Engineered Closed-Loop Mineral Storage (ECLMS):

A Conceptual Korean CCS Model Bridging Ex-situ Mineralization and Geological Storage

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Abstract

The expansion of Carbon Border Adjustment Mechanism (CBAM) and the European Union's Emissions Trading System (EU ETS) has sharpened global expectations for permanence, traceability, and accounting integrity in carbon capture and storage (CCS). At the same time, several major industrial economies — including the Republic of Korea, Japan, and parts of Southeast Asia — face a structural deficit of natural geological storage reservoirs suitable for conventional CCS. Existing mineralization options, including ex-situ slurry reactors, in-situ basalt injection, and surficial mine tailings carbonation, occupy distinct niches but leave a regulatory grey zone for jurisdictions that lack large-scale saline aquifers yet possess abundant abandoned mine voids and alkaline industrial by-products. This perspective proposes Engineered Closed-Loop Mineral Storage (ECLMS) as a new conceptual CCS category. ECLMS combines (i) sealed underground containment in repurposed mine voids or engineered caverns, (ii) aqueous-phase mineral carbonation using slag, basalt, or olivine, and (iii) stabilization of CO_2 as dissolved bicarbonate (HCO_3^-) and precipitated carbonates within a closed system. We map ECLMS onto the four IPCC trapping mechanisms, distinguish it from adjacent categories (Carbfix-style in-situ injection, Carbon8-style products, Calcarea-style ocean dispersal, and the Korean Dogye colliery pilot), and outline its compatibility with EU ETS Article 12(3b), Commission Delegated Regulation (EU) 2024/2620, the EU Carbon Removal Certification Framework (CRCF), the Article 6.4 Paris Agreement Crediting Mechanism (PACM), and the IPCC 2006 inventory guidelines. First-order capacity estimates for a 10,000 m^3 reservoir suggest single-batch storage of approximately 2,250–6,900 tCO_2 (slag to olivine feedstock) and cumulative storage under semi-batch operation (Mode B) of approximately 4,500–21,000 tCO_2, with levelized costs in the range of USD 40–150 per ton of CO_2 stored. We argue that ECLMS is best understood not as a new technology but as a missing taxonomic category whose formal recognition would unlock CCS deployment in storage-deficit jurisdictions and complement, rather than compete with, existing pathways.

Keywords: *carbon capture and storage; mineral carbonation; abandoned mines; slag valorization; carbon accounting; CBAM; EU ETS; CRCF; Republic of Korea*

1. Introduction

1.1 Motivation: The geographically uneven CCS landscape

Carbon capture and storage is increasingly central to credible decarbonization pathways, particularly for hard-to-abate industrial sectors such as steel, cement, refining, and petrochemicals. The Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) have repeatedly identified CCS and engineered carbon dioxide removal (CDR) as indispensable components of net-zero scenarios [1, 2]. The European Union's Emissions Trading System (EU ETS), the Carbon Border Adjustment Mechanism (CBAM), and the Carbon Removal Certification Framework (CRCF) have together created the most demanding global regulatory environment for permanence, monitoring, and accounting integrity to date [3, 4, 5].

Yet the global distribution of natural geological storage capacity is profoundly uneven. North America, Norway, the United Kingdom, and Iceland combine large sedimentary basins with reactive basaltic provinces, supporting commercial-scale storage at projects such as Sleipner, Snohvit, Quest, and Carbfix [6, 7]. Several major industrial economies in East Asia and parts of Southeast Asia face a structural deficit. The Republic of Korea, for example, has limited onshore saline aquifer capacity, and its only large depleted offshore gas reservoir, the Donghae-1 gas field located 58 km southeast of Ulsan, is being converted to a CO_2 storage facility under a KRW 2.95 trillion CCS demonstration project (2025–2030) targeting 1.2 Mt CO_2 yr^{-1} storage capacity [8]. Japan and several ASEAN states face comparable constraints. Where domestic storage is scarce, options narrow to cross-border CO_2 transport, deep ocean injection (largely prohibited under the London Protocol), or alternative storage modalities.

This geographic asymmetry has direct implications for trade and competitiveness under CBAM. Where domestic CCS infrastructure is undeveloped, exporters of carbon-intensive goods to the EU face higher embedded emissions, larger CBAM certificate obligations, and limited capacity to claim Article 9 carbon-price deductions [4]. The asymmetry is increasingly recognized as a structural risk by Korean steel, cement, and chemical industries, all of which face high CBAM exposure.

1.2 The taxonomic gap

The current CCS taxonomy is anchored on a small number of well-defined categories. The IPCC 2005 Special Report on Carbon Dioxide Capture and Storage distinguishes geological storage in saline aquifers, depleted hydrocarbon reservoirs, and unmineable coal seams from in-situ mineral carbonation in mafic and ultramafic formations and from ex-situ mineral carbonation in surface reactors [9]. The EU CCS Directive (2009/31/EC) recognizes only geological storage [10]. EU ETS Article 12(3b), introduced through Directive (EU) 2023/959, exempts CO_2 considered “permanently chemically bound in a product” from the obligation to surrender allowances [3]. The associated Commission Delegated Regulation (EU) 2024/2620 limits this category, in practice, to mineral-carbonate-based construction products such as carbonated aggregates, cement, concrete, bricks, and tiles [11].

Each of these categories has a clear geological or industrial referent. None, however, accommodates a system in which captured CO_2 is reacted with alkaline minerals inside a sealed underground void, retained in dissolved bicarbonate form together with precipitated carbonates, and is neither marketed as a product nor injected into a natural rock formation. Yet this configuration is precisely what is technically feasible — and increasingly relevant — in jurisdictions with abundant abandoned mine voids, large alkaline industrial waste streams, and limited natural CCS capacity. The Republic of Korea offers a particularly clear example: a national pilot at the Dogye colliery in Samcheok City is already exploring CO_2 fixation through reaction with alkaline materials and emplacement of solidified products as mine backfill [12].

This perspective argues that the absence of a recognized taxonomic category for engineered, closed-loop, aqueous-phase mineralization in artificial subsurface reservoirs is not merely a labeling problem. It has substantive consequences for accounting, monitoring, regulation, and capital flow. Without an explicit category, projects face uncertain treatment under EU ETS deductions, CBAM Article 9 deductions, CRCF certification, and PACM methodologies. The result is regulatory ambiguity that suppresses investment in precisely the kinds of low-cost, locally-resourced CCS solutions that storage-deficit jurisdictions most need.

1.3 Contribution and structure

We propose Engineered Closed-Loop Mineral Storage (ECLMS) as a conceptual CCS category to fill this gap. The proposal is positioned as a perspective and methodology framework, not as an empirical study. We do not present new experimental data; instead, we synthesize existing data from slag, basalt, and olivine carbonation literature, examine the regulatory architecture of EU ETS, CBAM, CRCF, PACM, and the IPCC inventory guidelines, and articulate how ECLMS maps onto each. We acknowledge the empirical limits of a perspective paper and call explicitly for pilot-scale validation before any of the operating modes proposed here can be deployed at commercial scale.

The paper is organized as follows. Section 2 reviews the current taxonomy and identifies the regulatory grey zone. Section 3 defines the ECLMS framework. Section 4 develops first-order capacity estimates and a Korean reservoir resource inventory. Section 5 outlines an MRV framework adapted to closed-loop systems. Section 6 maps ECLMS onto major regulatory and accounting tracks. Section 7 discusses Korean pilot demonstrations. Section 8 concludes with a research and policy agenda. The contribution is taxonomic and policy-analytic; its target audiences are regulatory bodies (EU Commission DG CLIMA, the Article 6.4 Supervisory Body, IPCC TFI), national policy agencies in storage-deficit jurisdictions, the CCS research community, and industrial actors with high CBAM exposure.

2. Background: The current CCS taxonomy and its regulatory expression

Before introducing ECLMS, we briefly review how existing CCS and mineralization options are organized in scientific and regulatory literature. The aim is not a comprehensive review (for which see [9, 13, 14, 15]) but to surface the boundaries between categories and the gap that ECLMS occupies.

2.1 Geological storage

Geological storage involves injection of supercritical or dissolved CO_2 into deep porous rock formations — saline aquifers, depleted hydrocarbon reservoirs, or unmineable coal seams [9]. Containment relies on a combination of structural, residual, solubility, and mineral trapping [16, 17]. Commercial-scale demonstrations include Sleipner, Snohvit, Quest, and Gorgon. The EU CCS Directive (2009/31/EC) provides the legal framework for permitting and long-term liability transfer [10]. Korea's onshore sedimentary basins are limited in extent and have proven politically contentious following the 2017 Mw 5.4 Pohang earthquake. The earthquake has been attributed by leading studies to fluid injection at the Heunghae Enhanced Geothermal System (EGS) pilot in Pohang [18]. A separate small-scale CCS demonstration in the Janggi basin offshore Yeongil Bay — operated by the Korea Institute of Geoscience and Mineral Resources (KIGAM), and the first sub-100-tonne CO_2 injection achieved in Korea (March 2017) — was suspended as a precautionary measure after the November 2017 earthquake, and the offshore facility was dismantled by the Korean government in February 2023, after a government investigation concluded the CCS pilot was not causally linked to the earthquake. The geological storage pathway is therefore narrow in Korea, with practical activity concentrated in the offshore Donghae-1 conversion.

2.2 In-situ mineral carbonation

In-situ mineralization injects CO_2-charged water into reactive mafic or ultramafic rocks, where dissolved CO_2 reacts with formation cations (Ca^{2+}, Mg^{2+}, Fe^{2+}) to precipitate stable carbonates within months to years [7, 19]. The Carbfix project in Iceland is the canonical demonstration, with monitoring confirming over 95% mineralization within two years [7]. Carbfix-derived methodologies have been developed for the voluntary carbon market and submitted for international standardization [21]. This pathway requires a suitable natural mafic or ultramafic formation; Korea has limited large-scale basalt provinces (Jeju Island and parts of the eastern coast contain basalt, but neither offers the scale or homogeneity of Iceland's basalt plateaus or the Columbia River Basalt Group [20]).

2.3 Ex-situ mineral carbonation

Ex-situ mineralization conducts the carbonation reaction in surface reactors, typically as aqueous slurry or fluidized-bed processes [9, 22, 23]. Feedstocks include natural silicate minerals (olivine, serpentine, wollastonite) and alkaline industrial wastes (steel slag, cement kiln dust, fly ash, paper mill waste, mine tailings). Iron and steel slags are particularly attractive because their high CaO content (typically 30 – 60%) yields high theoretical CO_2 uptake (up to 0.4 – 0.5 tCO_2/t slag) [24, 25, 26]. Reviews of slag-based ex-situ mineralization estimate that approximately 310 Mt CO_2 yr^{-1} could be sequestered globally through carbonation of alkaline industrial wastes [25]. Several commercial pathways have emerged: Carbon8 Systems' Accelerated Carbonation Technology (ACT) produces synthetic aggregates [27]; Solidia Technologies and Carbicrete reformulate cement and concrete with carbonated chemistries [28]. A persistent feature of ex-situ approaches is that CO_2 storage is achieved as solid carbonate minerals released to the marketplace as construction products. The boundaries of the EU 2024/2620 Annex reflect this: only construction products based on mineral carbonates are considered to permanently chemically bind CO_2 [11].

2.4 Surficial mine tailings carbonation

A specialized variant operates on ultramafic mine tailings (chrysotile, nickel, platinum group metal mines), where natural weathering already produces measurable carbonation rates [29]. Engineered approaches accelerate this process through tailings turnover, irrigation, or active CO_2 injection. Estimated annual potential is on the order of tens of $MtCO_2$ globally, but applicability is limited to sites with suitable mineralogy and sufficient tailings volume [30].

2.5 Marine carbon dioxide removal

Marine CDR includes ocean alkalinity enhancement (OAE), direct ocean capture (DOC), and engineered approaches that store captured industrial CO_2 as bicarbonate in seawater [31, 32]. Calcarea, a Caltech spinoff, exemplifies the latter: ship flue gas reacts with seawater and limestone, producing dissolved bicarbonate that is released into the open ocean [33]. The London Protocol restricts ocean dumping; engineered marine CDR sits in an ongoing legal and scientific debate [32, 34]. Importantly, marine CDR releases the carbon-bearing fluid into a natural body of water, distinguishing it from closed engineered systems.

2.6 The regulatory architecture and the grey zone

Beyond the scientific taxonomy, the regulatory expression of these categories shapes investment and deployment. Three regulatory streams are relevant for CO_2 fixation in industrial point sources serving CBAM-exposed exporters.

First, EU ETS Article 12(3b), introduced by Directive (EU) 2023/959, permits exemption from allowance surrender where CO_2 is “permanently chemically bound in a product” [3]. Commission Delegated Regulation (EU) 2024/2620 specifies the requirements: the binding must occur through an active and controlled utilization process; the bound CO_2 must remain chemically bound for “at least several centuries” under normal use and end-of-life conditions; and products subject to high-temperature combustion in normal end-of-life pathways are excluded [11]. The Annex enumerates only construction products based on mineral carbonates as currently qualifying. Plastics, e-fuels, urea, and short-lived chemical intermediates are excluded by virtue of their end-of-life trajectories.

Second, the EU CCS Directive (2009/31/EC) governs storage in geological formations [10]. Its scope is restricted to natural underground formations meeting specified geological criteria; it does not contemplate engineered closed reservoirs filled with aqueous slurry.

Third, the EU CRCF (Regulation (EU) 2024/3012) establishes a certification framework for permanent carbon removals, carbon farming, and carbon storage in products [5]. Permanent carbon removal methodologies are being developed in waves: DACCS, BECCS, and biochar in the first wave; enhanced rock weathering (ERW), ocean alkalinity enhancement, and mineralization in subsequent waves [35]. The CRCF “several centuries” durability standard parallels the EU ETS Article 12(3b) requirement.

An ECLMS-type system falls between these categories. It is not a marketed mineral product (failing the EU 2024/2620 Annex test as currently written). It is not a natural geological formation (failing the EU CCS Directive scope as currently written). It involves carbonation reactions with industrial alkaline feedstock (resembling ex-situ mineralization) but inside a sealed subsurface void with persistent aqueous phase (resembling solubility trapping in a saline aquifer). It is not marine CDR. The configuration is technically coherent and policy-relevant, but no current category captures it.

The PACM under Article 6.4 of the Paris Agreement is in early operational stages. The Supervisory Body adopted standards on baselines, additionality, leakage, suppressed demand, and non-permanence/reversals in 2025, and approved the first methodology (landfill gas) in October 2025 [36]. Methodologies for engineered mineralization remain to be developed. ECLMS would in principle be eligible for PACM methodology submission, but no precedent exists.

This regulatory pluralism, combined with the geographic asymmetry described in Section 1.1, motivates a focused taxonomic intervention: the formal recognition of an engineered closed-loop mineralization category that can integrate into multiple regulatory tracks without being forced into a category that does not fit.

3. The ECLMS framework

3.1 Definition

We define Engineered Closed-Loop Mineral Storage (ECLMS) as follows:

> *ECLMS is the storage of captured anthropogenic CO_2 in a sealed engineered subsurface containment, through aqueous-phase reaction with introduced alkaline mineral feedstock, resulting in durable retention of carbon as dissolved bicarbonate ions and precipitated carbonate minerals. The system is engineered (not relying on natural geological reservoirs alone), closed-loop (with no intentional release of carbon-bearing fluid to natural water bodies or the atmosphere), and mineralization-based (relying on alkaline-earth metal cation chemistry rather than purely physical trapping).*

Three elements are essential. First, the containment is sealed and engineered, meaning that the structural integrity of the storage volume does not depend solely on caprock geology but is supplemented by the geometry of an existing or constructed cavity (typically a repurposed mine void) and any necessary engineered seals. Second, the working medium is aqueous: the reaction proceeds in liquid water, with CO_2 dissolved as dissolved inorganic carbon (DIC) species and ultimately stabilized as bicarbonate and carbonate minerals. Third, mineralization provides the chemical permanence: alkaline-earth cations from introduced feedstock react with carbonate species to form thermodynamically stable carbonate minerals, with dissolved bicarbonate as a kinetic intermediate.

3.2 Conceptual architecture

The ECLMS system comprises six functional components:

- Containment vessel: A sealed underground void such as a repurposed coal mine, abandoned limestone or metal mine, or a purpose-built rock cavern. Containment is provided by surrounding rock plus engineered seals at access shafts and adits.
- Aqueous medium: Water (potentially recycled brine or treated industrial wastewater) fills the reactive volume and serves as both reaction solvent and storage matrix for dissolved bicarbonate.
- Alkaline mineral feedstock: Industrial by-products (BOF/EAF/BF slag, fly ash, cement kiln dust) or natural minerals (basalt, olivine, serpentine fines, limestone) provide Ca^{2+}, Mg^{2+}, and alkalinity. Feedstock is introduced initially and may be replenished as the system ages.
- CO_2 injection system: Captured CO_2 from a point source (steelmaking, cement, refining, power generation) is delivered to the reservoir, dissolved into the aqueous phase under modest pressure (typically 1 – 10 bar).
- Monitoring infrastructure: Sensors (pH, DIC, ion-selective electrodes for Ca^{2+} and Mg^{2+}, alkalinity) provide real-time assessment of reaction progress and containment integrity. Surrounding monitoring wells track any potential leakage to groundwater.

- Optional product handling: In semi-batch operation, precipitated carbonates may be periodically extracted for use as construction materials or aggregates, returning reactive volume to the system.

3.3 Operating modes

ECLMS can be operated in three distinct modes, each with different accounting and policy implications.

Mode A: Fully closed (no extraction)

Mode A operates in two distinct phases. During the active injection phase (typically several years), pre-ground slag and water are emplaced as a slurry and captured CO_2 is delivered to the reservoir at modest headspace pressure (1–10 bar). CO_2 dissolves into the aqueous phase and reacts with alkaline-earth cations to form carbonates; as reaction proceeds, CO_2 is consumed and headspace pressure decays, prompting periodic re-injection to maintain the reaction driving force. Injection continues until the feedstock approaches stoichiometric exhaustion and uptake rate plateaus — a natural operational endpoint detectable from the pressure–injection record. At this endpoint the reservoir contains predominantly solid carbonate minerals (the bulk of stored carbon), a buffered aqueous phase carrying a small dissolved-bicarbonate inventory, and a minimal residual gas-phase CO_2 headspace by operational design. The reservoir is then permanently sealed, with periodic alkalinity replenishment optional but no further CO_2 input required. This two-phase lifecycle most closely resembles geological storage from an accounting perspective. It maximizes containment integrity, minimizes monitoring complexity, and — as developed in Section 5.2 — yields a fundamentally different post-closure failure profile than gas- or supercritical-phase CCS. Per-reservoir capacity is bounded by initial feedstock loading.

Mode B: Semi-batch with mineral replenishment

Feedstock is introduced; CO_2 reacts; precipitated carbonates accumulate. After a residence period (typically months to years), settled solids are partially extracted via dedicated drainage systems. New feedstock is introduced, restoring reactive capacity. The aqueous phase remains in the reservoir continuously; only solids are removed. This mode increases throughput while preserving the closed-loop character. Extracted carbonates may be disposed (returning to a stable mineral form on the surface) or used in construction.

Mode C: Hybrid with downstream product recovery

Mode C extends Mode B by routing extracted carbonates to product applications meeting EU 2024/2620 Annex criteria. CO_2 stored as dissolved bicarbonate remains in the reservoir while CO_2 stored in extracted carbonates qualifies as product-bound CO_2. This dual-track approach allows simultaneous use of two regulatory pathways: storage-based accounting for the reservoir component and product-based accounting for the construction-product component.

3.4 Mapping to IPCC trapping mechanisms

ECLMS engages three of the four canonical trapping mechanisms identified in IPCC and CCS literature for geological storage [9, 16, 17]:

Trapping mechanism	Conventional geological CCS	ECLMS realization
Structural	Caprock and stratigraphic seal	Engineered seals plus host rock; full structural containment provided by closed cavity geometry
Residual (capillary)	Capillary trapping in pore networks	Not active (not a porous-media injection system)
Solubility	CO_2 dissolution in formation brine	Active and accelerated; primary kinetic pathway
Mineral	Slow reaction with formation minerals over centuries	Active and accelerated; primary thermodynamic endpoint via reaction with introduced alkaline feedstock

Table 1. Mapping of ECLMS to the four IPCC trapping mechanisms. Note that residual trapping is not relevant for non-porous-media systems; structural trapping is achieved through engineered means rather than natural caprock alone.

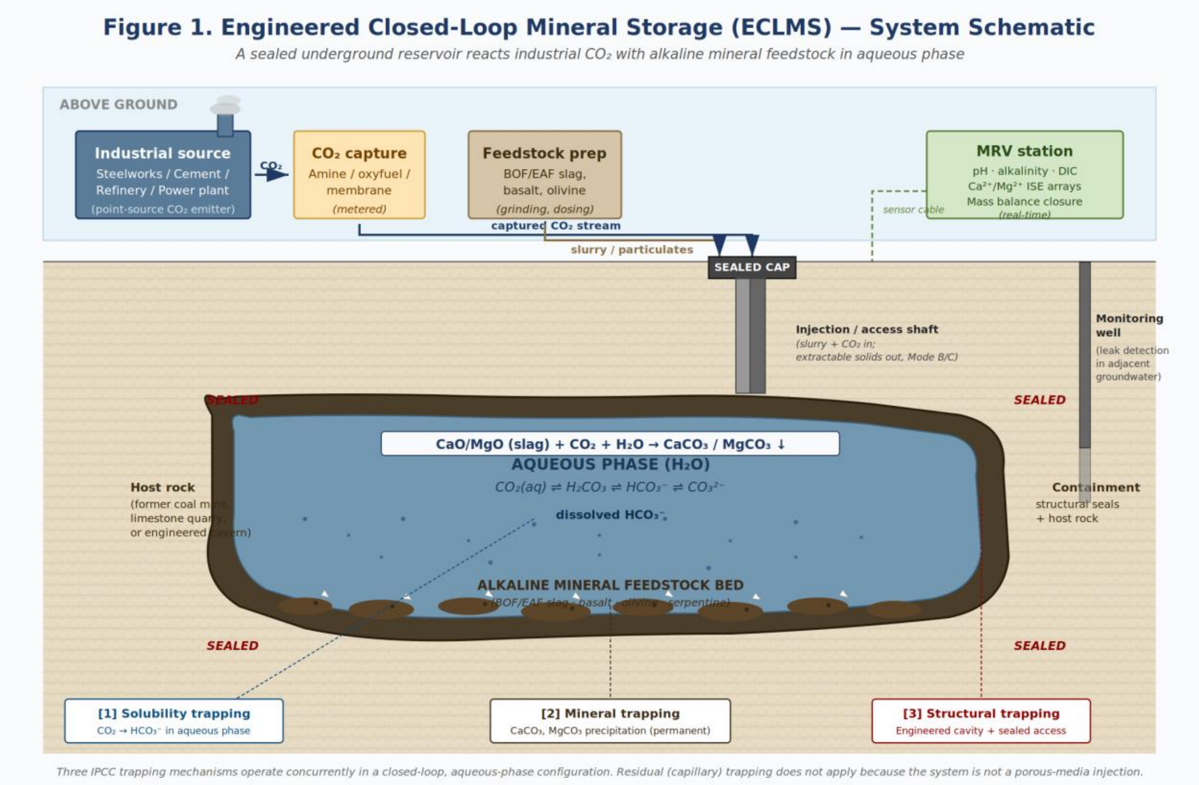

Figure 1. ECLMS system schematic. Industrial CO_2 captured at the point source is delivered to a sealed underground reservoir together with alkaline mineral feedstock and aqueous medium. Three IPCC trapping mechanisms (solubility, mineral, structural) operate concurrently in the closed-loop configuration. Real-time MRV is provided by surface instrumentation, with adjacent monitoring wells for leak detection in surrounding groundwater.

From a permanence standpoint, ECLMS combines the rapid kinetics of ex-situ reactor systems (enabled by ground feedstock, controlled pH, and engineered mixing) with the secure containment of geological storage (provided by the sealed subsurface void). The thermodynamic endpoint, calcium and magnesium carbonates, is the same geologically stable phase produced by all mineralization-based approaches.

3.5 Distinction from adjacent categories

Table 2 summarizes how ECLMS differs from each of the existing categories surveyed in Section 2.

Adjacent category	Reaction location	Storage matrix	Carbon endpoint	Distinction from ECLMS
In-situ basalt (Carbfix)	Natural rock formation	Natural pore space and minerals	In-situ carbonate	ECLMS uses engineered cavity and introduced feedstock; not dependent on natural reactive rock
Ex-situ surface reactor	Surface vessel	Reactor	Solid product (extracted)	ECLMS retains aqueous phase and operates underground; does not require surface industrial footprint
Surficial mine tailings	Surface tailings pile	Tailings	In-situ carbonate within tailings	ECLMS reaction occurs in sealed aqueous reservoir, not exposed surface piles
Carbon8/Carbstone (products)	Surface reactor	Construction product	Solid in marketed product	ECLMS may produce extracted carbonates but core storage is in-reservoir; products are optional
Calcarea (ocean bicarbonate)	Surface reactor	Open ocean	Dissolved bicarbonate (released)	ECLMS retains bicarbonate in closed reservoir; no marine release
EU 2024/2620 Annex products	Industrial process	Construction product	Mineral carbonate in product	ECLMS reservoir storage is not a marketed product; Mode C may produce qualifying co-products
Korean Dogye colliery pilot	Surface reactor (pre-reaction)	Mine void as backfill	Solid backfill	ECLMS reaction occurs in-reservoir, not pre-formed; aqueous phase and bicarbonate retained

Table 2. Distinction of ECLMS from adjacent categories. ECLMS is differentiated by the combination of engineered subsurface containment, in-reservoir aqueous-phase reaction, and retention of both dissolved bicarbonate and precipitated carbonates without release to natural water bodies.

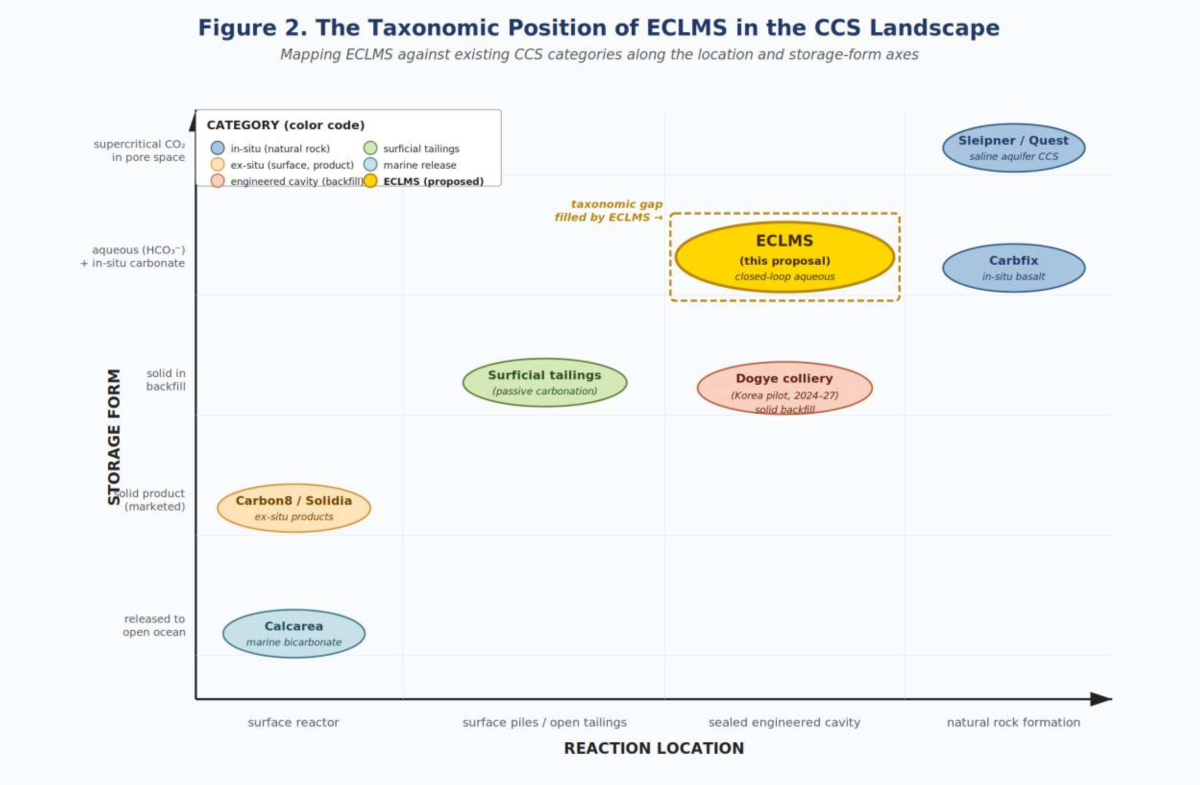

Figure 2. Taxonomic position of ECLMS in the CCS landscape, mapped along two axes: reaction location (surface reactor → sealed engineered cavity → natural rock formation) and storage form (released ocean → marketed product → backfill → aqueous bicarbonate plus in-situ carbonate → supercritical CO_2). ECLMS occupies a previously vacant cell in the landscape, intermediate between Carbfix-style natural in-situ mineralization, ex-situ product approaches (Carbon8, Solidia), and the Korean Dogye colliery pilot.

The Korean Dogye colliery pilot warrants particular attention. The pilot, announced in May 2024 and scheduled for the 2024 – 2027 period, plans to react industrial CO_2 with alkaline materials in surface reactors and emplace the resulting solidified products as mine backfill [12]. This is a closely related but distinct configuration: reaction occurs above ground, and the mine void serves primarily as a disposal volume for solid material. ECLMS proposes the alternative configuration in which the mine void itself becomes the reaction vessel, with aqueous phase and dissolved bicarbonate as integral storage components alongside precipitated carbonates. Dogye and ECLMS are best understood as two parallel Korean pathways exploring complementary uses of abandoned mine voids in CCS — Dogye demonstrating mine voids as storage volumes for ex-situ-produced solid carbonates, and ECLMS proposing in-reservoir aqueous-phase reaction. Each pathway has distinct chemistry, accounting, and engineering profiles, and neither is presented here as a successor to the other.

4. First-order capacity estimates

4.1 Approach and limitations

We provide order-of-magnitude estimates of cumulative CO_2 storage capacity for representative ECLMS reservoir geometries and feedstocks. These estimates are stoichiometric, drawing on published carbonation efficiencies for slag, basalt, and olivine. They are not substitutes for site-specific engineering analysis or pilot validation. We make explicit the assumptions used and provide sensitivity bounds.

Key assumptions: (i) reservoir total volume is fixed at the case-study value, with 50% occupied by alkaline solid feedstock and 50% by aqueous phase at start; (ii) feedstock is mechanically activated (typical $d_{50} = 50 – 100$ µm); (iii) operating temperature 25 – 40 °C; (iv) CO_2 partial pressure in the dissolved phase corresponds to 1 – 10 bar headspace; (v) carbonation efficiency depends on feedstock and is taken from published ranges. These assumptions are realistic for a well-engineered system but conservative compared to published high-temperature, high-pressure laboratory experiments [22, 23, 24, 25].

4.2 Single-batch capacity by feedstock

Theoretical maximum storage per ton of feedstock follows from CaO and MgO content using stoichiometric relationships:

$CaO + CO_2 \rightarrow CaCO_3$ (56 g CaO captures 44 g CO_2)

$MgO + CO_2 \rightarrow MgCO_3$ (40 g MgO captures 44 g CO_2)

Practical efficiency ranges are drawn from review literature [22, 23, 24, 25, 26, 27]. Table 3 summarizes results for a 10,000 m³ reservoir, with feedstock occupying 5,000 m³.

Feedstock	Bulk density (t/m³)	Mass loaded (t)	Theoretical max (tCO_2/t)	Practical efficiency	Single-batch capacity (tCO_2)
BOF/EAF slag (mean composition)	1.7	8,500	0.44	60 – 80%	2,250 – 3,000
Basalt (typical)	2.9	14,500	0.17	5 – 20%	120 – 500
Basalt (enhanced: fine grind, elevated T)	2.9	14,500	0.17	30 – 40%	740 – 990
Olivine (forsterite)	3.15	15,750	0.55	60 – 80%	5,200 – 6,900
$Ca(OH)_2$ (reference, fully hydrated lime)	2.2	11,000	0.59	90 – 95%	5,800 – 6,200

Table 3. First-order single-batch capacity estimates for a 10,000 m³ ECLMS reservoir at 50% feedstock packing. Practical efficiency ranges synthesize values reported across the slag and silicate carbonation literature for moderate-temperature aqueous conditions; site-specific values will vary with mineralogy, grind size, and reactor design. Note: the 0.44 tCO_2/t

theoretical maximum for BOF/EAF slag corresponds to ~56% CaO-equivalent feedstock (upper bound of the 30–60% range cited in Section 2.3); slags with mean composition (~40–45% CaO) yield a theoretical maximum closer to 0.31–0.35 tCO_2/t.

4.3 Cumulative capacity under Mode B

Under Mode B (semi-batch with replenishment), partially exhausted feedstock is removed and replaced. Practical limits emerge from accumulated precipitate and access infrastructure. We estimate that two to three feedstock turnovers are realistic before maintenance becomes prohibitive, assuming periodic settled-solids extraction. Under this assumption, cumulative capacity for a 10,000 m^3 reservoir is approximately:

- BOF/EAF slag: 4,500 – 9,000 tCO_2 cumulative
- Basalt (enhanced): 1,500 – 3,000 tCO_2 cumulative
- Olivine: 10,000 – 21,000 tCO_2 cumulative

Throughput rate is governed by carbonation kinetics. At moderate conditions, slag carbonation completes over months to a few years for the bulk of the feedstock; basalt and olivine require longer residence times. Annual processing rate per reservoir is typically 1,000 – 5,000 $tCO_2\ yr^{-1}$ for slag-based systems.

4.4 Aggregate national-scale potential: an illustrative case for the Republic of Korea

According to data published by the Korea Iron and Steel Association (KOSA), Korea generated approximately 25.3 Mt of steel slag in 2023 (14.6 Mt blast-furnace slag and 10.7 Mt steelmaking slag), with an industry-wide recycling rate of 94.1% [46]. Approximately 89% of blast-furnace slag (≈12.4 Mt) is currently used as cement raw material, with smaller fractions used as fill aggregate (≈5%) and road base (≈4%) [46]. Korea's 2024 crude steel production was 63.6 Mt, ranking sixth globally [47]. Generation ratios are approximately 400 kg blast-furnace slag and 170 kg steelmaking slag per ton of crude steel [48]. Industry recycling targets for 2024 were 100% for blast-furnace slag and 98.7% for steelmaking slag, reflecting a mature secondary materials market in which most slag is already directed to higher-value uses.

This high baseline utilization has direct consequences for ECLMS feedstock strategy. As with any mineral-CCS pathway that uses slag as feedstock — including Korea's Dogye colliery pilot, which similarly converts steel slag to solid carbonates for mine emplacement — diverting blast-furnace (BF) slag away from cement clinker substitution would, in principle, impose a system-level emissions penalty proportional to the carbon intensity of displaced Portland clinker (~0.85 tCO_2/t clinker) [28]. This is a sector-wide accounting challenge for Korean mineral CCS, not specific to ECLMS, and a full consequential life-cycle analysis is required before deployment claims for any such pathway. A particularly attractive ECLMS feedstock segment, however, is the fraction of basic-oxygen-furnace (BOF), electric-arc-furnace (EAF), and ladle slags whose high free-CaO content makes them volumetrically unstable for cement applications: these slags are penalized in cement markets precisely because of the same reactivity that benefits ECLMS, making this segment a structural sweet spot rather than a competitive battleground. The residual ~11% of BF slag (~1.6 Mt yr^{-1}) currently routed to lower-value uses such as fill aggregate and road base, and any future slag volumes liberated by hydrogen-DRI conversion in steelmaking, further expand the addressable feedstock without aggravating cement-displacement accounting. A first-order envelope assuming diversion of approximately 10% of Korea's annual slag generation to ECLMS yields theoretical annual storage of:

$$25.3\ \text{Mt} \times 0.10 \times 0.30\ \text{tCO}_2/\text{t} \approx 0.76\ \text{Mt CO}_2\ \text{yr}^{-1}$$

Korean abandoned mine void volume is on the order of tens of millions of cubic meters across former coal mines (Taebaek, Jeongseon, Samcheok), former limestone and dolomite mines (Danyang, Jecheon, Yeongwol), and former metal and quarry sites. Even fractional utilization provides reservoir capacity well in excess of multi-decade slag-based ECLMS deployment. With the closure of the Dogye colliery in June 2025 — ending 89 years of operation and marking the end of the state-owned Korea Coal Corporation's mining era [49] — substantial new void volume becomes available specifically in the Samcheok-Taebaek coal belt. We do not develop a detailed national inventory here; this illustrative calculation is intended only to show that capacity is not the binding constraint.

These estimates are first-order, stoichiometric, and should not be interpreted as deployment forecasts. Site selection, regulatory approval, capture costs, and consequential life-cycle accounting (including displaced cement-substitution emissions where applicable) all impose practical limits. Full LCA parameterized for Korean steel-cement-mine triads is identified as a research priority (Section 8.2).

4.5 Korean reservoir resource inventory

A central premise of this paper is that storage-deficit jurisdictions can leverage non-conventional reservoir resources — abandoned mine voids and engineered caverns — in place of natural saline aquifers. We provide here a first-order inventory for the Republic of Korea, distinguishing four resource tiers and contrasting them with the limited natural saline aquifer endowment.

4.5.1 The natural saline aquifer deficit

Korea's natural saline aquifer capacity has been the subject of multiple national assessments. Theoretical (volumetric) estimates published by the Ministry of Oceans and Fisheries identified approximately 5.1 $GtCO_2$ of P_{50} storage in the southwestern Ulleung Basin alone [51]. KIGAM and other studies have evaluated additional offshore basins (Gunsan East sub-basin: ~2.0 $GtCO_2$ theoretical; Namhaedo sub-basin: ~1.2 $GtCO_2$ theoretical) [52]. However, capacity at the more demanding 2.5-tier evaluation (incorporating well-log calibration and storage efficiency factors) reduces conservatively-estimated practical capacity to approximately 0.3 – 0.6 $GtCO_2$ nationally [52]. Onshore saline aquifers are explicitly excluded from these national assessments as too small to support large-scale deployment. The Donghae-1 conversion project (2025 – 2030) targeting 1.2 Mt CO_2 yr^{-1} represents the largest near-term commitment of this scarce capacity [8]. Korea's natural saline aquifer endowment is therefore best characterized as limited and substantially pre-allocated.

4.5.2 Abandoned mine voids: Tier 1–3 inventory

Korea's abandoned mine inventory, by contrast, is unusually rich. We organize it into three tiers ordered by deployment readiness.

Tier 1 — immediately accessible, operational infrastructure. This tier comprises non-coal mines with documented void geometry and existing access (e.g., the Eonyang amethyst mine in Ulju, Ulsan, with approximately 2.5 km of galleries on two levels and a documented 500-m artificial water channel of 2 m depth [53]) and abandoned limestone, dolomite, and metal mines in Danyang, Jecheon, Yeongwol, Bonghwa, and Uljin counties. Estimated cumulative void volume in Tier 1 is on the order of $1 – 5 \times 10^6$ m^3.

Tier 2 — recently closed coal mines with mature post-closure planning. The Dogye colliery (closed 30 June 2025), the Jangseong colliery (closed 2024), and the Hwasun colliery (closed 2023) collectively cover approximately 89, 54, and 60 years of operation respectively [49]. The Dogye colliery alone produced 43 Mt of coal over its lifetime; assuming a coal in-situ density of approximately 1.3 t/m^3 and that 10 – 15% of the originally-mined volume remains accessible after subsidence and backfill, the residual gallery volume is on the order of $3 – 5 \times 10^6$ m^3 for Dogye alone, with comparable volumes available at Jangseong and Hwasun. Tier 2 cumulative volume is estimated at $0.8 – 1.5 \times 10^7$ m^3.

Tier 3 — the broader inventory of historical Korean coal and metal mines. Korea's coal-mining history extends through the Taebaek-Jeongseon-Samcheok belt, the Mungyeong basin, the Hwasun field in Jeollanam-do, and various smaller fields. Metal mining (former gold, silver, tungsten, lead-zinc operations) and large-scale limestone and dolomite quarrying (Danyang, Jecheon) extend the resource base further. Cumulative Tier 3 void volume is estimated at $5 – 13 \times 10^7$ m^3, though much of this requires substantial site characterization and remediation before any ECLMS application could be considered. Detailed inventories are held by the Korea Mine Reclamation and Mineral Resources Corporation (KOMIR) and would form the empirical foundation for any national deployment plan.

4.5.3 Engineered caverns and other underground containment

A separate resource is the existing inventory of engineered underground storage caverns developed for liquefied petroleum gas (LPG) and other hydrocarbon storage. Korean LPG storage caverns at Incheon and Ulsan, typically located 100 – 200 m below surface and using the water-curtain principle for hydraulic isolation, demonstrate decades-long containment integrity [54]. Reported water chemistry inside the

Incheon LPG cavern includes pH 8.1 – 12.4 (reflecting cement grouting effects), Na-Cl-type composition, and reducing conditions [54]. These chemical conditions are favorable for slag carbonation reactions; the caverns themselves are not currently designated for CO_2 storage but illustrate the technical feasibility of large-volume aqueous-phase containment in Korean granitic and gneissic terrain. The same underground rock cavern technology that supports LPG storage and is now being studied for liquid hydrogen storage [55] is directly transferable to purpose-built ECLMS reservoirs in regions without suitable abandoned mines.

4.5.4 Capacity matching: feedstock as the binding constraint

Combining the slag feedstock estimate from Section 4.4 with the reservoir inventory above clarifies the binding constraint on Korean ECLMS deployment. Annual slag throughput of 0.76 Mt CO_2 yr^{-1} (10% of slag generation, 0.30 tCO_2/t efficiency) at typical reservoir loading densities translates to an annual reservoir consumption of approximately $2 – 5 \times 10^4$ m^3 yr^{-1}. Over a 30-year deployment horizon this requires $0.6 – 1.5 \times 10^6$ m^3 of cumulative reservoir capacity. This volume is well within Tier 1 alone and corresponds to a small fraction of Tier 2. The implication is clear: in Korea, reservoir capacity is not the binding constraint on ECLMS deployment. The binding constraint is the supply of alkaline feedstock and, beyond that, capture cost. This is a structurally favorable configuration for a storage-deficit jurisdiction — it inverts the usual constraint pattern of CCS, in which reservoir characterization and permitting dominate project economics.

4.6 Levelized cost (order of magnitude)

Levelized cost of CO_2 avoidance for ECLMS depends on capture cost (the dominant component, typically USD 50 – 120/tCO_2 for industrial point sources), feedstock processing cost, reservoir preparation cost, and MRV cost. Drawing on ex-situ mineralization techno-economic literature [22, 25, 28] and adjusting for the use of repurposed mine voids (which substantially reduces civil engineering cost relative to constructed reactors), we estimate ECLMS levelized cost in the range USD 40 – 150 per ton of CO_2 stored. This is competitive with in-situ CCS (USD 60 – 150/t in mature basins [37]) and substantially lower than DACCS (USD 300 – 600/t at present [38]). Detailed techno-economic analysis is beyond the scope of this perspective and is identified as a research priority in Section 8.

5. Monitoring, reporting, and verification framework

Robust MRV is decisive for any CCS approach to enter compliance markets, voluntary carbon markets, or national inventories. We sketch an MRV framework adapted to the closed-loop, aqueous-phase character of ECLMS, and argue that the resulting framework is, in several respects, simpler than MRV for natural geological storage.

5.1 Closed-system simplification and core measurement set

Conventional geological storage MRV must contend with three-dimensional plume migration over kilometers of subsurface, with monitoring achieved indirectly through seismic surveys, pressure transients, and downhole logs [39, 40]. ECLMS, by contrast, confines the working volume to a sealed cavity of known geometry. Carbon mass balance reduces to a closed control volume problem: CO_2 in (metered at injection), CO_2 chemically partitioned among gas phase, dissolved CO_2, bicarbonate, carbonate, and precipitated minerals (assessed via aqueous chemistry), and any leakage out (assessed via surrounding monitoring wells). The pressure–injection time series itself functions as a built-in primary MRV signal: during the active injection phase, headspace pressure decays as CO_2 is consumed by carbonation, requiring intermittent top-up injection; the decay rate progressively slows as feedstock approaches exhaustion, and the system asymptotes to a stable low-pressure state when carbonation is effectively complete. The transition to this stable state constitutes an operationally observable endpoint for transferring the reservoir from active management to permanent closure.

We propose the following minimum measurement set: continuous metering of injected CO_2 mass; continuous aqueous-phase monitoring of pH, alkalinity, dissolved inorganic carbon (DIC), and electrical conductivity; ion-selective electrode (ISE) measurement of Ca^{2+} and, where relevant, Mg^{2+} activity; periodic solid-phase sampling for X-ray diffraction (XRD), thermogravimetric analysis (TGA), or scanning electron microscopy (SEM) to verify carbonate mineralogy and quantify precipitate accumulation; pressure monitoring of the sealed reservoir; surrounding groundwater monitoring wells; and periodic mass balance reconciliation. The combination of pH, alkalinity, DIC, and Ca^{2+} activity is sufficient to determine DIC speciation and to estimate the saturation state of relevant carbonate minerals through standard aqueous thermodynamic models [41]. ISE-based measurement is mature in industrial water chemistry and increasingly used in environmental biogeochemistry.

5.2 Permanence verification and standards alignment

Permanence in ECLMS rests on three pillars: the thermodynamic stability of carbonate minerals, well-established over geological timescales [9, 16]; the structural containment of the engineered void; and the persistence of buffered alkaline conditions that maintain the bicarbonate phase against re-acidification. A fourth, distinguishing pillar is the speciation of stored carbon at permanent closure. Because Mode A is operated until carbonation is effectively complete (Section 3.3), the reservoir at closure contains the bulk of injected carbon in solid carbonate minerals and a smaller fraction as dissolved bicarbonate in a buffered aqueous phase, with minimal residual gas-phase CO_2 by design. This inverts the conventional CCS permanence problem: where gas- and supercritical-phase CCS must guarantee that a mobile, buoyant, low-density CO_2 inventory remains immobilized over centuries, ECLMS at closure stores carbon predominantly in immobile, high-density, thermodynamically stable mineral form. Catastrophic containment failure scenarios — for example seismic damage to the cavern or breach of engineered seals — would disperse carbonate solids and bicarbonate-bearing brine into surrounding rock and groundwater, where carbon remains chemically bound; the practical degradation pathway is acidic redissolution to bicarbonate, which is itself a sequestered species, not gaseous CO_2. This failure mode is mechanistically equivalent to natural carbonate weathering, which operates over millennial timescales and constitutes one of the dominant long-term sinks in the geological carbon cycle. ECLMS therefore offers a categorically different permanence proposition from CCS pathways that store carbon in mobile fluid form. Long-term verification requires periodic confirmation that pH and alkalinity remain in ranges that preclude bicarbonate decomposition, and that no leakage is detected in surrounding monitoring wells. Compared to in-situ geological CCS, ECLMS offers superior permanence verification at a fraction of the cost; compared to ex-situ reactor systems producing marketed carbonate products, ECLMS removes the need to track product fate after sale, which has been a longstanding accounting concern under the EU 2024/2620 framework [11, 42].

Existing CCS MRV standards (ISO 27914 for geological storage, ISO 27919 for monitoring, EU Monitoring and Reporting Regulation Article 49) provide partial templates [43]. We propose that ECLMS MRV be developed as an explicit module aligned with these standards but adapted for the closed-loop aqueous configuration. Alignment with the IPCC 2006 Guidelines for National Greenhouse Gas Inventories, particularly Volume 2 Chapter 5 on CCS, would enable inclusion in national inventory reports [44].

6. Accounting and regulatory pathways

We now examine how ECLMS would be treated under each major accounting framework. The discussion is normative as well as descriptive: we identify both the current text-based interpretation and the modifications needed for explicit recognition.

6.1 EU ETS Article 12(3b) and Delegated Regulation 2024/2620

Under current text, the EU ETS exemption for permanently chemically bound CO_2 is operationalized through the Annex of Commission Delegated Regulation (EU) 2024/2620, which lists only construction products based on mineral carbonates [11]. ECLMS in Modes A and B does not produce a marketed construction product; the carbonate phase is retained in the reservoir. Under the current Annex, ECLMS Modes A and B are not eligible for Article 12(3b) exemption. ECLMS Mode C, by virtue of producing extracted carbonates that may be used in construction products, can in principle qualify under the existing Annex for the product-bound fraction of CO_2.

However, Article 4 of Regulation 2024/2620 establishes a procedure for reviewing and updating the Annex based on "relevant technological developments and innovation in the field of permanent carbon storage in products" and "improvements in monitoring, reporting and verification practices." We argue in Section 8 that an extension of the Annex to include closed-loop in-reservoir mineralization is justifiable on three grounds: (i) the chemical permanence (carbonate minerals plus buffered bicarbonate) meets the same "several centuries" standard as Annex-listed products; (ii) the closed-loop configuration eliminates the end-of-life uncertainty that constrains the current product-based wording; (iii) the engineering containment provides equal or greater integrity than the recycled construction-and-demolition pathway used to justify the existing Annex.

6.2 EU CCS Directive

Directive 2009/31/EC defines geological storage as "injection accompanied by storage of CO_2 streams in underground geological formations" [10]. The literal interpretation excludes engineered closed reservoirs not residing in qualifying natural geological formations. However, the policy intent is the secure containment of injected CO_2, and the Directive's safeguards (site characterization, permitting, monitoring, leakage liability, post-closure transfer) translate naturally to ECLMS sites. Repurposed mine voids in some cases qualify directly, since the host rock formation is itself a natural geological formation; the mine void is an engineered modification of that formation. We argue that an interpretive note or amendment recognizing repurposed mine voids as eligible storage volumes, subject to the Directive's safeguards adapted for the aqueous closed-loop configuration, would be a parsimonious extension.

6.3 EU Carbon Removal Certification Framework

Regulation (EU) 2024/3012 establishes the CRCF and requires “several centuries” durability for permanent carbon removal certificates [5]. Methodology development is staged in waves: DACCS, BECCS, and biochar in the first wave [35], with the European Commission adopting the first set of permanent removal methodologies under the CRCF in February 2026. Mineralization is part of subsequent waves. ECLMS aligns with CRCF on durability and on the engineered, controlled character of the activity.

A jurisdictional caveat: ECLMS as proposed here primarily serves point-source emission reduction (a CCS function) rather than atmospheric removal (a CDR function). The CRCF accommodates both “permanent carbon removals” and “carbon storage in products,” but not unambiguously a “permanent storage of point-source captured CO_2” as a third category. This is a definitional issue that deserves explicit address. One option is to treat ECLMS storage of biogenic or atmospheric CO_2 as CDR-eligible while treating storage of fossil CO_2 as CCS-eligible (i.e., emission reduction rather than removal). This bifurcation is consistent with the broader CCS/CDR distinction.

6.4 Article 6.4 PACM

The Article 6.4 Supervisory Body has approved standards on baselines, additionality, leakage, and non-permanence/reversals, and approved its first methodology (landfill gas) in October 2025 [36]. ECLMS is in principle eligible for methodology submission. The non-permanence/reversal standard requires explicit risk assessment and, in higher-risk cases, buffer pool contributions or insurance mechanisms.

ECLMS has favorable characteristics on the non-permanence dimension: chemical permanence of carbonates is intrinsic, and the closed engineered system limits exogenous reversal pathways. Methodology submission would need to specify (i) baseline scenario (counterfactual emissions absent the project), (ii) additionality (financial and policy tests), (iii) leakage (slag diversion from existing uses), and (iv) reversal risk quantification. Methodology submissions are made through host-country Designated National Authorities, with concurrent stakeholder input under Supervisory Body procedures.

6.5 IPCC inventory guidelines

The IPCC 2006 Guidelines, with the 2019 Refinement, provide reporting categories under Volume 2 Chapter 5 for CCS activities [44]. ECLMS would be reportable under existing CCS categories with appropriate adaptation. Specifically, captured CO_2 is reported as not emitted at the source; storage volumes and any monitored leakage are reported under the storage activity. The closed-loop nature simplifies leakage reporting: continuous monitoring of the sealed system substitutes for the multi-decadal post-injection plume tracking required for natural saline aquifer storage.

6.6 CBAM Article 9 and the carbon-price deduction

CBAM Article 9 permits deduction of carbon prices effectively paid in the country of origin from the CBAM certificate obligation [4]. The deduction is conditional on the absence of compensating rebates or other forms of carbon-price reduction. If K-ETS were to recognize ECLMS-stored CO_2 as deducted from emissions, the resulting K-ETS allowance saving would be reflected in the carbon-price deduction, provided the K-ETS recognition aligns with EU criteria for permanence and accounting integrity. This alignment is the practical reason why an explicit ECLMS category is valuable: it provides a defensible technical and regulatory basis for K-ETS deduction that is intelligible to EU verifiers.

7. Korean pilot demonstrations and policy context

7.1 Dogye colliery pilot as first-of-a-kind

The Dogye colliery pilot in Samcheok City, Gangwon Special Self-Governing Province illustrates both the policy momentum and the technical proximity to the ECLMS concept. The project, formally titled the "Abandoned Mine CO_2 Land Storage Demonstration Project" (폐갱도 이산화탄소 육상저장 실증사업), runs from 2024 through 2027 with an initial public budget of KRW 6.76 billion and is positioned as Korea's first onshore CCS demonstration [12]. Participants include POSCO Holdings, KOMIR, Tekros Water and Energy, Carbonco, the Ministry of Trade, Industry and Energy, and Samcheok City [12, 50]. The technical premise is to react steel slag with industrial CO_2 in surface processing to produce calcium carbonate solids, which are then emplaced as backfill in the abandoned colliery galleries [50]. The Dogye colliery itself was officially closed on 30 June 2025 after 89 years of operation, and the Korea Environment Corporation (K-eco) was selected in June 2025 as the lead agency for the Recycling Environmental Assessment, with assessment activities ongoing through 2026 [49, 50].

Dogye is technically distinct from full ECLMS in two ways: the carbonation reaction occurs above ground in surface processing, with the mine void serving as a storage volume for solidified products; and the project does not foreground the aqueous-phase, dissolved-bicarbonate stabilization that is central to ECLMS Modes A and B. Nonetheless, Dogye provides the institutional scaffolding (KOMIR involvement, Ministry support, municipal commitment, public funding, formal environmental assessment) and the social-license demonstration that an ECLMS deployment would require. The Dogye pilot and ECLMS-type configurations are best treated as parallel branches of a shared Korean institutional learning curve on CCS in abandoned mines. Dogye establishes the policy, permitting, environmental-assessment, and stakeholder-engagement templates relevant to any Korean mine-void CCS project. Subsequent Korean pilots — whether following the Dogye approach, the ECLMS approach, or hybrid configurations — would build on this shared institutional foundation. The configurations should be evaluated on their own technical and regulatory merits rather than positioned in a successional hierarchy. Such an extension would deliver substantially higher per-reservoir capacity through replenishable feedstock and dissolved-phase buffering, lower above-ground footprint, and closer alignment with the structural-trapping logic of geological CCS.

7.2 Coastal steelmaking sites as natural ECLMS hubs

Korean coastal steelmaking complexes — POSCO's Pohang and Gwangyang works, Hyundai Steel's Dangjin works — combine large CO_2 emission point sources with on-site slag generation, deep harbor infrastructure, and proximity to coal mines and limestone quarries with significant void volumes within transport range. With Korea's 2024 crude steel production of 63.6 Mt (sixth globally) [47], these complexes generate approximately 25 Mt of slag annually [46] and represent a substantial fraction of national industrial CO_2 emissions. An integrated ECLMS deployment would couple CO_2 capture from the steelmaking process with slag-based aqueous mineralization in repurposed mine voids in nearby provinces, with capture, on-site dewatering and grinding, and pipeline or rail transport of slurry to mine sites forming a contiguous logistics chain. These sites are also among the most CBAM-exposed Korean industrial assets; effective CBAM cost mitigation requires storage solutions whose accounting is recognized at the EU verifier interface, and ECLMS recognition would directly translate K-ETS allowance savings into CBAM Article 9 deductions.

7.3 Korean policy environment

Korea's CCUS Act (formally, the「Act on Carbon Dioxide Capture, Transport, Storage and Utilization」), promulgated on 6 February 2024 and entered into force on 7 February 2025 per its supplementary provisions, provides the legal foundation for CCS storage permitting, MRV, project support, and industrial cluster designation [45]. The Act establishes administrative and financial support mechanisms for CCUS R&D, demonstration projects, and industrialization, with permitting consolidation through legal fictions (의제) covering pressure vessels, marine area use, and related authorizations [45]. The Act is technology-agnostic in formulation, focusing on procedural integrity rather than enumerating specific storage modalities. ECLMS would in principle be eligible under the Act, subject to implementing regulations now under development.

The K-ETS, currently in its fourth phase (2026 – 2030), recognizes deductions for CO_2 captured and used in qualifying applications, including transfer to sequestration facilities. Implementing regulations have progressively expanded the eligible categories. An explicit recognition of ECLMS as a sequestration facility category, with associated MRV requirements, would be a natural extension and would align Korean accounting with prospective EU recognition.

The 2025 Korean government reorganization has consolidated climate and energy functions in a new Ministry of Climate, Energy and Environment, with industrial policy retained in a slimmed-down Ministry of Trade and Industry. This transition creates an opportunity to introduce a coherent ECLMS framework within the new ministerial architecture rather than retrofitting it onto fragmented predecessor responsibilities.

8. Discussion: research and policy agenda

8.1 What this paper does and does not claim

This perspective claims that ECLMS is a technically coherent and policy-relevant CCS configuration that does not currently fit cleanly into any recognized accounting or regulatory category, and that explicit recognition would unlock deployment in storage-deficit jurisdictions. We do not claim that ECLMS is technically validated at pilot or commercial scale, that the cost estimates are accurate to better than order of magnitude, or that the modes proposed will all prove practical. Pilot-scale experimental validation, including coupled experimental and reactive-transport modeling work, is a prerequisite for any deployment claim. ECLMS is best understood as a complementary modality, expanding the toolkit available to jurisdictions with abundant alkaline by-products, mine void resources, and CBAM exposure — not as a substitute for natural geological storage or for ex-situ products.

8.2 Research priorities

We identify five priorities for empirical and analytical research.

- Bench-scale aqueous carbonation kinetics under closed-loop conditions, with particular attention to the dynamic balance between dissolved bicarbonate and precipitated carbonate phases in slag and basalt systems.
- Pilot-scale demonstration in a representative Korean abandoned mine, including site characterization, hydraulic isolation engineering, instrumentation, and a multi-year reaction monitoring campaign.
- Reactive-transport modeling of multi-year reservoir evolution, coupled with the experimental work in (a) and (b), to establish the long-term trajectory of pH, alkalinity, and mineral assemblage.
- Detailed techno-economic analysis covering capture, transport, feedstock processing, reservoir preparation, MRV, and lifecycle decommissioning, parameterized for representative Korean steel-cement-mine triads.
- Geomechanical and hydrogeological characterization of candidate reservoirs, scaled to the deployment pathway. Where ECLMS is deployed in repurposed coal-mine voids, characterization must address: (i) hydraulic-loading-induced reactivation of mine subsidence and roof-collapse history in multi-level workings; (ii) sealing integrity across the typically large number of shafts, adits, and ventilation crosscuts; (iii) interaction between alkaline ECLMS slurry and pre-existing acid mine drainage (AMD) chemistry, including potential mobilization of metals; and (iv) management of residual coal-bed methane. Where ECLMS is deployed in engineered caverns of the Incheon–Ulsan LPG-storage type (Section 4.5.3) or in purpose-built rock caverns, items (i)–(iv) largely fall away, and characterization reduces to standard underground-storage site selection plus

verification of seal integrity under aqueous-alkaline conditions. In either pathway, site-specific induced-seismicity assessment is required — which, in the post-2017 Pohang policy environment, must be addressed empirically rather than asserted, even for low-pressure aqueous configurations. Coupled environmental and social impact assessment must accompany the geomechanical work, covering regional groundwater chemistry under alkaline slurry leakage scenarios, downstream ecological receptors, and structured engagement with former mining communities and local governments whose social license is decisive for siting.

8.3 Policy recommendations

We make six policy recommendations addressed to specific institutional venues.

- To DG CLIMA: under Article 4 of Regulation 2024/2620, review and update the Annex to consider including closed-loop in-reservoir mineralization as a recognized permanent storage modality, conditioned on appropriate MRV and containment standards.
- To DG CLIMA and the CRCF Expert Group: in the methodology development for mineralization-based permanent carbon removal, accommodate the engineered closed-loop in-reservoir configuration as a sub-category alongside in-situ and ex-situ approaches.
- To the Article 6.4 Supervisory Body and Methodological Expert Panel: include closed-loop engineered mineralization in the work plan, with attention to the distinct accounting of point-source captured CO_2 versus atmospheric removals.
- To the IPCC TFI: provide guidance, in the next refinement cycle, on inventory treatment of ECLMS-type storage under Volume 2 Chapter 5, ensuring consistency with existing CCS reporting categories.
- To Korean ministries (Climate, Energy and Environment; Trade and Industry): develop CCUS Act implementing regulations that explicitly recognize ECLMS-type configurations, and align K-ETS deduction rules with EU permanence criteria to ensure CBAM Article 9 recognition.
- To Korean industry (POSCO, Hyundai Steel, cement majors) and KOMIR: convene a public-private consortium to develop a Korean pilot extending the Dogye colliery experience toward full ECLMS configuration, with international scientific advisory engagement to support concurrent international standardization.

8.4 International applicability

Although this paper foregrounds the Korean context, ECLMS is potentially relevant to any jurisdiction combining limited natural geological CCS capacity, abundant abandoned mine void volume, and substantial alkaline industrial waste streams. Japan, Vietnam, Indonesia, Malaysia, the Philippines, and parts of India share aspects of this profile. China possesses substantial natural saline aquifer capacity but also has very large slag and mine void inventories and could deploy ECLMS as a complement to conventional CCS. The framework is not Korea-specific, and its international standardization would directly support cross-border CCS deployment.

8.5 Conclusion

The expansion of CBAM and the tightening of EU permanence standards have created strong incentives for credible CCS deployment in CBAM-exposed jurisdictions. Where natural geological storage is unavailable or undeveloped, the existing CCS taxonomy leaves a structural gap. ECLMS — closed-loop, aqueous-phase, in-reservoir mineralization in repurposed mine voids — is a technically coherent and policy-relevant modality that occupies this gap. The Korean Dogye colliery pilot offers a first-of-a-kind reference point. With appropriate regulatory recognition, MRV standardization, and pilot-scale empirical validation, ECLMS can become a practical complement to existing CCS pathways and a basis for accountable, CBAM-compliant CCS deployment in storage-deficit jurisdictions. We submit this perspective to invite empirical, regulatory, and industrial engagement.

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Conflicts of interest

The authors declare no financial conflicts of interest. The authors have no affiliation with any commercial entity active in the CCS, mineralization, or carbon credit sectors.

Data availability

This paper presents no new experimental data. Capacity and cost estimates are derived from publicly available literature cited in the references. Calculation worksheets are available from the corresponding author on request.

Author contributions

BongKwan Song: conceptualization, formal analysis, writing (original draft). SeoYeon Kim: formal analysis, writing (review and editing). Both authors approved the final manuscript.

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End of manuscript.