# Dissolved Inorganic Carbon as Ocean Carbon Storage

## DURABILITY AND RISKS

OCEAN VISIONS

## Executive Summary


Carbon capture and storage could play an important role in reducing emissions from hard-to-abate sectors, including maritime transport and other industries that may continue to use carbon-containing fuels during the transition to a low-carbon economy. Most storage efforts have focused on injecting compressed carbon dioxide into underground geologic formations. However, suitable geology is not available everywhere, purifying and compressing carbon dioxide is energy intensive, and transporting carbon dioxide to storage sites adds cost, infrastructure needs, and operational complexity.

Ocean-based dissolved inorganic carbon storage is underappreciated in the carbon management community but is underpinned by sound scientific fundamentals and could complement geologic sequestration, particularly in coastal and ocean settings. Its relevance has increased as technology developers have begun piloting ship-based and coastal systems that react carbon dioxide from vessel exhaust, industrial flue gas, or atmospheric removal with water and limestone in engineered reactors. This process, called accelerated weathering of limestone, converts much of the carbon dioxide into bicarbonate and carbonate ions before the treated water is discharged. These forms of carbon together make up dissolved inorganic carbon.

Once bicarbonate and carbonate ions are added to the ocean, their removal is governed by slow geochemical processes, giving dissolved inorganic carbon storage durability of tens of thousands of years. However, most carbon capture and storage frameworks were designed for underground injection and do not yet clearly address this ocean-based storage pathway.

Taken together, these characteristics support treating dissolved inorganic carbon storage as a durable complement to geologic sequestration, particularly where capture and storage can occur at the same location. However, deployment will require substantial process-water handling and careful management of conversion efficiency and local environmental effects. The immediate priority is to test these systems at relevant scales and establish transparent standards for comparing their performance, costs, and risks with other storage options.



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# Dissolved Inorganic Carbon: The Largest Reservoir of Carbon

When carbon dioxide ($CO_2$) dissolves into water, a small fraction reacts with water molecules to form carbonic acid. A fraction of the carbonic acid separates into a bicarbonate ion ($HCO_3^-$) and a hydrogen ion ($H^+$) in a reversible process. Some of that bicarbonate can react further, becoming a carbonate ion ($CO_3^{2-}$) and another hydrogen ion ($H^+$).[1] These forms—carbon dioxide, bicarbonate, and carbonate—underpin basic ocean chemistry with the carbon shifting between these chemical forms, governed by well-understood reactions:

$$CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+ \quad (1)$$

$$HCO_3^- \rightleftharpoons CO_3^{2-} + H^+ \quad (2)$$

The ability of water to absorb carbon dioxide is increased by the process of adding alkaline materials to water. In the natural alkalinity cycle, alkalinity comes from a well-established origin: the weathering of rocks on land. Rainwater and carbon dioxide react to form carbonic acid, which reacts with carbonate (see equation 3 below) and silicate minerals to produce dissolved bicarbonate along with cations such as calcium and magnesium; rivers then carry these compounds to the ocean.[2]

$$CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^- \quad (3)$$

Over millions of years, this weathering process has resulted in an oceanic reservoir of approximately 38,000 billion tons, or gigatons, of dissolved carbon, with nearly 90% in the form of bicarbonate, and another ~9% in the form of carbonate and the rest being dissolved carbon dioxide gas and carbonic acid. For comparison, the atmosphere holds only 870 gigatons of carbon, and the entire biosphere and soils combined hold 3350 gigatons. The ocean is therefore the largest reservoir in the natural carbon cycle.[3]

| KEY NUMBERS | | |
|---|---|---|
| **~38,000 Gt C** | **~44x** | **≥10,000 yrs** |
| Dissolved inorganic carbon stored in the ocean | More carbon in the ocean than in the atmosphere | Expected durability of dissolved inorganic carbon storage |

### Why Dissolved Inorganic Carbon Storage Is Durable on Climate-Relevant Timescales

Once carbon dioxide has reacted with water and rock to form carbonate and bicarbonate, the carbon is stored in the ocean (see Figure 1). While carbon dioxide molecules can move back and forth between the water and the atmosphere, bicarbonate and carbonate ions held in solution cannot leave the ocean and would first have to

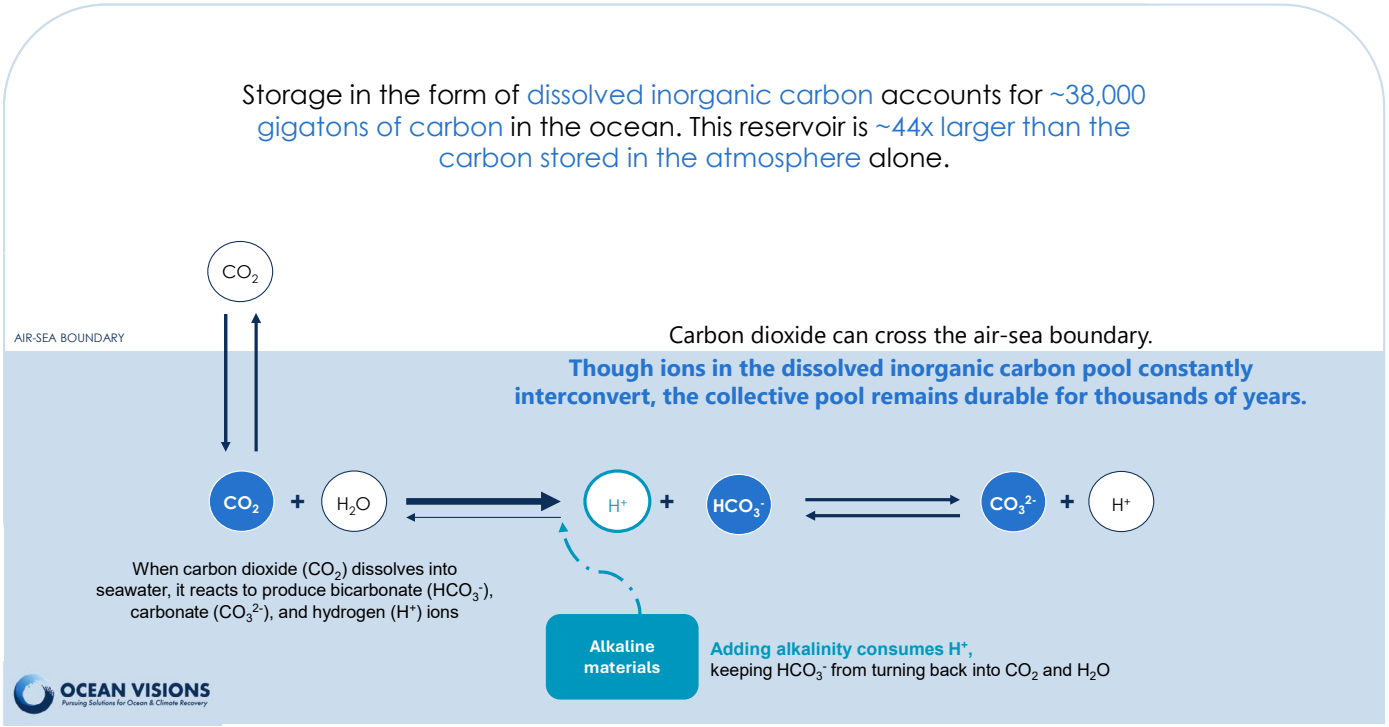


**Figure 1.** Carbon dioxide converted into bicarbonate, the dominant and durable form of dissolved inorganic carbon in seawater. Sources: Renforth and Henderson, 2017; NASEM, 2022

be converted back into dissolved carbon dioxide before leaving the water. In the natural system, the addition of alkalinity alters the chemical equilibrium to ensure that most carbon remains stored durably as bicarbonate and carbonate instead of reverting back to carbonic acid.

The removal of alkalinity added to the ocean is governed by slow, well-characterized geochemical feedback loops.[4,5,6] Over geological timescales, this altered chemistry promotes marine calcification, and the subsequent generation of aqueous carbon dioxide (see equation 4 below).

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2(aq) + H_2O \quad (4)$$

These slow processes of weathering and calcification set the ultimate durability of the remaining dissolved inorganic carbon storage to be at least 10,000 years.[2] This reservoir exceeds the 1,000-year storage durability threshold required to permanently neutralize fossil fuel emissions.[7]

Alkalinity can also be produced and introduced to the ocean deliberately, for instance through accelerated weathering of limestone (AWL), an engineered process in which carbon dioxide-rich gas is reacted with crushed limestone and water to produce dissolved calcium, bicarbonate, and a minor amount of carbonate ions. The resulting stream generates dissolved inorganic carbon equivalent to that produced by natural weathering of carbonate minerals (governed by equation 3), with their removal similarly governed by processes (governed by equation 4) that take at least 10,000 years.[8]

Indeed, the carbon accounting registry Isometric deems projects using this method of storage to have "No Observable Risk of Reversal."[9]

### Comparison between Geologic Storage and Dissolved Inorganic Carbon Storage

Geologic storage refers primarily to the process where carbon dioxide gas is compressed and injected into deep saline aquifers or depleted oil and gas reservoirs, where it is physically "sealed" beneath a layer of impermeable cap rock. This is the most established form, with industrial offshore storage projects operational since 1996.[10]

**Table 1.** Comparisons of geologic and Dissolved Inorganic Carbon Storage with regards to storage form, infrastructure and siting, verification, principal risks, and expected durability.

| STORAGE PATHWAYS | GEOLOGIC STORAGE | DISSOLVED INORGANIC CARBON STORAGE |
|---|---|---|
| **Storage form** | Compressed carbon dioxide beneath cap rock. | Carbon dioxide converted primarily into dissolved bicarbonate and carbonate ions in water. |
| **Infrastructure and siting** | Requires suitable geology, carbon dioxide purification, compression, transport, and injection infrastructure. | Storage operates near the capture source but requires substantial process-water handling and access to an appropriate receiving water body. |
| **Verification** | Tracks the injected carbon dioxide plume, well integrity, pressure, and potential leakage; monitoring may continue for decades after injection. | Measures gross conversion at discharge and accounts separately for unreacted carbon dioxide and any carbonate precipitation. |
| **Principal risks** | Leakage, well-integrity failure, induced seismicity, and surface uplift. | Feedstock or gas-stream contaminants, intake effects, pH changes, carbonate precipitation, and local discharge impacts. |
| **Expected durability** | **At least 10,000 years.** | **At least 10,000 years.** |

In practice, the pathways differ most in their deployment constraints. Geologic storage depends on suitable subsurface formations and requires carbon dioxide purification, compression, transport, injection, permitting, and long-term monitoring.[11] Dissolved inorganic carbon storage can instead operate near the capture source and avoid underground space and pressure constraints, but it remains at pilot scale and requires substantial process-water handling, access to appropriate receiving waters, and demonstration of reliable performance at relevant scale (see Table 1 for a summary of the comparison).[2,11]

## Technology Pathways

Accelerated weathering of limestone and dissolved inorganic carbon storage is at an early stage of development. The underlying chemistry (governed by equation 3) has been studied since at least the early 2000s[8], and laboratory and modeling work is well represented in the peer-reviewed literature[12], but engineered systems have not yet operated at industrial scale. Several technology developers are now advancing reactor designs toward pilot testing in both shipboard and coastal configurations. The near-term priority is demonstration at relevant scale, paired with monitoring sufficient to verify both storage durability and local environmental performance.

The pathways share a common underlying design: carbon dioxide gas (from an industrial flue gas stream, a ship's exhaust, or captured from the atmosphere) is brought into contact with water and an alkaline mineral (typically a calcium or magnesium-bearing feedstock) inside an enclosed, engineered reactor. Inside that reactor, the carbon dioxide dissolves into the water, reacts with the mineral, and is converted into dissolved inorganic carbon (primarily bicarbonate and carbonate ions) before the resulting water is returned to a natural water body (Figure 2).

Whether this approach constitutes carbon capture and storage (CCS) or carbon dioxide removal (CDR) depends on the source of the carbon dioxide. When it stores carbon dioxide captured from point source fossil-fuel or industrial emissions, it is CCS and avoids emissions into the atmosphere. When it stores carbon dioxide previously emitted to the atmosphere or ocean, it is CDR and produces a net atmospheric drawdown.

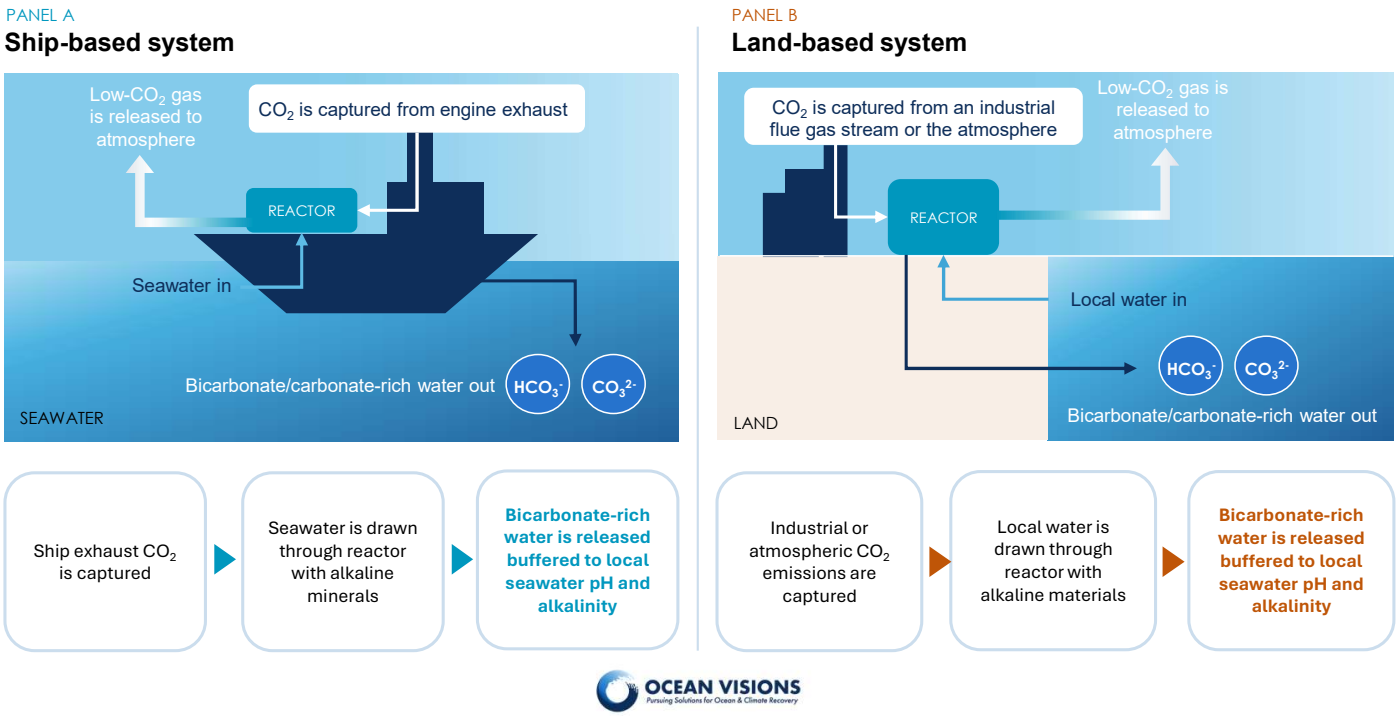


**Figure 2.** Ship-based (left) and land-based (right) reactor-based pathways for dissolved inorganic carbon storage.

### *Fully buffered versus partially buffered designs*

Across both ship-based and coastal storage systems utilizing the AWL process, a central design choice is whether the reactor is "partially buffered" or "fully buffered." In partially buffered AWL, the water is discharged after reacting with limestone alone. An excess of carbon dioxide must be supplied to overcome the thermodynamics of dissolution of limestone in seawater; therefore, some of the captured carbon dioxide is often still present as un-neutralized carbonic acid. This creates a risk that this unbuffered carbon dioxide can return to the atmosphere. While the fraction of carbon dioxide converted into dissolved inorganic carbon is durably sequestered, the overall carbon capture efficiency of the process is decreased. This release of some captured carbon dioxide is quantified and adjusted for in carbon accounting frameworks. Improved reactor designs (for example, the use of staged reactors) and the use of finer limestone particles are being considered to increase limestone dissolution rates.[13]

In fully buffered AWL, a supplementary source of alkalinity (such as calcium hydroxide) is added to neutralize any leftover carbon dioxide. Buffering raises the fraction of carbon that stays stored, avoids acidifying the receiving water, and prevents the remaining carbon dioxide from returning to the atmosphere. However, it adds cost and requires energy (and thus carbon dioxide emissions) to produce the supplementary alkaline feedstock.[11,13] Improving dissolution efficiency without a large energy or carbon dioxide penalty is a central engineering problem across both buffered and partially buffered designs.

### *Ship-based systems*

Technology developers such as Calcarea are designing ship-based reactor systems that can be installed onboard vessels to capture carbon dioxide directly from engine exhaust. These designs use seawater already drawn through the ship for cooling or ballast purposes and circulate it through a limestone-filled reactor. The resulting water could be released continuously while the ship is underway, avoiding the need to store, compress, or offload the captured carbon dioxide at port.

### *Coastal industrial systems*

Technology developers like Crew Carbon, pHathom, Planeteers, and Vycarb are designing land-based reactor systems for industrial coastal emitters such as wastewater treatment plants, biomass power plants, cement plants, and other facilities that produce carbon dioxide streams. In addition to storing carbon dioxide emitted by industrial processes, these systems could use carbon dioxide removed from the atmosphere, for example at a power plant that burns biomass that captured carbon dioxide from the atmosphere. Current designs draw in local water, react it with carbon dioxide and mineral feedstock on-site, and discharge the resulting dissolved inorganic carbon-rich water to an adjacent water body under applicable water-quality regulatory frameworks.

The developers named above are illustrative examples of organizations working on reactor-based carbon capture and dissolved inorganic carbon storage. This explainer is not a comprehensive survey of technology developers or reactor designs, and the field is evolving quickly.

## Relationship to ocean alkalinity enhancement

Reactor-based AWL fits within the broader family of approaches that add alkalinity to seawater, which includes ocean alkalinity enhancement (OAE). In reactor-based AWL, a concentrated carbon dioxide stream reacts with water and limestone inside an engineered system. The concentrated carbon dioxide supplies the acidity needed to dissolve limestone, which allows the process to use a widely available feedstock. Many OAE approaches add alkalinity to seawater first, with carbon dioxide uptake occurring subsequently, and typically require feedstocks that are undersaturated in seawater, such as lime or brucite. Lime must be produced from limestone through energy-intensive processing, and brucite is less readily available.

The most significant difference is one of measurement. When the reaction occurs within a controlled reactor, gross storage can be quantified directly at the point of discharge, with maximum subsequent outgassing and any secondary precipitation accounted for separately to calculate net storage. Where alkalinity is added first and carbon dioxide uptake follows over months to years, that uptake is generally inferred through modeling rather than measured at the point of release. These differences give the two approaches distinct feedstock and monitoring, reporting, and verification (MRV) requirements.

## Key Risks of Accelerated Weathering of Limestone and Dissolved Inorganic Carbon Storage

The principal risks of accelerated weathering of limestone and dissolved inorganic carbon storage arise from the engineered process and its local interface with receiving waters. Table 2 summarizes the potential effects and the corresponding mitigation and monitoring measures.

**Table 2.** Operational safeguards and monitoring measures for managing the principal risks of dissolved inorganic carbon storage.

| RISK OR PARAMETER | POTENTIAL EFFECT | MITIGATION AND MONITORING MEASURES |
|---|---|---|
| **pH** | Discharge water may have a pH different from the receiving water, potentially stressing ecosystems near the outfall. | Promote rapid dispersion and mixing to meet applicable thresholds. Set upper and lower pH thresholds and perform continuous monitoring. |
| **Secondary precipitation** | Alkalinity spikes at the point of discharge may result in secondary precipitation of calcium carbonate upon release of the process waters. This secondary precipitation can release carbon dioxide and reduce carbon storage efficiency. | Use rapid mixing and dispersion to limit precipitation. Discharge in deeper and colder waters, where calcium carbonate solubility is higher. |
| **Salinity and temperature** | Changes from local background conditions could affect organisms near the discharge point. | Use rapid mixing where needed to ensure salinity and temperature match receiving-water conditions with permitted variance. |
| **Mineral feedstocks and flue gases** | Feedstocks may contain toxic metals, while sulfur or nitrogen oxides in flue gas can form strong acids and contribute to acidification, eutrophication, and biodiversity loss. | Screen mineral feedstocks for contaminants, use appropriately scrubbed gas streams, and treat process water so it meets applicable discharge limits. |
| **Intake effects** | Larger organisms may be impinged on screens, while larvae, eggs, and smaller organisms may be entrained through the system. | Use appropriate screening and low approach velocities; avoid sensitive locations; and, where feasible, reuse existing cooling, ballast water, or industrial intake and outfall infrastructure.[11] |

## Conclusion

Accelerated weathering of limestone coupled with dissolved inorganic carbon storage is not a new carbon management concept, but real-world deployment is relatively new. The durability of storage over climate-relevant timescales is well established: once carbon dioxide reacts with the alkaline minerals and enters the ocean's dissolved inorganic carbon pool, removal is governed by slow geochemical processes operating over tens of thousands of years or longer.

Dissolved inorganic carbon storage could therefore complement geologic sequestration where suitable geology is unavailable, carbon dioxide transport is impractical, or existing water-handling infrastructure creates a favorable deployment setting. Unlike geologic storage, it avoids underground injection and long-distance transport of compressed carbon dioxide, but it requires large volumes of processed water and careful management of discharge chemistry, feedstock contaminants, intake effects, and local ecological responses.

**Accelerated weathering of limestone with dissolved inorganic carbon storage may be a scalable approach to carbon capture and storage as a complement to underground geologic storage. To unlock this potential, policymakers should support: field demonstrations that test reactor designs and verify net carbon storage, environmental impact characterizations and mitigation strategies, establishment of permitting pathways including monitoring requirements, and methods to transparently compare lifecycle costs and risks with geologic storage.**

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## MISSION

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