewardship fund mechanism	Closure certification should not be assumed to extinguish every residual claim [52].
Northern Lights	Norwegian storage permit and national implementation of EEA framework	Monitoring, well integrity, closure plan, competent-authority acceptance	Transfer is conditional on applicable legal and permit tests	Phase 1 operation does not establish future transfer outcome [29].
Porthos, Ravenna, Greensand	EU Directive plus national implementation and permits	Monitoring, corrective measures, closure, evidence of permanent containment	Conditional transfer and financial contribution under applicable law	Construction or early operation provides limited closure evidence [31–35,51].
Gorgon	Western Australian project-specific legislation and approvals	Reservoir-model updates, geophysical and environmental monitoring, decommissioning plans	Government source describes conditional handover only after closure risk requirements	Do not substitute generic Australian offshore rules for the Barrow Island framework [37].
Moomba and Otway	South Australian or Victorian project-specific framework	Operating, monitoring, abandonment, and closure requirements depend on license	State-specific mechanism	Australian projects cannot be assigned one national transfer rule [39,41–43].
Tomakomai	Japanese demonstration and post-injection program	Continued monitoring after campaign completion	Demonstration-specific government oversight	Research completion is not commercial responsibility transfer [44].

A specific wording is needed for financial assurance. A trust, surety bond, letter of credit, insurance, escrow account, or self-insurance test may be used for ensuring future operations within the US Class VI program [44]. But the face amount of such instruments is not equal to the expenses of the project. Fees, collateral limitations, deposits, income, release, and closure or remediation expenses have different impacts on the economy. Stewardship contribution is also a unique approach, as funds are transferred due to the statute or agreement.

5.2. Project and Jurisdiction Comparison

The stewardship concepts described in Section 5.1 are implemented through a variety of regulatory, contractual, and project-specific mechanisms across jurisdictions. While most frameworks require monitoring, verification, closure planning, and demonstration of long-term containment, the evidentiary thresholds for closure and the nature of post-closure responsibility differ considerably. Table 8 compares selected CCS projects and regulatory frameworks, focusing on the evidence required before closure, the mechanisms available for long-term stewardship, and key cautions regarding interpretation of responsibility transfer. The comparison illustrates that stewardship and liability arrangements are highly jurisdiction-specific and should not be generalized across projects. Similar terms such as "closure," "transfer," "release," or "stewardship" may have different legal and regulatory implications depending on the governing statute, permit conditions, and project agreements.

A common observation across the reviewed projects is that responsibility transfer, where available, is typically contingent on demonstrating compliance with prescribed monitoring, corrective action, and closure requirements rather than occurring automatically after a fixed period. Furthermore, the transfer of regulatory responsibility does not necessarily extinguish all potential future obligations or claims. Accordingly, project proponents and regulators should evaluate stewardship provisions within the context of the applicable legal and regulatory framework rather than relying solely on terminology or practices adopted elsewhere.

The examples presented in Table 8 demonstrate that there is no single international model for post-closure stewardship of geologically stored CO_2. Instead, jurisdictions have adopted a range of approaches that reflect their legal systems, resource ownership regimes, and regulatory objectives. Although the specific mechanisms differ, all reviewed frameworks rely on the collection of technical evidence to support closure decisions and to provide confidence in the long-term containment of injected CO_2. These differences reinforce the importance of distinguishing between regulatory closure, transfer of stewardship responsibilities, financial assurance requirements, and residual liabilities when comparing CCS projects across jurisdictions.

5.3. Comparative Implications for Storage Economics

US approach requires the approved post-injection plan and monitoring until non-endangerment is proven. The federal regulation has a 50-year default monitoring period, but it may be replaced by an approved alternative and earlier closure if site-specific evidence supports it [50]. Thus, fifty years is neither a universal assumption of the project nor a statutory transfer date. The associated financial responsibility must cover corrective action, plugging, post-injection care, closure, and emergency response, and must be updated as plans and cost estimations evolve [49].

The European Union Directive offers the possibility of conditional transferring after fulfilling certain technical, financial, and administrative requirements, using the minimum period of at least twenty years and a financial contribution covering at least thirty years of future monitoring after transfer, unless the competent authority agrees with earlier evidence [46]. But the thirty-year contribution basis should not be confused with a universal operator monitoring period. National implementation and permits still matter.

The Quest framework provides an alternative model of agreement, closure certification, and post-closure stewardship [52]. Northern Lights and other offshore projects use the national storage regime and project permits in Norway. Gorgon works according to the project-specific Western Australian legislation and permissions, but other projects in Australia may operate under other states or offshore regimes [37,53]. Each regime alters

the time of expenditures, locked money, evidence gathering, and residual exposure. This set cannot be reliably accounted for by the use of a single closure period for every project.

In terms of the economic assessment, there are four items to keep apart: the physical work required for monitoring, closure, and correction; the amount covered by the instrument; the cost and liquidity effect of the instrument; and the non-refundable contribution supporting public stewardship. Mixing these can lead to a double-counting of obligations or a mistake of treating locked money as already spent. Comparisons of projects should include responsible party, trigger, duration, instrument, condition of release, and residual liability separately.

6. Critical Discussion

6.1. Contribution of the Applied Framework

The primary addition of the project review is not a new list of projects or a screening criterion. It is the separation of evidence into comparison classes depending on particular decisions. The project reviews that exist now describe capacity, injection, cost, and monitoring side by side. This review reveals that the definitions and boundaries of these quantities dictate whether or not they can be aggregated. The framework changes the analytical question from "which project is the most similar" to "which project will support this variable or decision under which condition".

The application of the framework brings three results. First, none of the projects is a universal analogue. Second, the most useful analogies concern mechanisms and decisions rather than the magnitude of quantities. Third, commercial and stewardship architecture can render physical comparisons meaningless despite similar reservoirs. These findings justify the modular selection of analogues and avoid using one similarity measure that conceals fatal differences.

This approach is particularly relevant to techno-economic analyses of storage projects only. Without it, integrated project expenditures are divided by a variable that does not belong to the same boundary; design capacity is used instead of delivered injection, and financial assurance is added to the physical work it covers. The framework does not resolve uncertainty. It makes the source of uncertainty and the extra evidence clear.

6.2. Cross-Project Synthesis

For saline projects, pressure and connected volume recur as development constraints. Sleipner provides experience with long-term plume monitoring, Snøhvit provides interval and pressure contingency, In Salah provides geomechanically coupled behavior, and the Illinois and Canadian projects provide onshore industrial and research counterparts. The integrated lesson is not a common rate but the requirement to link rate commitments to completion-scale testing, pressure response, operating availability, and contingency options.

For depleted-field projects, the prospect of well, platform, and pipeline reuse is accompanied by integrity issues, pressure issues, thermal issues, access issues, and ownership issues. Porthos, Ravenna, Greensand, and Moomba provide examples at different stages and with different commercial models. Reuse should thus be considered a screened development option, not necessarily an economic one. The appropriate basis for comparison is therefore acquisition, inspection, conversion, remediation, surveillance, and ultimately abandonment.

For projects that rely heavily on monitoring, the transferable insight is a design principle: observations must be judged in terms of a detection objective and a decision process. While commercial projects need not feature research intensity, sparse monitoring does not justify closure conclusions because there is no anomaly in the data. For network projects, the transferable insight is another design principle: reservoir capacity, booked capacity, and

throughput are three different things. The utilization of networks is as much a function of customer projects and interfaces as storage.

The economic information is asymmetric. Commercial announcements announce investment and provide more frequent support than component costs attributable to storage. Technical publications publish reservoir behavior more often than allocation. Regulatory sources publish responsibilities more frequently than their project funding schedule. A robust numerical dataset will therefore require reconciliation between engineering, financial, contractual, and legal documents rather than extraction from project databases.

6.3. Limitations and Evidence Priorities

This is an integrative review of selected cases, not a systematic inventory. Purposive sampling is employed, and the availability of sources favors mature, publicly supported, and research-oriented projects. Selection criteria and source list are included, but the initial manuscript search cannot be retraced as an inventory process. Synthesis was undertaken by a single author without replication. These limitations constrain claims about prevalence, relationships, and representativeness.

The status of projects is time-critical. Table 4 applies descriptions dated by sources and cuts off evidence after 12 September 2026. Operator statements can create milestones and design intention but may not demonstrate sustained usage, independent verification, or future schedule. The example of Porthos proves the necessity of updating status, since its earlier projection for 2026 changed to the second half of 2027 at best [32]. Such control of dates is required every time this review is updated.

Most public economic reports are incomplete and heterogeneous. In this review, we do not calculate or estimate storage costs, do not normalize currencies, and do not derive unit costs from combined investments. Moreover, we do not test the suggested framework prospectively in terms of investment decisions. Future studies need to make available the field-level dataset that will include exact source references, observation period, original units, transformations, boundaries of ownership, cost maturity, well availability, and assumptions on closure.

Also, legal summaries here serve only for comparative orientation but not for legal advice. Legal statutes, regulations, permits, project agreements, civil liabilities, pore-space rights, and indemnities can change and can exist in combination. A project-specific legal study is needed in order to determine responsibilities or financial obligations. In the same way, monitoring performance and containment conclusions should be based on a technical review of detection limits, alternative models, and permit criteria.

A further research step is not the creation of an even bigger unfiltered project list. It is the creation of a more appropriate dataset. Prioritized fields include completion-scale injectivity and pressure, history of active wells, interruption and ramp-up history, confirmed mass of injected fluid, storage-related expenditures, sharing of common facilities, monitoring objectives and performance, assurance instruments, and closure/transfer decision-making. After having such fields available for a sufficient number of comparable projects, quantitative analysis is possible without mixing economic objects.

7. Conclusions

The comparability of geological CO_2 storage projects is limited to the specific question asked. The nineteen selected cases prove that capacity design, contracted services, observed injection, finite mass of the campaign, and cumulative storage represent different evidence. Pooling them into a single performance distribution or using author-derived annual rates is impossible without aligned operating records.

Screening and economic assessment are limited by development choices. Pressure response, injectivity, connected volume, well status, monitoring detection, reuse of infrastructure, and offshore accessibility impact the steps needed to achieve and confirm the storage. Project expertise reveals those mechanisms, but a site-specific assessment is necessary to translate their effect size.

In addition, the economics of storage involve boundaries. Integrated CCS cost, transport and storage infrastructure, tariffs, community acceptance, financing, and financial assurance refer to distinct entities. The selected projects do not provide a standardized public set of numbers to compare storage costs numerically. The valid application is qualitative—finding out what is included, who owns what, maturity, quantification basis, commercial interactions, and gaps in information.

Also, stewardship is a series of funded responsibilities rather than a single generic post-injection period. Examples from US Class VI, Alberta, the EU, Norway, and Australia are distinct in monitoring, closing down, financial liability, transfer, and residual liability. Those responsibilities need to be assigned to relevant organizations and permits for comparative economic assessment.

Therefore, the framework applied here classifies the evidence from each project as direct, conditional, mechanism, commercial, or unsuitable for a particular choice. The value of this approach lies in preserving the lessons learned without suggesting their general applicability. Future techno-economic analyses should start with a comparability analysis first.

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Appendix A. Project Evidence Ledger

The ledger shows the primary sources of evidence for each project case and the limitations that were considered in interpretation. It is not a replacement for the actual permit, report or study conducted.

Table A1. Project-level source and evidence audit.

Project	Principal Source Class	Fields Supported	Retained Limitation	Ref.
Illinois Basin-Decatur	DOE/NETL project record	Campaign mass, formation, depth, research purpose	Technical context; detailed commercial cost not used	[18]
Illinois Industrial CCS	DOE project record	Design scale and industrial purpose	Current multi-year utilization not inferred from design	[19]
Red Trail Energy	North Dakota regulator announcement	First injection under state primacy	Limited public technical and economic fields	[20]

Table A1. *Cont.*

Project	Principal Source Class	Fields Supported	Retained Limitation	Ref.
Quest	Alberta annual report, Shell page, NRCan and project presentation	Operation, depth, design, ownership, funding, historical allocation	Integrated project; component allocation is date-specific	[21–23]
Aquistore	Peer-reviewed characterization and NRCan record	Depth, formation, monitoring and research design	Research purpose limits commercial transfer	[24,25]
Sleipner	Norwegian government project summary	Offshore saline setting and reported maximum	Project-linked offshore context	[26]
Snøhvit	Operator and Norwegian Directorate	Setting, depth, rate description, pressure and interval context	Site-specific pressure history	[26–28]
Northern Lights	Operator milestone and project pages	First injection, phase capacity, ownership, infrastructure, support	Early operation; T&S boundary bundled	[29,30]
Porthos	FID and 2026 schedule update	Investment, subsidy, capacity, depth, construction and revised start	No observed utilization; storage cost not separated	[31,32]
Ravenna	Joint-venture announcement	Injection start, phase scale, depth, reused infrastructure	Operator source; early phase	[33]
Greensand Future	Operator announcement	Pilot history, initial target, shipping and depleted-field concept	Target status requires future update	[34]
Ketzin	GFZ project record	Research injection and post-injection context	Small research campaign	[45]
Carbfix2	Project source	Dissolved injection and reactive basalt architecture	Distinct mechanism and water-conditioning boundary	[46]
In Salah	Peer-reviewed studies	Cumulative mass, deformation, pressure, geomechanics	Injection ended; mechanism, not cost magnitude	[35,36]
Gorgon	WA government, parliamentary and national sources	Design, depth, start, stored mass, monitoring and project framework	Embedded LNG economics	[37–39]
Moomba	Geoscience Australia and operator	Start, wells, fields, phase scale, stored mass and cost claim	Cost claim covers integrated chain	[39,40]
Otway	Peer-reviewed paper and research operator	Monitoring, tests, cumulative milestone and research role	Episodic program, not commercial utilization	[41–43]
Tomakomai	Japan CCS summary report	Target, cumulative injection, reservoirs and monitoring phase	Demonstration-specific governance	[44]

Table A1. *Cont.*

Project	Principal Source Class	Fields Supported	Retained Limitation	Ref.
Shenhua Ordos	Peer-reviewed project study	Deep saline multilayer demonstration context	Bibliographic and operating detail remain limited	[47]

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