Support to the development of methodologies for the certification of industrial carbon removals with permanent storage

Review of carbon removal by direct ocean carbon capture and storage (DOCCS)

Prepared by Martin Johnson, Zara Popstoyanova, Chris Malins and Jonathan Lonsdale under service request CLIMATE-30420

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European Commission

Directorate General for Climate Action

Directorate C – Innovation for a Low Carbon, Resilient Economy

By email: CLIMA-FWC-001@ec.europa.eu

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A report submitted by ICF S.A., Cerulogy and Ecodiversity

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Contents

Summary

Direct ocean carbon capture and storage (DOCCS) is a carbon dioxide removal method in which the pH of seawater is manipulated to extract carbon. Typically, electrochemistry is used to separate seawater or brine into acid and base parts, the former being used to acidify seawater and drive off CO_2, for permanent storage in e.g. geological reservoirs. Prior to release of the CO_2-depleted seawater, the base component of the brine is mixed into the seawater, restoring its alkalinity and leaving it with a deficit of CO_2 and dissolved inorganic carbon relative to the atmosphere. Natural air-sea CO_2 uptake will re-equilibrate the released water with the atmosphere over time, leading to carbon removal. At 100% efficiency, seawater carbonate chemistry after-re-equilibration would be returned exactly to its pre-treatment state (i.e. the amount of carbon removal achieved would exactly match the quantity of CO_2 stored in geological reservoirs or in precipitated carbonate minerals), although extraction and equilibration inefficiencies mean some deviation is likely.

This review covers the theoretical background to DOCCS, issues affecting its carbon removal efficacy and challenges for reliable quantification of the CO_2 durably stored by a given removal action. The work is delivered in the context of the EU's Carbon Removals and Carbon Farming Regulation (CRCF), under which a methodology to allow DOCCS to generate carbon removal units could be developed. One certification body, Isometric, has already published a methodology for crediting DOCCS in the voluntary carbon market; this existing work is reviewed to shed light on various quantification, baselining, and sustainability issues.

Quantification challenges lie in the necessary use of numerical models to predict the removal of CO_2 from the atmosphere during the re-equilibration process. This occurs over years and on wide spatial scales, and depends on carbon cycle feedbacks such as the secondary precipitation of carbonate minerals or the inhibition of natural alkalinity fluxes due to elevated pH. DOCCS leads to no permanent change in ocean chemistry, which distinguishes it from OAE approaches where the addition of alkalinity does change seawater chemistry, albeit subtly. There is therefore a lower potential in the case of DOCCS for any feedback on the quantity of delivered carbon removal delivered due to modified seawater chemistry altering the residence time or durability of DIC or rates of carbonate precipitation. DOCCS, however, has the practical disadvantage of requiring storage in e.g. geological reservoirs as well as durable DIC storage in the ocean, increasing the burden on operators as there is a need to monitor and quantify losses from both stores. We argue, however, that losses from the ocean DIC pool only need to be considered in the case where any excess acidity arising from the electrochemical step is lost to the environment, in which case it will result in a direct release of an equivalent amount of the stored CO_2. In other cases, where external influences lead to the ocean-atmosphere CO_2 balance to be altered, there is either no difference or less loss in the DOCCS case compared to the counterfactual.

Risks to marine ecosystems are considered and are found to be localised to release points and ameliorated rapidly by dilution, but still subject to considerable uncertainty pending further research. Sustained DOCCS actions at large scale may result in larger areas of surface seawater being continuously depleted in CO_2. Up to a point this represents a mitigation of ocean acidification (which is due to elevated atmospheric CO_2), but a larger ongoing depletion of CO_2 in surface seawater may have impacts on marine ecosystems and the carbon cycle which are not currently foreseeable. Clear guardrails, thresholds, ongoing research and monitoring will be required to inform and mitigate any potential issues.

1 Introduction and context

The European Union (EU) has adopted a Carbon Removals and Carbon Farming Regulation (CRCF) (European Union, 2024). The Regulation aims to boost innovative carbon dioxide removal (CDR) approaches and sustainable carbon farming solutions, and contribute to the EU's climate, environmental and zero-pollution goals. It is intended to improve the EU's capacity to quantify and verify carbon removals, with transparency to ensure trust from stakeholders. The European Commission, supported by experts, is developing tailored certification methodologies for carbon removal activities.

The Regulation sets out rules for the independent verification of carbon removals, as well as rules to recognise certification schemes that can be used to demonstrate compliance with the EU framework. To ensure the quality and comparability of carbon removals, the Regulation establishes four QU.A.L.ITY criteria:

1. Quantification – Carbon removal activities need to deliver unambiguous benefits for the climate and be measured, monitored, and reported accurately.

2. Additionality – Carbon removal activities need to go beyond existing practices and what is required by law.

3. Long-term storage – Certificates are linked to the duration of carbon storage and should ensure long-term storage.

4. Sustainability – Carbon removal activities must contribute to sustainability objectives such as climate change adaptation, circular economy, water and marine resources, and biodiversity.

This report on **Direct Ocean Carbon Capture and Storage (DOCCS)** forms part of the same programme of work as the companion report on OAE (REF) and follows its structure closely. Many of the scientific principles and certification considerations are shared between the two approaches, and cross-references are provided throughout to minimise duplication.

1.1 Direct removal of CO_2 from seawater[1]

Direct ocean carbon capture and storage is a CDR method that manipulates the carbonate system in seawater to extract CO_2 in some form, typically gaseous. The processed seawater is depleted in CO_2 and so will absorb CO_2 from the atmosphere to compensate.

Unlike other durable marine CDR such as ocean alkalinity enhancement, the terminal carbon store in DOCCS is typically not bicarbonate ions in the ocean, but rather permanent engineered storage of $CO_{2(g)}$ e.g. in geological reservoirs such as exhausted gas fields. To the extent that such storage capacity is limited, DOCCS could therefore be competing with emissions reduction efforts by carbon capture and storage (CCS) and with other CDR methods that also rely on such stores. The capacity and durability of such engineered storage are of course essential to successful CDR under DOCCS, but as this is common to other CCS-based methods those issues are not considered in this report; rather it is focussed on the method of

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[1] Various names are used for this process e.g. Direct Ocean Capture (DOC), Direct Ocean Capture and Storage (DOCS), Direct Ocean Carbon Capture (DOCC) Direct Ocean Carbon Capture and Storage (DOCCS), Ocean Alkalinity Shunting, Direct Ocean Removal.

achieving the extraction of DIC from seawater and the subsequent extraction of CO_2 from the atmosphere by the treated seawater.

Aside from the terminal carbon store and the specifics of seawater carbonate chemistry manipulation, DOCCS has much in common with OAE and shares much background theory. Furthermore, there are many common issues regarding quantification and potential ecosystem impacts, such as the broad temporal and spatial scale on which complete re-equilibration with the atmosphere may occur. Therefore, to avoid extensive repetition, this report makes regular reference back to our earlier review of Ocean Alkalinity Enhancement (https://www.cerulogy.com/wp-content/uploads/2025/09/ICF_CRCF-OAE-Review_Jul2025.pdf, henceforth 'OAE report').

1.1.1 Acid and base pathways for DOCCS

Two separate classes of DOCCS pathways have been identified (Aleta et al., 2023; Isometric, 2025a). In the *base pathway*, solid carbonate precipitation is induced from seawater (e.g. Karo et al., 2024), and in the *acid pathway*, reduction in pH drives the release of CO_2 gas that is subsequently captured and stored (Eisaman et al., 2012). Both pathways are examined further in Section 2.2.

1.1.2 Electrolytic seawater mineralisation

Electrolytic sea CO_2 water mineralisation (ESM) is a related process that also uses electrolysis to split seawater into acid and base streams (La Plante et al., 2023). The alkaline stream is equilibrated with the atmosphere to absorb CO_2 and in the process some stable solid carbonates and hydroxides, such as calcium or magnesium carbonates, or magnesium hydroxides are formed. ESM achieves CO_2 capture and mineralisation in a closed system rather than through manipulated (i.e. CO_2-depleted) seawater being released into the ocean for equilibration in nature. The acid by-product of electrolysis is neutralised using alkaline mineral feedstocks, creating clear methodological overlaps with OAE. Equatic (www.equatic.tech) are developing this method and have pilot projects ongoing. The process is described in detail by (La Plante et al., 2021, 2023).

Although ESM shares electrochemical and mineral alkalinity foundations with DOCCS and OAE, its operational configuration and carbon storage pathway are fundamentally different. Because the CO_2 is captured and mineralised within a contained process, ESM is more appropriately categorised as a variant of direct air capture with mineralisation (DAC-M). It does not rely on re-equilibration between seawater and the atmosphere, which is central to DOCCS and OAE mechanisms.

For this reason, ESM is excluded from the scope of this review. Certification methodologies for ESM have recently been published by Isometric (Isometric, 2025b) and Puro.Earth (the latter being under the name DAC-OS – Direct Air Capture with Ocean Storage; (Puro.Earth, 2025)). The Commission may wish to consider ESM in future work under the CRCF.

1.2 Glossary of terms and key underpinning concepts

This section provides a concise overview of the key physical and chemical principles relevant to DOCCS. It summarises essential aspects of the marine carbonate system, air–sea exchange of CO_2, and carbonate mineral saturation and precipitation. Full derivations, parameterisations, and further details are available in the companion OAE report (Section 1.2), which should be consulted for further detail.

1.2.1 The carbonate system in seawater

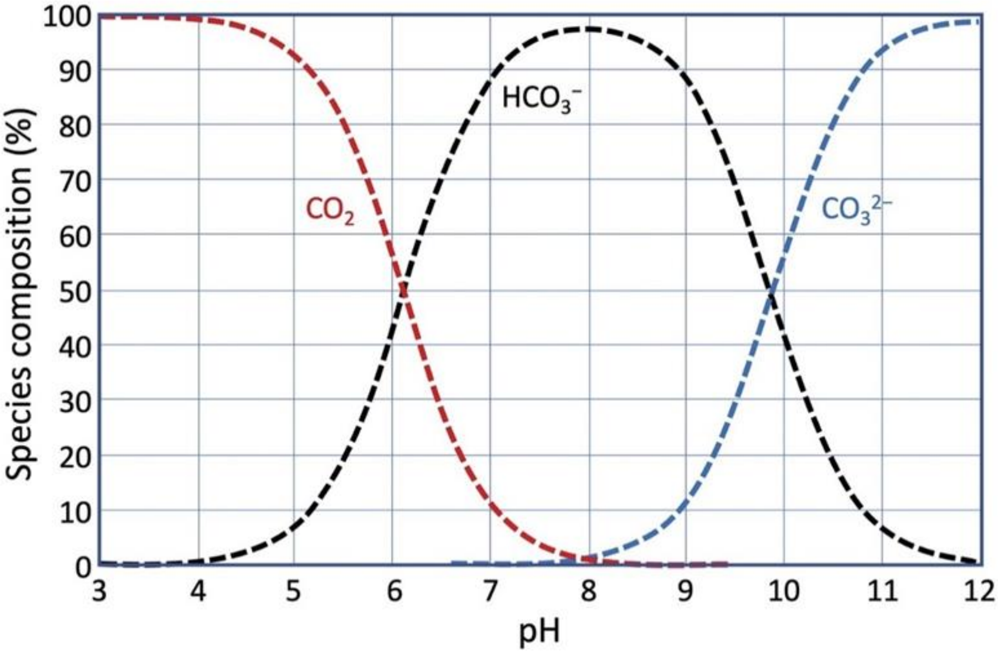
The carbonate system consists of dissolved CO_2, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions in equilibrium (Equation [1], with dissolved inorganic carbon (DIC) being the sum of the concentrations of these 3 chemical species.

$$\mathrm{CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)} \rightleftharpoons H^+_{(aq)} + HCO_3^-{}_{(aq)} \rightleftharpoons 2H^+_{(aq)} + CO_3^{2-}{}_{(aq)}} \qquad [1]$$

At typical seawater pH (~8.1), bicarbonate dominates total dissolved inorganic carbon (DIC).

A Bjerrum plot (Figure 1.1) illustrates how the relative proportions of the chemical species making up DIC change with pH. As pH decreases, equilibrium shifts towards dissolved free CO_2, which can exchange with the atmosphere across the sea surface. Increasing pH favours carbonate ions and therefore the precipitation of solid (calcium) carbonate. This relationship underpins both DOCCS and OAE: manipulating pH alters species distribution and thereby the potential for CO_2 exchange or carbonate precipitation.

Figure 1.1 Bjerrum plot of the speciation of DIC in seawater



Source: Rohling (2023)

Total Alkalinity (TA) is defined as the excess of proton acceptors (bases) over proton donors (acids). Seawater is a complex mixture of many minor proton acceptors and donors but the dominant control on alkalinity and pH is the carbonate system. In an idealised seawater solution made by dissolving sodium chloride and sodium bicarbonate in water and allowing equilibration with the atmosphere, TA can be expressed as:

$$\mathrm{TA = 2[CO_3^{2-}] + [HCO_3^-] + [OH^-] - [H^+]} \qquad [2]$$

The balance between DIC and total alkalinity (TA) defines the pH, DIC speciation and buffering capacity of seawater.

1.2.2 Air-sea exchange of CO_2

Air–sea CO_2 exchange is governed by the difference between the partial pressure of CO_2 in air ($pCO_{2(atm)}$) and in surface seawater ($pCO_{2\,(sw)}$)[2]. The net flux at the sea surface is proportional to this difference, which controls the direction and relative magnitude of the flux. The absolute magnitude is controlled by a kinetic term known as the transfer velocity, k, which depends on meteorological conditions and sea state (e.g. Garbe et al., 2014). Water leaving a DOCCS facility is depleted in DIC and therefore has lowered $pCO_{2\,(sw)}$, promoting CO_2 uptake from the atmosphere governed by Equation [3.

$$F_{CO2} = k * (pCO_{2(atm)} - pCO_{2(sw)}) \qquad [3]$$

1.2.3 Carbonate saturation and precipitation

The saturation state of calcium carbonate (Ω) describes the thermodynamic tendency for mineral precipitation or dissolution:

$$\Omega = [Ca^{2+}{}_{(aq)}][CO_3{}^{2-}{}_{(aq)}] \,/\, K_{SP} \qquad [4]$$

Where square brackets denote concentration[3]. K_{SP} is the solubility product – a thermodynamic term defining mineral solubility. When $\Omega > 1$, precipitation of calcium carbonate is favoured; when $\Omega < 1$, dissolution occurs. Each carbonate mineral has its own solubility product, meaning saturation thresholds vary among mineral types. Among calcium carbonate minerals, aragonite is more soluble than calcite, and both are considerably less soluble than magnesium carbonates or mixed calcium–magnesium carbonates such as dolomite. These minerals therefore precipitate under different conditions (pH, temperature, salinity) depending on their K_{sp} values and the surrounding seawater chemistry.

While Ω determines the thermodynamic state of calcium carbonate (undersaturated / supersaturated), kinetics may determine the likelihood of e.g. spontaneous precipitation from seawater. For example, most of the ocean is slightly supersaturated with respect to aragonite but spontaneous precipitation is not observed because kinetics of precipitation are extremely slow under normal seawater conditions.

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[2] Partial pressure is the fractional contribution (of CO_2) to total atmospheric pressure. The present day partial pressure of CO_2 in the atmosphere is around 420 µatm (microatmospheres), which is equivalent to 420 parts per million by volume (420ppm). Often the term 'surface ocean pCO_2' (or $pCO_{2(sw)}$) is used to express the seawater concentration in atmospheric units. More correctly, fugacity ($fCO2_{([atm/sw])}$), which corrects for non-ideality of CO_2 gas should be used if measuring or modelling processes involving air-sea CO2 fluxes, but pCO2 serves for conceptual purposes.

[3] For the purposes of explaining the principles, we use concentration, but in reality, the *activity* of the dissolved ions is what determines saturation state. The activity is affected by interaction with other ions and molecules dissolved in the medium (seawater). Activity, denoted by curly braces '{X}' is the product of the concentration and the *activity coefficient*, which can vary from 1 (activity= concentration) to as low as 0.2 for some species in seawater. When measuring or modelling carbonate system processes, activity should be used.

2 Carbon removals by Direct Ocean Capture

DOCCS uses electrochemistry (or in some proposed methods, photochemistry or redox cycling), to split seawater or brine into sodium hydroxide ($Na^+ OH^-$) and hydrochloric acid ($H^+ Cl^-$) solutions. These are then used to deliberately alter seawater pH and therefore carbonate chemistry to extract dissolved inorganic carbon (DIC) in the form of gaseous CO_2 or solid mineral carbonates. The treated water’s alkalinity is then restored to its original levels and the water returned to the ocean depleted in DIC, where it draws down atmospheric CO_2 as it re-equilibrates.

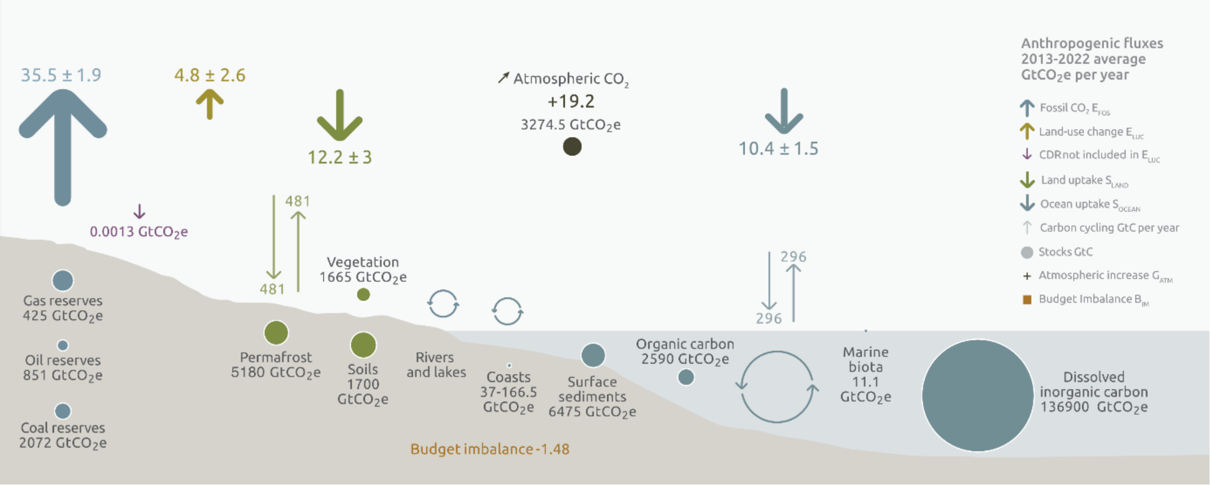
Because both OAE and DOCCS manipulate the carbonate system, they share many mechanistic principles, but they differ in several important respects. OAE operates by increasing total alkalinity to enhance the ocean’s natural CO_2 storage capacity, leaving the captured carbon dissolved as bicarbonate within seawater. In contrast, DOCCS reduces dissolved inorganic carbon (DIC) directly and stores CO_2 in some form outside of the ocean system.

Both pathways ultimately produce seawater that, once released, has a DIC deficit relative to the atmosphere and will therefore absorb CO_2 as it re-equilibrates in the ocean. The efficiency and temporal evolution of this equilibration process are discussed further in Section 2.3.

2.1 Carbon storage in the ocean

Dissolved inorganic carbon in the ocean is by far the largest reservoir in the ocean-atmosphere-biosphere system, accounting for roughly 40 times more carbon than is stored in the atmosphere as CO_2 ((Friedlingstein et al., 2025); Figure 2.1). This ocean DIC pool is broadly in equilibrium with the atmosphere over long timescales, via the carbonate system and ocean-atmosphere CO_2 exchange, mediated by the timescale of ocean circulation and ventilation (Siegel et al., 2021).

Figure 2.1 The present-day global carbon cycle



Adapted from Friedlingstein et al., 2025

To date roughly one third of anthropogenic CO_2 emissions have been taken up by the ocean surface through air-sea gas exchange. The driving force of the uptake is the undersaturation of the ocean with respect to atmospheric CO_2. So far, the ocean sink has increased broadly in proportion to increasing anthropogenic CO_2 (Friedlingstein et al., 2025), but this is not limitless as physical-chemical limits (saturation) or biogeochemical feedbacks may start to inhibit uptake; and as climate feedbacks impact ocean circulation and ecosystems. Removal of DIC from surface seawater as achieved with DOCCS methods will lead to additional undersaturation and therefore net uptake of CO_2.

The ocean's vertical structure is important when considering the interaction with, and uptake of, atmospheric CO_2. The surface ocean, which is in direct contact with the atmosphere, tends towards equilibrium with atmospheric CO_2 on relatively short timescales – typically within months to a few years – allowing it to quickly respond to changes in atmospheric concentrations or seawater DIC and alkalinity changes. In contrast, the deep ocean exchanges with the atmosphere only through slow ocean circulation processes, such as thermohaline mixing, which occur over centuries to millennia (Siegel et al., 2021). This vertical separation means that while the surface ocean can rapidly absorb and release CO_2, the deep ocean serves as a long-term reservoir, effectively sequestering carbon away from the atmosphere for hundreds to thousands of years.

Even without anthropogenic increases in atmospheric CO_2, the ocean would be a net sink of CO_2, due to a range of biologically mediated and physical processes, known collectively as the 'ocean carbon pumps', which act to deplete DIC in the surface layer of the ocean and concentrate it in the deep (DeVries, 2022). The present day ocean is naturally absorbing on the order of 10 $GtCO_2$ yr^{-1}. This is the small residual of large gross fluxes into and out of the ocean of ~290 $GtCO_2$ yr^{-1}. Many regions of the ocean vary seasonally from source to sink, driven by temperature and the biological cycle of photosynthesis-respiration (Fay et al., 2024; Legge et al., 2015). Other areas, such as cold downwelling regions are a continuous sink and yet others (e.g. locations of upwelling CO_2 rich water or terrestrially-influenced regions) may be continuous sources. Net fluxes of CO_2 between the atmosphere and ocean can be affected equally by DOCCS activities that decrease a natural emission or that increase a natural sink.

2.1.2 Durability and reversals

The durability of carbon storage under DOCCS depends firstly on the permanence of the storage of the extracted CO_2. Where the captured CO_2 is injected into geological formations, storage durations may extend over millennia, as with conventional CCS, and with the same potential losses and inefficiencies. These are addressed elsewhere (Directorate-General for Climate Action (European Commission), 2025) and we do not consider them further in this review.

DOCCS also relies on the durability of the dissolved inorganic carbon taken up by and stored in the ocean in response to the DOCCS-driven DIC depletion. As explained in detail in the corresponding section of the OAE report (Section 2.1.2), bicarbonate is stored durably on a timescale of many thousands of years unless or until:

- some external source of acidity is added to the ocean or alkalinity is removed such that the pH of the ocean is shifted, or
- the atmospheric concentration of CO_2 is reduced by other CDR or natural processes to below the ocean surface $pCO_{2(sw)}$, and DIC begins to be released back into the atmosphere through the connected equilibria of the carbonate system and ocean-atmosphere CO_2 exchange.

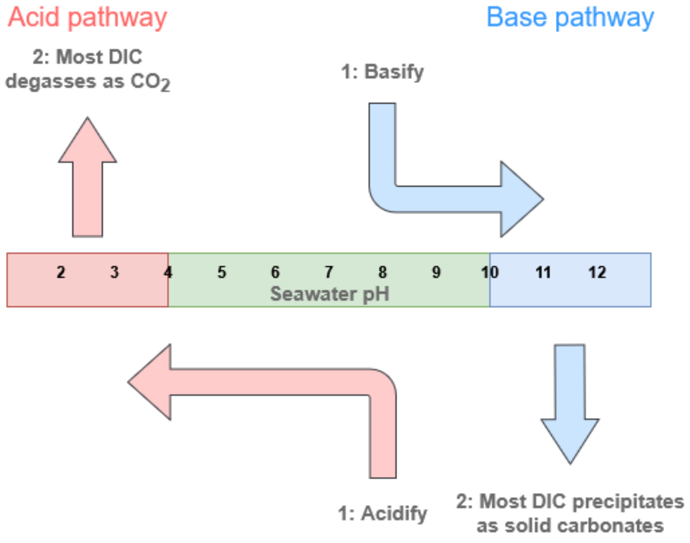
Either of these scenarios would occur independently of DOCCS activity and would influence the entire (surface) oceanic DIC pool equally. Since fully equilibrated DOCCS water is chemically identical to background seawater (Section 2.2), such global shifts would not constitute a specific reversal of DOCCS-driven removals. Following detailed discussion in the OAE report, it may not be useful or appropriate to apply the reversals concept in the same way for ocean DIC storage as for geological storage, but this warrants further consideration.

2.2 Methods of achieving DOCCS

DOCCS systems achieve dissolved inorganic carbon (DIC) removal through two main pathways – acid and base – summarised schematically in Figure 2.2. Both involve driving the seawater carbonate system to extremes of pH to extract carbon in gaseous or mineral form, after which alkalinity must be restored before the water is returned to the ocean to prevent loss of the stored carbon through ocean acidification.

Both DOCCS pathways require generation of acid and base streams, most commonly achieved via electrolysis or electrodialysis of seawater or brine. This allows separation of ions across membranes to produce acidic (H^+ Cl^-) and basic (Na^+ OH^-) solutions. These approaches are analogous in design to electrochemical ocean alkalinity enhancement (eOAE) systems described in Section 2.2.3 of the OAE report.

Figure 2.2 DOCCS pathways to extract DIC from seawater through manipulation of pH



2.2.2 Acid route: drive off CO_2 to permanent storage

In this method, acid is added to seawater, lowering pH (red arrow / line in Figure 2.3), shifting the carbonate equilibrium towards dissolved free $CO_{2(sw)}$. This raises $pCO_{2\ (sw)}$, allowing the gas to be stripped physically by processes such as vacuum extraction and/or diffusion across membranes. After CO_2 removal, alkalinity is restored using hydroxide generated from the base stream of the electrochemical system (green arrow / line in Figure 2.3), so that the discharged seawater approximates its initial alkalinity but remains depleted in DIC. The seawater can then absorb CO_2 and will tend to return to its original state. Theoretically, the initial and final states the of the carbonate system under DOCCS are identical, assuming complete equilibration.

Importantly, the acid and base generated in acid pathway DOCCS are theoretically used up stoichiometrically (i.e. in equal proportions): the hydroxide produced in the base stream is used to restore alkalinity in the treated seawater after CO_2 removal. In practice, some divergence from this balance might arise due to the extraction efficiency of CO_2[4], potentially resulting in excess acidity (under-extraction) or excess base (overextraction, e.g. under vacuum). This would constitute a loss in the former case and co-delivered eOAE in the latter. This contrasts with the base route, which will always create a significant net excess of acidity due to the removal of alkalinity from the system during precipitation of carbonates, which must be restored (Figure 2.4).

2.2.3 Base route: precipitate solid carbonates

Here, base is added to seawater to raise the pH and thereby increase carbonate ion concentration until carbonate minerals precipitate. This pathway directly removes DIC as solid carbonate minerals. Precipitation of carbonates removes alkalinity from the seawater, and it is likely that ‘runaway precipitation’ may lead to greater amounts of alkalinity being removed than was added in first place (Figure 2.4). Therefore, depending on the amount of carbonate precipitated, acid or base may need to be added to restore the seawater's alkalinity prior to discharge. In either case, as alkalinity has been removed from the water and must be restored, there will be an excess of acidity ‘left over’. The thermodynamics and kinetics of this process depend strongly on local saturation states and mineral composition, and may be difficult to predict, so careful monitoring of post-precipitation alkalinity would be necessary to ensure the correct treatment is applied to restore alkalinity prior to release.

The base route clearly requires a greater energy input due to the loss of alkalinity from the system and has the challenge of processing the excess acidity (as with eOAE). However, it does not incur the lifecycle emissions or fugitive losses associated with geological or engineered CO_2 storage, although these must be balanced against the same for acidity neutralisation. The base route has much less coverage in the scientific literature than the acid route and to our knowledge only one early-stage initiative at R&D scale is currently developing base route DOCCS. For this reason, the major focus of this report hereon is the acid route, although some consideration of differences for the base route is given where appropriate.

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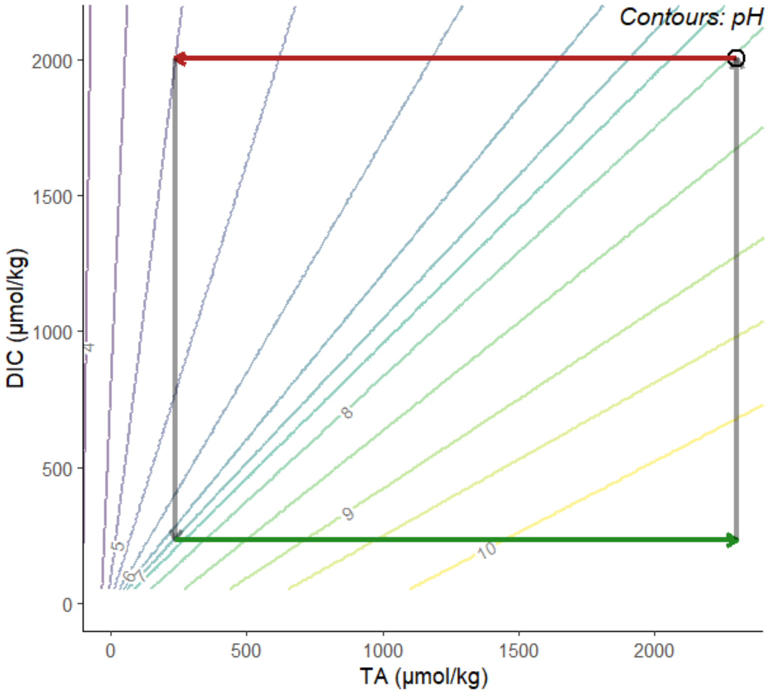
[4] Specifically the extraction efficiency relative to the equilibrium state with atmospheric CO_2 in the acidified state. If less than 100% (equilibrium not achieved), there will be excess acid after alkalinity is restored and so CO_2 will be lost to the atmosphere (the opposite of OAE). If e.g. under vacuum, more CO_2 is removed that would have been under equilibrium with the atmosphere (efficiency >100%) there will be excess base and some ocean alkalinity enhancement would be co-delivered with DOCS.

Figure 2.3 Acid pathway DOCCS process represented through carbonate system changes



Step	Description	pH	pCO_2	CO_2	HCO_3^-	CO_3^{2-}	DIC	TA	Ω_{arag}
-	initial	8.02	425	12	1798	204	2014	2300	3.2
1	to pH 5 (add 2059 μmol/kg acid)	5.00	62321	1763	251	0	2014	241	0.0
2	equilibrate	7.11	425	12	221	3	236	241	0.0
3	add 2059 μmol/kg of alkalinity	10.38	0	0	9	227	236	2300	3.6
4	equilibrate	8.02	425	12	1798	204	2014	2300	3.2

Top: Deffeyes diagram describing the pathway through TA/DIC space; bottom: table detailing carbonate system changes in each step, corresponding to arrows above as follows.

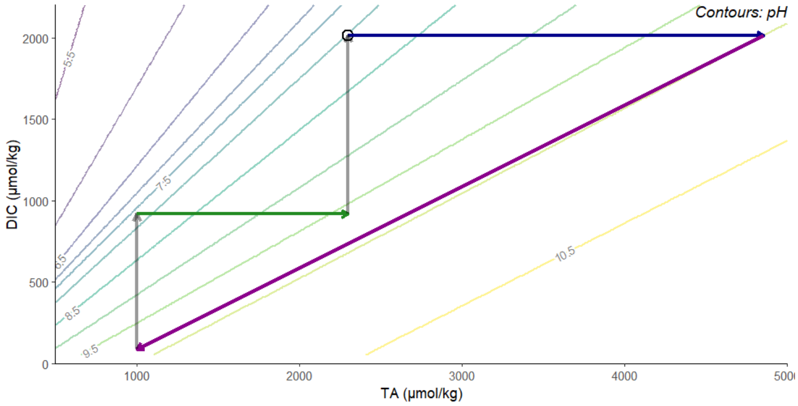
1) [red arrow] acidification of seawater to increase $pCO_{2(sw)}$;

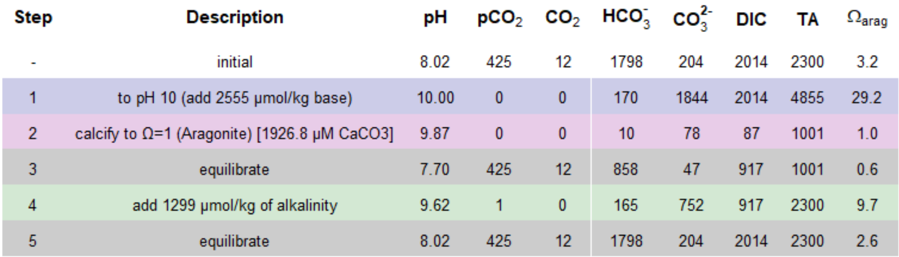
2) [grey arrow] controlled extraction of the excess CO_2 from the seawater to its new equilibrium state with atmospheric CO_2;

3) [green arrow] addition of the base produced concurrently with the acid added in step 1, returning the seawater to its starting alkalinity;

4) [grey arrow] re-equilibration with the atmosphere.

Figure 2.4 Example base pathway DOCCS process





Step	Description	pH	pCO_2	CO_2	HCO_3^-	CO_3^{2-}	DIC	TA	Ω_{arag}
-	initial	8.02	425	12	1798	204	2014	2300	3.2
1	to pH 10 (add 2555 µmol/kg base)	10.00	0	0	170	1844	2014	4855	29.2
2	calcify to Ω=1 (Aragonite) [1926.8 µM CaCO3]	9.87	0	0	10	78	87	1001	1.0
3	equilibrate	7.70	425	12	858	47	917	1001	0.6
4	add 1299 µmol/kg of alkalinity	9.62	1	0	165	752	917	2300	9.7
5	equilibrate	8.02	425	12	1798	204	2014	2300	2.6

1) [purple]. pH /alkalinity is increased through addition of base (OH^- ions) to drive spontaneous precipitation of calcium carbonate.

2) [magenta] Calcification occurs rapidly until the point where Ω=1 (aragonite saturation).

3) [grey] shows the DIC uptake that would occur due to the re-equilibration following step 2.

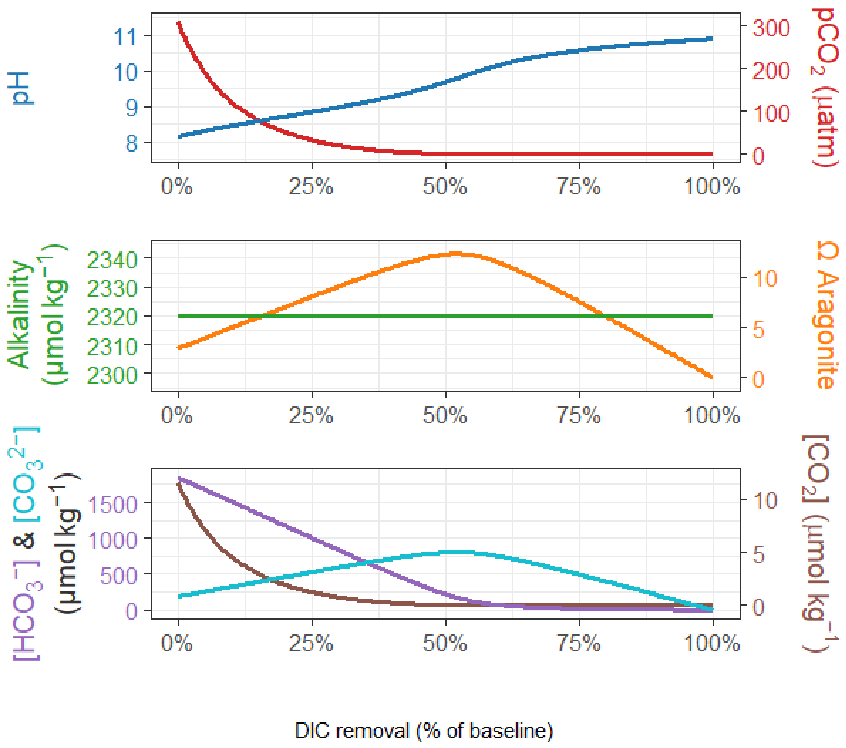
4) [green] Further alkalinity addition to restore the system to starting alkalinity.

5) [grey] DIC uptake to return the system to atmospheric equilibrium and initial state.

2.2.4 Impact of DIC removal on the seawater carbonate system

The net impact of DIC removal by DOCCS is to increase pH and alter DIC speciation, while alkalinity is managed so that it remains at its initial level. The response of the carbonate system is non-linear (Figure 2.5), meaning that different local impacts could be envisaged for different levels of removal per unit volume of treated water. Dilution of treated water will move the carbonate system back along the same carbonate system changes in reverse until the point of complete dilution (discussed in Section 2.3.6).

Figure 2.5 The carbonate system state in DOCCS outflow vs concentration of DIC removed. Alkalinity is kept constant because under DOCCS, outflow alkalinity should always be returned to its original value.



Calculated using SeaCarb package in R (Gattuso et al., 2024)

2.3 Efficiency of CDR by DOC

DOCCS has a particular characteristic that is unusual for CDR methods: the carbon extracted to storage in the process is *not* the carbon that is removed from the atmosphere and therefore is not directly creditable. Rather it is the corresponding uptake of carbon from the atmosphere as the surface-ocean/atmosphere system re-equilibrates that can be credited as carbon removal. Therefore the losses related to and the durability of both the geologic[5] and oceanic carbon stores must both be considered in quantification.

2.3.1 Quantifying carbon removal by DOCCS

In order to quantify net carbon removal by DOCCS it is essential to know: i) the amount of carbon removed from seawater (directly measured in the extraction facility); ii) lifecycle emissions and losses associated with the durable storage of carbon in the terminal (geologic) store; and iii) the efficiency of the net uptake of CO_2 from the atmosphere, relative to the known amount of DIC removed from seawater. Of these, i) is relatively trivial and ii) is addressed elsewhere so the focus of this section is the quantification of ocean uptake (iii).

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[5] Or other permanent store for captured carbon.

2.3.2 Capture efficiency of DOCCS, η_{DOCCS}

In DOCCS, atmospheric carbon removal occurs through the discharge of seawater that is depleted in dissolved inorganic carbon (DIC) (vs enhanced alkalinity under OAE). As the discharged water re-equilibrates with the atmosphere, this DIC deficit drives CO_2 uptake from the air. After hypothetical complete re-equilibration of treated water, dissolved inorganic carbon is restored to its original values in seawater and alkalinity remains unchanged (0, 0). The efficiency of DIC uptake (i.e. what proportion of the DIC deficit in outflow water is replenished from the atmosphere) is a key consideration analogous to the efficiency term in atmospheric equilibration following OAE (OAE report section 2.3). Here we define the efficiency of DOCCS as the ratio of the change in DIC taken up across the air-sea interface per unit DIC extracted from seawater in the DOCCS process:

$$\eta_{\mathrm{DOCCS}} = \Delta\mathrm{DIC}_{\mathrm{AIR\_SEA}} \,/\, \Delta\mathrm{DIC}_{\mathrm{EXTRACTED}} \qquad [5]$$

For OAE, the theoretical maximum efficiency η_T, (of unit DIC taken up into the ocean per unit alkalinity added) can never reach 1 because of carbonate system buffering mediating the alkalinity addition (Section 2.3.2, OAE report). However, the same does not apply to DIC removal by DOCCS, where the theoretical maximum efficiency, $\eta_T = 1$. This is because the DIC storage capacity of seawater is unaffected by DIC removal if alkalinity is unchanged, therefore the amount removed can be fully replenished under air-sea exchange. However, any imbalance in alkalinity resulting from the DOCCS process will both change the total potential quantity of DIC storage and the maximum theoretical efficiency.

The maximum theoretical efficiency is unlikely to ever be attained in a real-world deployment. The two primary limits to efficiency are incomplete equilibration with the atmosphere (Section 2.3.3) and secondary precipitation of carbonates in seawater local to the release point of DOCCS-treated water (Section 2.3.4). Further reductions in efficiency may arise from biogeochemical feedbacks in the marine system, including increased biological precipitation of calcium carbonate and potential inhibition of natural weathering-derived alkalinity fluxes (Section 2.3.5) driven by elevated pH prior to equilibration. Under DOCCS the net change in carbonate chemistry in seawater is zero following complete equilibration which suggests second order feedbacks on calcifiers, natural alkalinity fluxes and the natural marine carbon cycle are less likely than for OAE, where chemistry is fundamentally (if only slightly) changed through net alkalinity increase. This also means that sustained DOCCS at large scale would be less likely to lead to systemic change to the global ocean carbonate system state than OAE.

2.3.3 Efficiency limits due to incomplete equilibration with the atmosphere

The re-equilibration of DOCCS-treated seawater with the atmosphere is an open-system process influenced by ocean mixing and transport. Complete equilibration is unlikely to be achieved in practice on relevant timescales. Following discharge, DIC-depleted waters are mixed vertically and advected horizontally, which can reduce their contact with the atmosphere and interrupt or slow the uptake of atmospheric CO_2. As a result, the timing and location of CO_2 uptake may be decoupled from the site of DOCCS treatment, occurring months to years later or potentially far from the original release area.

Immediately following DOCCS discharge, the air–sea CO_2 gradient is steepest, leading to rapid initial uptake. As the DIC deficit is diluted by mixing, the flux declines until equilibrium is reached. Most CO_2 reabsorption is therefore expected to occur during the early equilibration phase, typically within months (dependent on local conditions), with some proportion of the total removals taking multiple years to complete. The equilibration efficiency achievable within a relevant timeframe for DOCCS is directly analogous to the OAE equilibration factor, which is influenced by the season and location of deployment (Fennel et al., 2023; Ho et al., 2023; Wang et al., 2023; Zhou et al., 2024) and can be estimated using modelling tools such as the OAE efficiency tool developed by Carbon Plan (https://carbonplan.org/research/oae-efficiency, following Zhou et al., 2025).

For DOCCS, this factor can be interpreted as the proportion of DIC removed to the terminal store that is ultimately compensated by atmospheric CO_2 drawdown within a relevant timeframe. Quantification of this factor, as for OAE, requires coupled ocean–biogeochemical modelling (Fennel et al., 2023; Ho et al., 2023), which must be central to DOCCS MRV design (Section 2.4).

2.3.4 Efficiency losses due to secondary precipitation of carbonates

Seawater depleted in DIC has elevated pH and consequently saturation state (Ω_{arag}) and so, as per OAE, there is a risk of losses due to secondary precipitation (OAE report Section 2.3.4), which depend on local conditions and the carbonate system state of the outflow for DOCCS (e.g. (Hooper et al., 2025)). However the potential impact on pH and Ω_{arag} of a given amount of potential carbon removal for OAE and DOCCS differ because (i) $\eta_{T\_DOCCS} = 1$ and $\eta_{T\_OAE} < 1$, but also ii) increasing alkalinity vs removal of DIC affect the carbonate system differently. Carbonate system calculations reveal that i) DOCCS has a smaller impact on Ω_{arag} than OAE for an equal amount of DIC removal / alkalinity addition, ii) this is compounded by the maximum attainable efficiency for OAE being only 85% of the alkalinity addition and iii) although the impact on Ω_{arag} is smaller the increase in pH is greater (Table 2.1).

	Initial state	DOCCS	OAE (non-carbonate)	OAE (carbonate)
η_T	-	1	~0.85	~0.85
Maximum possible CO_2 uptake to DIC (µM)	-	100	85	35
pH (pre-equilibration)	8.03	8.21	8.20	8.18
Ω_{arag} (pre-equilibration)	2.3	3.3	3.4	3.5

Table 2.1 Impact of DOCCS and OAE actions on pH and aragonite saturation state

Calculations using SeaCarb package in R. In each case 100µM of either DIC removal (DOCCS) or alkalinity addition (OAE) was undertaken from initial conditions of pCO_2 = 425, TA = 2320, T=15. Impact of $[Ca^{2+}]$ changes on Ω_{arag} under carbonate OAE is not considered, but is relatively minor.

This difference arises because DOCCS removes DIC (and therefore reduces carbonate concentration and thus Ω_{arag} for a given pH), whereas OAE adds alkalinity, therefore increasing pH while maintaining DIC and increasing buffering. This is important when considering the appropriate thresholds of pH and Ω_{arag} for avoiding secondary precipitation, such as the guideline values of pH < 8.8 and/or Ω_{arag} < 5 proposed by (Moras et al., 2022) .

Starting with the same initial state as Table 2.1, further calculations demonstrate that in all cases, Ω_{arag} = 5 is reached before pH exceeds 8.8. Any of 270 µM DIC removal, 250 µM non-carbonate alkalinity addition, or 225 µM calcium carbonate addition will result in a saturation state (Ω_{arag}) of 5.0. The resulting pH values are 8.47, 8.40 and 8.33, respectively and will result in maximum attainable CO_2 uptakes of 270, 213 and 79 µM respectively. DOCCS therefore results in the greater pH swing but allows larger uptake of CO_2 before guideline safe thresholds are reached. It's worth noting that under the base route calcium ions are removed, leading to a further decrease in Ω_{arag} and therefore even greater capacity to take up CO_2 without threshold exceedance. This may be a benefit locally to DOCCS facilities but on a wider scale, removal of calcium ions exerts further pressure on natural calcification under ocean acidification, so this broader scale impact must also be considered for base route DOCCS.

As noted in the OAE report, thresholds to prevent secondary precipitation are for a particular location may be location-specific. Consideration of Temperature, salinity, ecosystem state, seawater chemistry and method-specific chemistry will be important.

2.3.5 Other carbon cycle feedbacks

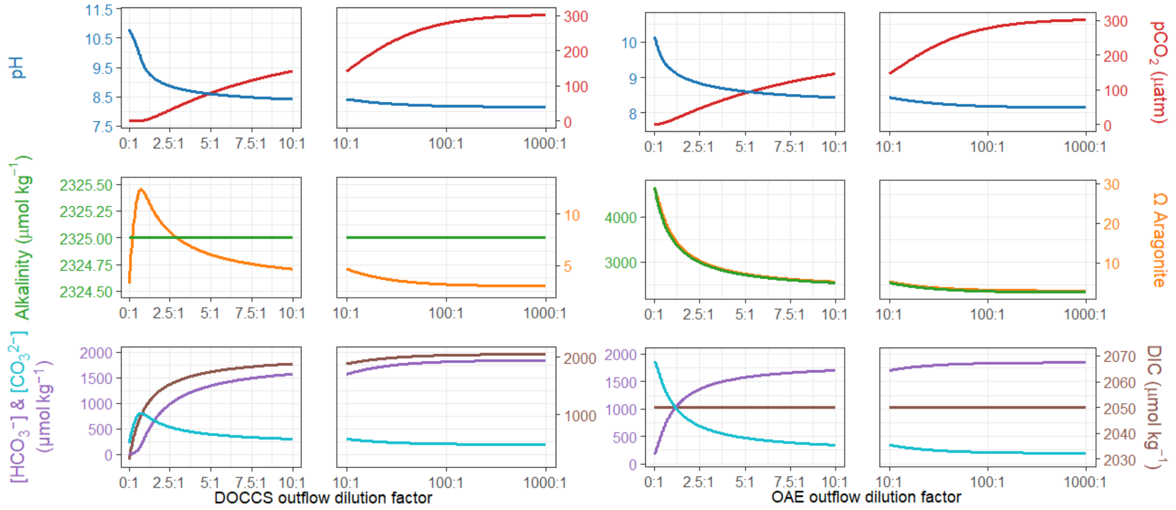
Locally to release points, where high concentrations of un-equilibrated DOCCS outflow may lead to sustained changes in carbonate chemistry, other losses may be introduced through carbon cycle feedbacks. Calcification-related feedbacks (suppression of natural alkalinity fluxes from natural weathering in marine sediments and changes in biogenic calcification) may lead to losses (OAE report section 2.3.5), but as demonstrated above, the impact on saturation states (Ω_{arag}) is less for DOCCS than OAE for a given carbon removal so these feedbacks will be less likely to occur than in the OAE case. Importantly, after successful re-equilibration, the chemistry of seawater is unchanged under DOCCS so no systematic widescale carbon cycle feedbacks are likely from large scale (i.e. Gt) deployment of DOCCS, as opposed to OAE where this may be an issue.

The biological carbon pump may also be impacted in a number of ways, although again limited to local impacts at release sites assuming large amounts of un-equilibrated DOCCS outflow does not propagate through the surface ocean (unlikely). As well as the impacts of increased calcification and changes to phytoplankton community structure, there is a potential impact on absolute productivity due to reduced DIC availability inhibiting photosynthesis (Hooper et al., 2025).

2.3.6 Dilution from coastal outflows

Dilution of DOCCS (or eOAE) outflows happens relatively rapidly. Under typical conditions, dilutions of a factor of 100 or more are typically expected within a few metres of the outflow (nearfield) within a plume of a few hundred litres per second outflow and under relatively slow currents ((Faccetti, 2020; Inan, 2019)). However, exceptional (transient) conditions that isolate jets from mixing or greater outflow rates can lead to poorer dilution factors in the near field down to the low tens (Inan, 2019; Kang et al., 1999). Wider scale 3D hydrodynamic mixing models typically predict dilution factors greater than 50 (typically much greater than 100) at the km scale under high sustained outflow volumes into shallow enclosed bays (Ho et al under review, (Jenkins et al., 2012). Such poorly flushed locations may not be suitable for sustained high volume deployments but provide a useful benchmark for interpretation of dilution curves of DOCCS and OAE outflows (Figure 2.6), which demonstrates that even at dilutions of only 50-100 fold, pH and Ω_{arag} are well below the guideline thresholds of 8.8 and 5 proposed by (Moras et al., 2022). Such dilution modelling should form an integral part of project planning for DOCCS (and OAE).

Figure 2.6 Carbonate system dilution curves (after Hooper et al., 2025) from typical DOCCS and eOAE outflows, demonstrating the state of the carbonate system across a range of dilutions



Left panels dilution factor 0:1 (undiluted) to 10:1, linear x scale; right panels 10:1 to 1000:1 log scale. Undiluted outflow conditions for DOCCS (DIC reduced by ~1900 µmol kg^{-1} relative to surrounding seawater, taken from Hooper et al., 2025). OAE conditions selected to reproduce a similar magnitude of potential carbon drawdown from addition of non-carbonate alkalinity (1900/0.85 = 2325 µmol kg^{-1}). Calculated using SeaCarb package in R (Gattuso et al., 2024).

2.4 Monitoring DOCCS outcomes

Given that broadly the same issues apply and the same key parameters need monitoring, the monitoring and modelling requirements for DOCCS and OAE are the same, other than the need for additional monitoring of the durability of and losses from the terminal (geologic) carbon store of extracted CO_2 gas. Section 2.4 of the OAE report addresses the monitoring requirements in detail and these are summarised here.

In practice, monitoring should (i) establish a representative baseline including seasonality, (ii) provide routine measurements to ensure safe thresholds are not exceeded and impacts on water quality, biogeochemistry and ecosystems and within acceptable limits, and (iii) supply targeted data to calibrate and validate MRV models (mixing/dilution and air–sea CO_2 exchange), with need for more intensive process studies in early deployments and at new sites.

Minimum/core parameters:

- Temperature, salinity (incl. depth profiles where relevant)
- Carbonate system: at least two of TA, DIC, pH, pCO_2 (to constrain the system)

- Calculated aragonite saturation state (Ωarag) (with Ca^{2+} inferred from salinity where appropriate)
- Dissolved oxygen (DO)
- Turbidity and/or total suspended solids (TSS)
- Chlorophyll-a (Chl-a)

Project-/site-specific parameters (as needed for quantification / impacts and model validation):

- Hydrodynamics: currents, mixing/dispersion metrics; near-field plume characterization
- Air–sea gas exchange constraints (e.g., tracer-based studies; meteorology/wind as applicable)
- Nutrients (N, P, Si)
- Phytoplankton community
- Biogenic calcification indicators/rates and sediment porewater carbonate chemistry (where benthic interactions matter)

For DOCCS, modelling will be the primary tool for quantifying CO_2 uptake, retention, and potential redistribution in the ocean. Physical circulation models coupled to marine carbon cycle and gas-exchange modules are required to simulate how the CO_2-depleted seawater is transported, mixed, and exchanged with the atmosphere, and to assess resulting changes in carbonate chemistry and exposure of marine ecosystems. These models are used both in project design, e.g. to estimate medium-term (decadal) storage efficiency; and in MRV, where they translate operational data and limited in situ measurements into estimates of net atmospheric CO_2 removal.

Although global and regional ocean biogeochemical models are now well established, their accuracy for project-scale carbon storage depends critically on tuning and validation with site-specific data. The dominant limitations are uncertainty in air–sea gas exchange, vertical and lateral mixing, and baseline carbonate system state, all of which control how long injected CO_2 remains isolated from the atmosphere. Robust MRV therefore requires co-design of field measurements and modelling, assimilation of temperature, salinity, carbonate system and current data into models, and the use of ensembles or multi-model approaches to quantify uncertainty.

3 Assessment of relevant methodologies from private standards

3.1 Isometric Direct Ocean Capture & Storage Protocol

Isometric released version v1.0 of its Direct Ocean Capture and Storage (DOCS[6]) protocol in October 2025, after a 30-day public consultation ending in June 2025. The consultation gathered input from buyers, suppliers, and academics.

The Isometric protocol notes that commercial evaluation of DOCS projects is in its early stages, with limited field trials so far (less than five field trials reported). While direct ocean capture and other abiotic marine carbon removal methods could appear promising, Isometric suggests that further research is needed to fully understand their potential and impacts. Isometric claims that the protocol will be reviewed at least every two years or whenever there is an update to scientific literature that impacts net carbon removal quantification or the monitoring and modelling guidelines.

Isometric DOCS protocol follows the Isometric Standard (1.0.0) as the main guiding document and complies with ISO 14064-2:2019. The protocol is further informed by other ISO standards (ISO 14064-3: 2019, ISO 14040: 2006, ISO 14044: 2006).

Additional reference standards and protocols for DOCS that are identified as having been reviewed include:

- Criteria for High-Quality Carbon Dioxide Removal (Carbon Direct, Microsoft, 2025)
- Guide to Best Practices in Ocean Alkalinity Enhancement Research (Copernicus Publications, State Planet, 2023)
- Measurement, Reporting and Verification (MRV) Protocol for OAE Carbon Removal, V3 (Planetary Technologies, 2023)
- Carbon Dioxide Removal Pathway: Ocean Health and MRV (Captura, 2023)
- A Code of Conduct for Marine Carbon Dioxide Removal Research (Aspen Institute, 2021)
- BS EN 15978:2011: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method
- Scientific Background and Fundamentals of MRV: Direct Water Capture (CarbonBlue, 2024).

3.1.1 Scope

Direct Ocean Capture and Storage (DOCS) is a marine-based carbon dioxide removal method that extracts CO_2 from seawater and stores it in durable geological reservoirs designed to maintain storage for over 1,000 years. The treated seawater, with less CO_2, is returned to the ocean, resulting in re-equilibration process between the atmosphere and the ocean surface (i.e. the air-sea gas exchange), which causes atmospheric CO_2 drawdown.

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[6] We use Isometric's acronym in this section but their 'DOCS' is equivalent to this report's 'DOCCS'.

Isometric's carbon removal protocol applies to projects that adjust the pH and alkalinity of seawater to extract dissolved inorganic carbon (DIC). The relevant DOCCS methods are chemical looping, electrochemical and photochemical separation of DIC from seawater, resulting in one of the following outcomes:

- Acid route: acidifying seawater increases gaseous CO_2, enabling its capture;
- Base route: raising the pH increases carbonate ion concentrations, which then form solid calcium carbonate and precipitate out.

The Isometric methodology identifies two carbon flux processes:

- CO_2 extracted from seawater and stored in a durable reservoir
- CO_2 removed from the atmosphere via air-sea gas exchange.

Only the second process is credited, but the first carbon flux process is mandatory for credit issuance. Isometric methodology requires an evaluation of CO_2 removal efficiency via air-sea equilibration prior to issuing credits. The methodology treats reduced ocean outgassing and increased ocean CO_2 uptake symmetrically, i.e. both increased ocean uptake and reduced natural ocean outgassing are treated as removals.

According to this version of the protocol, projects are required to discharge brackish water or seawater with reduced DIC into the surface ocean from a fixed location. It is noted that the that future versions of the protocol may broaden the project eligibility criteria.

The quantification framework is designed for DOCCS projects that lower seawater partial pressure of CO_2 (pCO_2) without changing total alkalinity. If a project does alter total alkalinity, which affects the ocean's buffering capacity and carbon chemistry, then the standard calculation approach explained below needs to be adjusted to account for those changes. These modifications must be approved by Isometric. Uncertainty at each step of the quantification model must be determined.

3.1.2 Quantification

Isometric states that measuring air-sea CO_2 fluxes is currently challenging due to various spatial and temporal scales involved in DOCCS. Quantification is presently dependent on biogeochemical ocean models (Air-Sea CO_2 Uptake module) that are validated through global and regional oceanographic datasets and site-specific measurements. The model quantifies air-sea CO_2 fluxes by simulating equilibration for both project and baseline scenarios.

The DOCS reporting period pertains to the duration within which total net carbon removals ($\boldsymbol{CO_{2^{e}}}_{\boldsymbol{Removal,RP}}$) are assessed and documented for verification purposes. For DOCS projects adhering to the Isometric protocol, the reporting period covers all project activities within a set timeframe, from DIC removal to seawater discharge, plus CO_2 processing, transport, and storage. The total net CO_2e removal is determined using measurements and multi-scale modelling for each specified period.

3.1.2.1 Net carbon removals

The total net carbon removals are calculated for each reporting period as follows, in units of tCO_2e:

$$CO_2e_{Removal,RP} = CO_2e_{Stored,RP} - CO_2e_{Counterfactual,RP} - CO_2e_{Emissions,RP} \qquad [6]$$

which (assuming no counter-factual emissions removals other than the air sea flux) is equivalent to:

$$CO_2e_{Removal,RP} = \Delta CO_2e_{AirSeaFlux,RP} - CO_2e_{Fugitive,RP} - CO_2e_{Emissions,RP} \qquad [7]$$

Where:

$\boldsymbol{CO_2e_{Removal,RP}}$ is the total net amount of CO_2 equivalents removed for the reporting period (RP).

$\boldsymbol{CO_2e_{Stored,RP}}$ is the total CO_2 removed from the atmosphere and durably stored in a reservoir. It is calculated as the increase in ocean CO_2 uptake via air-sea gas exchange ($\boldsymbol{CO_2{}^e{}_{AirSeaFlux,Intervention,RP}}$) minus any fugitive emissions ($\boldsymbol{CO_2e_{Fugitive,RP}}$) (i.e. the CO_2 that escapes before being stored).

$\boldsymbol{CO_2{}^e{}_{AirSeaFlux,Intervention,RP}}$ represents the total amount of carbon dioxide either absorbed by or released from the ocean during the reporting period as a result of the DOCS project. If the ocean absorbs CO_2, the value is positive, indicating successful carbon removal and storage as DIC. If the ocean releases CO_2, the value is negative, reflecting outgassing.

$\boldsymbol{CO_2e_{Counterfactual,RP}}$ refers to the total counterfactual CO_2 removed from the atmosphere and stored in the absence of the DOCS project. This refers to the amount of CO_2 that the ocean would naturally absorb or release over the reporting period if the DOCS project had not been implemented. It represents the CO_2 removal in the baseline scenario. It equals the air-sea CO_2 flux in the baseline ($CO_2e_{AirSeaFlux,Counterfactual,RP}$). A positive value indicates natural CO_2 absorption, while a negative value indicates natural outgassing. Potential miscellaneous emissions ($CO_2e_{MiscCounterfactual,RP}$) are also included as a term in the calculation of the counterfactual scenario for completeness; however, they are assigned a value of zero.

$\boldsymbol{CO_2e_{Emissions,RP}}$ is the total GHG emissions associated with the reporting period. This includes emissions associated with project establishment, emissions during the reporting period from operations, end-of-life emissions that would occur after the reporting period but allocated to the reporting period, and leakage emissions outside the system boundary. Isometric includes additional requirements in separate modules for calculating emissions from electricity and fuel consumption (Energy Use Accounting Module v1.2), emissions from the transportation of products and equipment (Transportation Emissions Accounting) and embodied emissions of equipment and consumables (Embodied Emissions Accounting) as per the GHG Accounting Module V1.0.

$\Delta\boldsymbol{CO_2{}^e{}_{AirSeaFlux,RP}}$ is the difference between the gross removal term and the counterfactual term. This term is a positive value, indicating increased CO_2 uptake or reduced ocean outgassing due to the DOCS project. Both the project and counterfactual values for air-sea flux are determined by modelling.

$\boldsymbol{CO_2e_{Fugitive,RP}}$ refers to the amount of CO_2 that was captured from seawater but escaped back into the atmosphere before it could be securely stored in a long-term reservoir. Fugitive emissions equal the difference between CO_2 captured by DOCS process and CO_2 stored in a durable storage. Projects operating under the DOCS protocol may use one or more of the Isometric storage modules[7] to determine the total amount of CO_2 sequestered in a durable storage reservoir.

The methodology notes that if any CO_2 that was previously stored by the project escapes from its long-term durable storage after carbon credits have been issued, it's considered a reversal.

3.1.2.2 Associated emissions

The methodology stipulates that all GHG emissions associated with DOCS project lifecycle activities must be accounted for i.e. a cradle-to-grave GHG statement. The protocol defines the system boundary to include all GHG sources, sinks and reservoirs associated with the DOCS project activity. Emissions may be associated to a specific 'deployment' (i.e. activity within a single crediting period) or to the facility as a whole (e.g. facility construction emissions).

This includes emissions related to project establishment (e.g. equipment and materials embodied emissions, equipment and materials transport to site, construction and installation, and Initial surveys and feasibility studies); emissions occurring during project operations (e.g. DOCS plant processes (e.g. emissions from energy used, consumables, waste processing), transport between DOCS facility and CO_2 storage site,CO_2 injection/storage processes, fugitive CO_2 emissions, CO_2 ocean uptake and MRV sampling, staff travel and surveys); anticipated direct and indirect emissions after the reporting period but allocated to it (e.g. emissions from decommissioning, long-term monitoring and surveys), and leakage emissions outside the project boundary due to induced market changes. All direct and indirect emission sources related to the DOCS project activity must be identified including any emissions outside the defined categories, which are referred to as miscellaneous emissions.

Emissions from project establishment are generated from the initiation of the project up to the point prior to the first removal activity. GHG emissions resulting from project establishment may be amortized over the projected lifetime of the project or allocated per unit of product output. The guidelines for emissions amortization can be found in Section 7 of the GHG Accounting Module v1.0.

Emissions resulting from operational activities are assigned to the reporting period in which they occur. These emissions are typically recurring and must be tracked over each reporting period to ensure accurate net carbon removal accounting.

For end-of-life emissions occurring after the reporting period, those directly related to a specific deployment must be quantified as part of that deployment's reporting period, while emissions associated with the facility as a whole (e.g. facility end of life decommissioning emissions) may use the same allocation method as for project establishment emissions. When a DOCS project reaches the point of planning to close a storage site, the protocol specifies that post-closure monitoring emissions should be quantified and assigned to the remaining removals to be stored at that site. If this is not feasible, emissions are to be allocated to other relevant DOCS

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[7] CO_2 Storage in Depleted Hydrocarbon Reservoirs

CO_2 Storage in Saline Aquifers

CO_2 Storage via In-Situ Mineralization in Mafic and Ultramafic Formations

CO_2 Storage via Ex-Situ Mineralization in Closed Engineered Systems

CO_2 Storage via Carbonation in the Built Environment projects or storage sites with approval from Isometric. If emissions are not assigned accordingly, the reversal process under the Isometric Standard will be initiated. For shared monitoring activities, emissions must be apportioned proportionally based on each entity's use of the storage facility.

The protocol requires that GHG accounting adheres to the Isometric GHG Accounting Module v1.0, which establishes a framework for quantifying and reporting GHG emissions across various CDR projects and methods. This framework sets out requirements for data quality, addresses materiality in emissions reporting, and outlines reporting rules for emissions amortisation, co-product allocation, by-product, and waste input accounting.

3.1.2.3 Uncertainty

The methodology requires accounting for uncertainty in the estimation of net carbon removals. It specifies that “the total net CO_2e removal for a specific reporting period must be determined with high confidence”. Projects are required to conduct an uncertainty analysis for the net carbon removal calculation, listing all key variables used in the calculation and their uncertainties. Minimum and maximum values of each variable must be provided. More detailed uncertainty information should be included if available. A sensitivity analysis is performed to show the impact of each input parameter's uncertainty on the net carbon removal calculation. Input variables that contribute less than 1% change in the net CO_2e removal can be excluded from the uncertainty analysis.

3.1.2.4 Measurement and modelling

The gross CO_2 removal via DOCS occurs across various spatial and temporal scales. The Isometric quantification framework for this process requires defining four specific spatiotemporal regimes, i.e. DOCS facility, mixing zone, near-field, and far-field. The process involves three main steps to characterise the spatiotemporal regimes of DOCS project activity of adding DIC-depleted seawater and its impact on air-sea CO_2 exchange.

- **Step 1 Measurements of seawater carbon capture (DOCS-facility regime):** The process begins with a direct assessment of the quantity of CO_2 extracted from seawater. This involves measuring the captured CO_2 stream. The cumulative mass and average concentration of CO_2 over the reporting period are then used to calculate the total amount of CO_2 removed from seawater. The measurements must be documented in the Project Design Document (PDD), including sampling methods, frequency, calibration, data reporting and quality control. The protocol states that monitoring data and measurement uncertainties, including the uncertainty in the amount of CO_2 captured, must be analysed and reported for every reporting period. The protocol requires a validation check: the measured CO_2 stream must align with the change in DIC levels measured between the incoming and outgoing seawater. If there is a significant discrepancy, an audit is triggered to investigate the cause.
- **Step 2 Upscaling of DIC-depleted plume (mixing zone and near-field regimes):** This step characterises the transport and mixing of DIC-depleted seawater to allow the quantification of air-sea CO_2 fluxes. In the mixing zone and near-field domain, the release of DIC-depleted seawater is the basis to define a forcing function in the air-sea CO_2 uptake ocean model. The protocol states that placing the DIC-depleted plume near the surface ocean optimises CO_2 drawdown, but the plume’s vertical and horizontal distribution must be assessed.

Certain processes can take place in the near-field domain and contribute to losses, which should be quantified and subtracted when determining the CDR forcing function applied to the ocean model used in Step 3.

Isometric presents three approaches to choose from for determining the time-variable CDR forcing function to be applied to the ocean model:

1) a validated coastal model (generally a 3D[8] though in some cases 1D, 2D or nested hydrodynamic models may be acceptable) to simulate CDR intervention dispersal;
2) seasonal tracer studies to measure depth profiles of tracers in the near-field domain, which may be used to calibrate and validate modelled results;
3) using sensitivity studies to demonstrate that the ocean model used to quantify air-sea CO_2 uptake ocean model is insensitive to different distributions and temporal variability (i.e. that it is not necessary to provide detailed spatial characterisation of the forcing function).

Isometric states that it is open to considering and accepting innovative and hybrid approaches combining these options on a case-by-case basis, provided they are well-supported. Most projects involve a density difference between effluent and marine waters, so it is recommended to use both a mixing zone model (e.g. CORMIX or Visual Plumes) and a near-field model. At this step, the protocol includes a validation check to ensure that the DIC-depletion in the forcing function does not surpass the measured CO_2 capture from seawater (as described in Step 1).

- **Step 3 Air-sea CO_2 uptake (near-field and far-field regimes):** Projects must quantify net CO_2 removal from air-sea gas exchange using an appropriate ocean model. Model used must be validated and meet the requirements of the Isometric's own module for Air-Sea CO_2 Uptake v1.1. The CDR forcing function is determined in Step 2 and implemented into the ocean model, which computes the $\Delta \boldsymbol{CO}_{\boldsymbol{2}^{e}\boldsymbol{AirSeaFlux,RP}}$. The model can also calculate the air-sea flux CO_2 uptake at given point in time. The air-sea CO_2 equilibration must be quantified over the coastal domain, the open-ocean domain, or both. It is not necessary to quantify air-sea gas exchange during the initial transport and mixing of the DIC-depleted plume in the coastal domain. Isometric emphasises the importance of implementing measures in the modelling process to prevent double counting between the coastal and open-ocean domains. Isometric requires a validation check for the ocean model, ensuring that the total CO_2 removed through air-sea gas exchange does not exceed the amount of CO_2 captured from seawater in Step 1.

3.1.2.5 Near-field losses

The Isometric protocol outlines three main processes that contribute to near-field losses and reduce the DOCS effectiveness. It is noted that the majority of the research on these loss factors is directly related to OAE project activity, which may not truly reflect the carbonate chemistry found in effluent from DOCS projects. Isometric highlights it is important to assess the loss terms in the context of project specific DOCS carbonate chemistry settings.

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[8] Examples of 3D hydrodynamic models include Delft3D, MIKE 3, TELEMAC 3D, FVCOM.

- Secondary precipitation involves the formation of calcium carbonate minerals in seawater leading to CO_2 outgassing. Abiotic precipitation rarely occurs in the open ocean due to the inhibition of spontaneous nucleation, with most carbonate production being biologically mediated. Isometric says that early research indicates a link between alkalinity loss from precipitation and higher total suspended solids (TSS) levels in receiving waters. Pipe roughness in effluent pipes can increase nucleation sites, making secondary precipitation most likely to occur in the effluent pipe, mixing zone, and coastal area. These processes generally decrease with increasing distance from the DOCS discharge. Spontaneous carbonate precipitation might occur in locations with exceptionally high saturation rates, but it is not commonly observed, according to Isometric's protocol. The protocol outlines an avoidance strategy to prevent secondary precipitation by effective dilution, establishing thresholds for pH and monitoring total alkalinity and TSS. The protocol also mentions secondary precipitation could be indicated by increased turbidity. While monitoring turbidity is advisable, distinguishing it from natural fluctuations can be challenging. Additionally, tracking alkalinity levels during periods of unusually low readings can also assist in detecting secondary precipitation.
- Biotic calcification refers to the process where marine organisms use alkalinity to form calcium carbonate shells and skeletons. The carbonate chemistry conditions promoted by DOCS, i.e. lowered H+ and elevated saturation state, could enhance calcification. Isometric indicates that the risk of alkalinity loss due to biotic calcification can vary depending on the specific project and location, such as the Black Sea, which naturally possesses elevated alkalinity levels and supports calcifying plankton. The protocol outlines a potential avoidance strategy to prevent biotic calcification by setting thresholds on pH and total alkalinity and monitoring changes in ocean biota.
- Modifying local carbonate chemistry, particularly near the seabed, could reduce natural sediment alkalinity fluxes, affecting project effectiveness. The protocol required DOCS projects to carefully control discharge rates and infrastructure design to minimise changes in pH and total alkalinity near the seabed. Thresholds for acceptable pH and total alkalinity levels should be supported by academic literature or laboratory analyses tailored to the specific deployment site. Quantification and monitoring methods include assessing benthic alkalinity fluxes and analysing net calcification changes at the seabed.

The protocol requires assessing the risk for each identified loss. If the losses are deemed negligible, an explanation must be provided. Otherwise, the losses must be quantified. Isometric highlights that there is difficulty and uncertainty in quantifying these processes, thus the protocol allows the following approaches to address losses:

- Avoiding losses by identifying strategies to mitigate conditions causing non-negligible loss terms, with monitoring for adherence;
- Estimating a conservative upper limit of near-field loss using scientific literature, calculations, or experiments;
- Conducting process-based modelling studies;
- Taking direct measurements;
- Employing justified alternative methods, approved by Isometric and Validation and Verification Bodies (VVB).

3.1.3 Indirect emissions and leakage

Isometric defines leakage emissions as GHG emissions resulting from the indirect effects of a project's activities that extend beyond the project's defined system boundary. This includes an increase in emissions due to the displacement caused by the project or through secondary impacts that elevate emissions elsewhere. For instance, the creation of a market for feedstocks might generate additional revenue within the source sector, influencing producer behaviour in ways that lead to increased GHG emissions. Isometric requires identifying potential leakage emissions sources, with at least replacement of consumables considered, but notes that, "It is the Project Proponent's responsibility to identify potential sources of market leakage emissions" – given that the proponent is not incentivised to identify additional indirect emissions that reduce unit issuance, it should not be taken for granted that sources of leakage emissions will be thoroughly identified unless specified in the certification requirements. Isometric requires the assessment of the effects of DOCS project operations on water, land use changes, and potential pressures on CO_2 transport and storage infrastructure. These emissions must be attributed to the reporting period in which they occur, although allocation across periods may be allowed in specific cases with Isometric's approval.

3.1.4 Additionality and baselining

Projects must demonstrate additionality by showing that the carbon removal would not have occurred without the project intervention. Isometric general standard introduces four pillars of additionality: financial, common practice, environmental and regulatory.

- Financial additionality can be demonstrated if either a) removals are the only source of revenue for the project, or b) that without carbon finance revenue the project has an IRR that is zero or lower or that is below the cost of capital or required return on equity for the project, and that the revenue from carbon credits will make that IRR positive or above the required rate of return (as appropriate), although there is provision made for project proponents to justify a higher IRR for the assessment. The standard is not prescriptive about what target IRR can be considered acceptable.
- According to the common practice analysis, projects below TRL 8 or 9 are considered additional without further analysis. Alternatively, a full analysis must justify that similar activities are not common practice in the project's geographic area.
- Regulatory additionality requires that the project is not legally required, though removals beyond the minimum legal requirement may be certified.
- Environmental additionality is defined as a net negative climate impact, which is presumably trivial for any carbon removal project generating credits and therefore does not seem to be a substantive addition to the additionality framework.

Additionality is determined at the time of initial project validation and is to be reviewed at every later project revalidation and when there are significant changes to project operations, new regulatory requirements or changes to project finance indicating carbon finance is no longer needed. If the project becomes not additional, it will be ineligible for future credits. Carbon credits issued under current or past crediting period will not be affected.

The methodology presumes a baseline scenario where DOCS project activities are absent, and infrastructure is not installed. In cases where projects integrate with existing infrastructure, the baseline scenario may account for any current discharge already present. The calculation for the baseline scenario encompasses the carbon removals that would have been naturally removed or emitted into the atmosphere and stored in the ocean over the same period as the project's duration. The impact of the DOCS project is assessed relative to these baseline conditions. The ocean baseline air-sea CO_2 fluxes are already accounted for in the calculation of the total net carbon removals within the term $\Delta \boldsymbol{CO}_{2^{e}}{}_{AirSeaFlux,RP}$.

Field measurements are needed to obtain marine data to validate the baseline model, which then informs the sampling plan design. The methodology notes that defining a baseline is difficult because climate change is constantly altering current ocean measurements.

3.1.5 Long-term storage and liability

Isometric DOCS projects involve two types of storage reservoirs: firstly, CO_2 extracted from seawater is stored in a durable reservoir (over 1,000 years) such as geological storage; secondly, CO_2 removed from the atmosphere through the process of air-sea equilibration is stored in the long-term (over 1,000 years) in the ocean as dissolved inorganic carbon (DIC). It is the carbon removal held in the second reservoir that is eligible for credit allocation, but the integrity of the first reservoir must be demonstrated for the project to qualify for credit issuance. For instance, Isometric explains if 10t CO_2 is removed from seawater and stored in Reservoir 1, and 9t CO_2 is absorbed from the atmosphere into the ocean as DIC (Reservoir 2), then credits are issued for 9t. If the 10t stored in Reservoir 1 is later released, the project results in a net emission of 1t CO_2.

Projects that implement the DOCS methodology may use one or more of the following Isometric storage modules to determine the total amount of CO_2 extracted from seawater and stored in a durable storage reservoir (i.e. Reservoir 1):

- CO_2 Storage in Depleted Hydrocarbon Reservoirs
- CO_2 Storage in Saline Aquifers
- CO_2 Storage via In-Situ Mineralization in Mafic and Ultramafic Formations
- CO_2 Storage via Ex-Situ Mineralization in Closed Engineered Systems
- CO_2 Storage via Carbonation in the Built Environment

Each of the storage module contains, permitting criteria, specific monitoring, reporting, and verification (MRV) requirements to analyse the stored CO_2 sequestered over time, assess reversal risks, and quantify GHG emissions related to reservoir monitoring.

Regarding the storage of CO_2 removed from the atmosphere (i.e. Reservoir 2), Isometric discusses durability and reversal risks of the DIC storage reservoir in a separate module Dissolved Inorganic Carbon Storage in Oceans v1.0. Two primary assumptions are made: first, that the net carbon removals have been fully quantified in accordance with the Isometric methodology; second, that all environmental and social safeguards are adhered to before ocean storage.

The module explains that the ocean's DIC reservoir is characterised by its residence time, which is the average duration a substance remains in a reservoir. For final storage DIC reservoir, this ranges from 10,000 to 100,000 years. Beyond this period, the true permanent storage of marine carbon on multimillion year timescales is the precipitation of solid carbonates to the sea floor, so approximately half of the captured carbon stored as DIC will be released back into the atmosphere. However, for the purpose of quantifying durable storage on a 1000-year timescale, the Isometric protocol does not take into account this very-long-term carbonate precipitation.

Long-term durability of ocean DIC storage can be lowered due to reversal risks like changes in CO_2 residence time with large-scale CDR implementation. Additionally, climate mitigation could lower atmospheric CO_2 enough to release ocean-stored carbon back into the atmosphere. This can happen if atmospheric CO_2 levels fall below those present in the ocean. Currently, CO_2 emissions continue to rise, and land-based CDR is insufficient to significantly impact global carbon fluxes.

Isometric requires that every storage reservoir used by a DOCS project has a dedicated buffer pool. The project's overall buffer pool would consist of the combined buffer pools for all reservoirs.

Isometric specifies that reversals in the storage of CO_2 removed from seawater and subsequently stored in geologic reservoirs may be identified through post-sequestration monitoring. The applicable storage modules contain details about the buffer pool size (based on project’s risk reversal score) and the procedures for allocating reversals. It is important to note that the buffer pool represents a percentage of the final credits issued, rather than a percentage of the CO_2 sequestered.

The DIC storage reservoir is categorised as having a very low risk level of reversal, corresponding to a 2% buffer pool contribution. It is acknowledged that changes in the global ocean DIC reservoir cannot be directly observed through measurements and attributed to a specific project. Isometric states that the reversal risk in ocean DIC storage is identified as a system-wide uncertainty that needs additional scientific research for better understanding and monitoring.

3.1.6 Sustainability

Environmental and socio-economic safeguard plans must be included in all major project phases, with comprehensive reports made available to stakeholders. These safeguards encompass environmental protection, social equity, community involvement, and respect for cultural values. All crediting projects are obligated to adhere to and verify these environmental and socio-economic safeguards. Isometric references the *Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration* (Chapters 2.1 and 2.2) to identify and assess risks associated with CDR projects in coastal and marine environments. The *Guide to Best Practices in Ocean Alkalinity Enhancement Research* (Chapters 10 and 11) is also referenced, with an emphasis on the need to differentiate between DOCS and OAE practices and their legal, social, and justice considerations.

The legal frameworks for marine CDR projects are still developing at various levels, including international, regional, and local. Permits might be needed for installing ocean intake, outfall, or effluent pipes. Isometric lists the minimum requirements for projects where project developers must obtain official permits from all relevant jurisdictional authorities including local rightsholders of the water body of the projects site and affected areas. Project developers must follow ratified provisions in international conventions such as the London Protocol; United Nation Convention on the Law of the Sea (UNCLOS); International Convention for the Prevention of

Pollution from Ships (MARPOL); Basel Convention and the EU Marine Strategy Framework Directive.

Project developers are required to perform an environmental and social risk assessment in accordance with the Isometric Standard, identifying potential risks and formulating customised mitigation strategies.

DOCS projects present a range of potential marine environmental risks, including the need for robust plans to manage, contain and dispose of any wastes and co-products safely. Abrupt or unplanned changes in the carbonate system, particularly at project termination, may disrupt ecosystems by causing sudden shifts in parameters such as pH, which can either benefit or harm aquatic organisms depending on the scale of change (and will affect different organisms in different ways). Such disruptions could trigger cascading effects on mineral precipitation, dissolved oxygen levels, the frequency of algal blooms, and/or the overall composition and functioning of ecosystems both locally and downstream. Additionally, the physical infrastructure required for project operations may contribute to increased erosion along coastlines and riverbanks, while marine organisms face risks of injury or entrapment during water intake and treatment processes.

The protocol recognises that expecting a project to demonstrate zero impact on the ocean ecosystem is “unrealistic”, noting challenges in attribution and the establishment of an appropriate baseline (i.e. the significant possibility that ecosystem status could deteriorate for reasons other than the CDR activity). Instead, it emphasises that project impacts should be evaluated holistically considering climate change risks (i.e. allowing that some negative impact on the ocean system may be acceptable in the context of significant climate benefit).

In terms of socio-economic safeguards, the protocol mandates an environmental justice review designed to account for local coastal infrastructure, marine uses, and the fair distribution of resources before choosing a site. Isometric also requires an evaluation of the potential impacts on fisheries, aquaculture, coastal industries, and ocean-based livelihoods.

There are requirements for engaging with local stakeholders, who may contribute to a more in-depth knowledge of the local system. Stakeholders may include local academia, indigenous groups, environmental groups, citizen associations, commercial and recreational fishermen, shellfish farmers, boaters, and recreational users.

Adaptive management strategies must be developed for information sharing with stakeholders and the public, emergency response, and conditions for stopping or pausing deployment (e.g. equipment malfunction, threshold exceedance, regulatory non-compliance, health and safety).

3.1.7 MRV

DOCS projects must be validated and net CO_2 removals verified by an independent third party. Verifiers are required to examine the documentation regarding the uncertainty of the GHG statement. Site visits are conducted during project validation, initial project verification, and at least once during the validation phase of each project. These site visits must comply with the requirements of ISO 14064-3.

The monitoring plan must be established before the project activities and includes details on monitoring duration, frequency, monitoring locations, sample collection methods, analytical methods, thresholds, data reporting procedures, and quality assurance and quality control protocols. The protocol requires that monitoring data and measurement uncertainties are analysed and documented for each reporting period. Isometric expects updates to monitoring guidance as sensor technology evolves, potentially improving measurement and monitoring capabilities over time. The DOCS project monitoring plan aims to measure net CO_2 removal, validate the models used for this quantification, ensure adherence to permitting requirements, monitor relevant environmental conditions, and detect any reversals in CO_2 storage. It also supports adaptive management by enabling project suspension should any negative impacts be identified.

The protocol outlines **pre-deployment requirements** related to the **ocean site** which include:

- official discharge permits from all relevant authorities governing the project site and surrounding waters; site description with detailed information on environmental conditions such as currents, tides, winds stratification and seasonal patterns;
- identification of other marine CDR activities co-located at the site;
- development of a mixing zone model (e.g. commercial models like CORMIX or Visual Plumes are allowed) to estimate initial dilution supported by a sensitivity analysis to ensure adherence to water quality limits;
- additional considerations of retention time (i.e. how long the effluent remains in the vicinity before dispersing) and advection/ejection events (natural processes which may transport the plume away);
- pre-deployment ocean monitoring of carbon chemistry parameters in appropriate monitoring locations;
- CO_2 extraction rates that ensure effluent pH remains within permitted limits; preparation of adequate plans for restoring effluent water quality before discharge, which includes measures to recover alkalinity and dissolved oxygen concentrations; and
- the identification of storage and disposal methods for hazardous by-products.

The methodology also outlines **CO_2 storage site requirements**, which involve determining the storage location and adhering to the procedures specified by the relevant Isometric storage reservoir modules, including securing permits and performing site characterisation to assess suitability and risks. Isometric requires a risk assessment tailored to DOCS projects in order to identify applicable reversal risk factors, which are incorporated into both the monitoring plan and project design document (PDD). The risks identified inform the required duration of monitoring and specific project monitoring needs. Isometric also uses a “Risk of Reversal Questionnaire” to determine the DOCS project's risk score, which is used to calculate buffer pool contributions. Projects are required to re-assess reversal risks at the start of each new crediting period, if monitoring reveals a reversal-related risk, or when an actual reversal event occurs. In all cases, reversal risks must be reassessed at least once every five years. Several factors influence the risk score: carbon form (organic or inorganic), storage method and location (subsurface or ocean), and proximity to reversal agents—physical or chemical conditions that could release CO_2.

The protocol sets thresholds on parameters for monitoring: 1) safety thresholds for effluent characteristics to be kept within safety limits before discharge; and 2) action thresholds for parameters measuring water quality and environmental changes (determination of action thresholds is explained in section 11.4.5 of the protocol and notes it is a challenge to establish a control site to isolate the DOCS impact from baseline). If seawater discharges occur during times when safety thresholds are violated, no carbon removals may be credited in relation to the DOCS activity on those volumes of water.

Isometric DOCS methodology requires operators to specify **monitoring locations** to ensure that the monitoring activities are spatially representative and allow for capturing all relevant aspects of the DOCS process and its environmental impacts. It is the responsibility of project developers to identify suitable monitoring sites. The methodology suggests that models are used to plan the sampling design for monitoring over the general monitoring locations within the DOCS system i.e. the CO_2 capture and discharge points (CO_2 stream is measured after extraction from seawater and again before storage to identify any fugitive emissions), seawater influent (measurements are taken at the intake pipe before any pre-treatment or CO_2 extraction) and seawater effluent (measurements of the water quality at the outflow pipe before discharge into the ocean, after CO_2 extraction and alkalinity restoration), edge of mixing zone (the region near the discharge point where initial dilution occurs and the water quality may be exceeded), and the deployment area (where ecological monitoring measurements occur in the broader surrounding marine environment i.e. outside the mixing zone). It is important to note that there are additional monitoring requirements depending on the type of storage utilised for the captured CO_2. The protocol requires a diagram of monitoring locations to be included in the project design document.

As already discussed, DOCS projects are required to measure the **concentration** and **mass of the captured CO_2 stream**, which is required to quantify the CO_2 removals. Therefore, CO_2 concentration must be monitored immediately after extraction and just before sequestration, using high-precision inline analysers for CO_2 concentration (e.g., NDIR or TDL) with strict calibration and data recording standards. For shared storage sites, CO_2 stream can be estimated at the transfer point using weight fractions. The mass of the captured and sequestered fluid is measured using calibrated mass flow meters, preferably Coriolis or thermal mass flow meters, with traceable calibration, proper maintenance and installation, and high accuracy.

If there are data gaps or missing calibration data, Isometric and the VVB must be informed, and the information must be recorded in the GHG statement. For parameters requiring frequent measurements, such as CO_2 concentration and mass in the CO_2 stream, Isometric allows for short data gaps (up to 30 minutes) to be addressed by averaging surrounding measurements, but for gaps longer than 30 minutes, only a 30-minute average is permitted, and the rest must be treated as zero. Data gaps must comprise less than 5% of the total carbon removals calculation data per reporting period to be creditable. Missed calibrations must be rectified promptly, and a conservative estimate agreed by all parties must be applied to the affected data.

The DOCS methodology requires **monitoring seawater effluent before ocean discharge**, measuring pH, total alkalinity, temperature, and salinity. Carbonate system measurements are also used to determine and confirm the quantity of carbon removed and the level of carbonate equilibrium in the effluent. Monitoring temperature and salinity determine the physical conditions of the effluent while the pH and alkalinity ensure that discharge remains within the permitted thresholds stipulated in the PDD. Isometric states that DOCS projects may lower alkalinity sampling frequency after demonstrating steady-state operation.

The protocol highlights that calculating alkalinity and DIC from pH and pCO_2 measurements can result in high uncertainty, especially in DOCS projects where pCO_2 levels are near zero. If a project chooses to use this method, it must still conduct routine bottle sampling to verify that the calculated values align with direct measurements. A third carbonate system variable to assess the initial state of carbonate system disequilibrium at the point of discharge is recommended.

Seawater effluent from DOCS projects must comply with pH safety thresholds set in permits, enforced either at the pipe outlet or after initial ocean mixing. Isometric requires calculation and monitoring of in-pipe pH levels to maintain compliance. DOCS projects must also measure influent seawater chemistry and ensure that effluent pH and dissolved oxygen (DO) are restored to safe levels before discharge into the ocean. If alkaline solids are removed during pre-treatment, they should be reintroduced to maintain seawater chemical balance and ecological safety. For effective DIC monitoring, it is necessary that the difference in DIC between the seawater influent and effluent corresponds to the quantity of CO_2 captured during the process.

The mixing zone is the area surrounding the discharge infrastructure where it is allowable for water quality criteria to be exceeded (i.e. in cases where the discharge itself would not meet water quality requirements, but will meet those requirements after some acceptable period of dilution). Permits which allow for a mixing zone require water quality criteria to be met at the edge of that mixing zone. The methodology notes that small-scale deployments may struggle to detect signals beyond the mixing zone and therefore that measurement should be concentrated at the edge of this zone. Increased sampling within the mixing zone is necessary due to turbulence effects. Beyond this zone, waters are less turbulent, allowing more representative impact measurements of the CDR intervention. Therefore, monitoring should focus on the edge of the mixing zone. In the mixing zone, temperature, salinity, two carbonate chemistry parameters (pH, TA, DIC, pCO_2), dissolved oxygen, turbidity, and total suspended solids are measured. The parameters monitored inform water quality, local carbonate saturation state, and loss term estimates. Burst sampling in the mixing zone is recommended, involving high-frequency data collection over short periods to understand turbulence effects on effluent distribution.

Isometric DOCS projects must implement site-specific biological and ecological monitoring guided by an **environmental risk assessment and mitigation strategy**, including periodic surveys to assess both functional and taxonomic diversity. While no formal action thresholds are imposed due to challenges in establishing ecological baselines, data collection remains essential for understanding long-term and cumulative impacts.

Isometric requires measurements for both validating models and providing inputs for models used in DOCS projects. Ocean data such as winds, currents, tides, waves, and turbulent mixing are critical inputs for models. These data can be collected at the field site or sourced from government agencies. It is recommended to measure air-sea carbon flux to validate modelled carbon flux. Methods include gradient method, eddy covariance, flux chambers, or dual tracer regression.

In summary, monitoring requirements cover the entire project lifecycle: before deployment, during operations, and after completion. Pre-deployment monitoring must establish a baseline of water chemistry and ecological conditions, with sufficient resolution to capture natural ocean variability. Monitoring duration and frequency depend on environmental risks, CO_2 capture period, site-specific water residence time, and seasons. Post-deployment monitoring must similarly reflect risk timescales and local conditions. Monitoring intensity can vary based on project capacity, discharge location sensitivity, operational phase, and seasonal environmental risks.

Isometric provides a summary of required and recommended monitoring parameters (section 11.6 of the protocol):

Required parameters for all DOCS projects by monitoring location include:

- CO_2 stream from DOCS facility: concentration of CO_2 and total mass;
- Seawater effluent: pH, TA, temperature, salinity, flow rate;
- Seawater influent: pH, TA, temperature, salinity, flow rate;
- Edge of mixing zone: temperature, salinity, any two carbonate system parameters, dissolved oxygen (DO), total suspended solids (TSS), turbidity.

Recommended parameters for DOCS projects by monitoring location include:

- Edge of mixing zone: third carbonate system parameter, Chlorophyll-a, dissolved inorganic nutrients;
- Deployment area: benthic community.

4 Review of known and potential issues

4.1 Quantification

Quantification of carbon removals by DOCCS relies on quantification of both the net removals to the terminal store (i.e. the carbon extracted from seawater, minus any losses) and the net removal from the atmosphere into the ocean DIC pool. The net removals are then calculated as the net removal from the atmosphere to the ocean, minus any losses associated with the storage to the terminal store, and accounting for any lifecycle emissions associated with the activity. The most challenging component of quantification is associated with the diffuse uptake of CO_2 by the ocean over large time and space scales, and quantification of associated loss terms. The challenges and solutions are very similar to those for OAE (see OAE report section 4.1) and are repeated in brief here.

4.1.1 Equilibration with atmospheric CO_2

As DIC-depleted water disperses, it will re-equilibrate with the atmosphere, removing atmospheric CO_2. The rate of this equilibration and the fraction that remains un-equilibrated within a given timeframe depends on vertical and horizonal mixing within the ocean and is variable with location, season and daily conditions. It can take a decade or more for the carbon removal to be completed, and the degree to which DOCCS-removed DIC remains unequilibrated (i.e. the proportion mixed out of reach of the atmosphere over long timescales) is a major control on the overall efficiency of the carbon removal per unit DIC removed (Section 2.3.3). Given the large spatial and temporal scale of equilibration with the atmosphere, it is necessary to rely on models to quantify carbon removals from the atmosphere. Coupled ocean-atmosphere models are relatively mature and able to accurately predict weather and climate on day-to-decadal timescales so are well suited to this task. However, there is still significant uncertainty, particularly around the application of ocean biogeochemical models to estimating CO_2 uptake at the sea surface in relation to CDR, which remains largely unvalidated (Ho et al., 2023). Large scale field experiments and intensive observations around early OAE deployments could be used to support validation of the models.

4.1.1.1 Key knowledge gaps

Uncertainty in air-sea CO_2 flux (the point at which carbon is removed) in models includes uncertainty about the exact timescales for the delivery of net removals, which could affect the appropriate rate of unit issue. A method to address this uncertainty will need to be implemented within any certification until such a point as the uncertainty can be appropriately constrained.

4.1.2 Secondary precipitation and other carbon cycle impacts

The risk of losses due to secondary precipitation locally to DOCCS activities is less than for OAE per unit removal potential (Section 2.3.4), due to the different mode of action (DIC removal vs alkalinity enhancement). However, DOCCS still raises pH and the saturation state of carbonate minerals in seawater, prior to CO_2 uptake and re-equilibration, so losses are still possible. These will need to be mitigated by establishing site-specific thresholds for pH and Ω that should not be exceeded and routine monitoring of such in the near field around release locations.

Impacts on marine productivity and community structure are also possible, local to DOCCS actions (Hooper et al., 2025). These may lead to carbon cycle responses which alter the natural carbon uptake from the atmosphere. These are not envisaged to represent substantial loss or gain terms for quantification, but their direction and magnitude are hitherto unstudied.

Unlike OAE, DOCCS has no net effect on ocean carbonate chemistry in surface waters after re-equilibration. Therefore, where large scale OAE actions to mitigate a significant proportion of excess global emissions might lead to global feedbacks due to modified ocean chemistry (greater alkalinity, higher DIC), DOCCS has no such large-scale feedback risk. However, the impacts of sustained surface DIC depletions from continual application of DOCCS at climate-relevant scales has not been studied. While this is a transient effect that will dissipate over a few years, its likely magnitude and effect on secondary precipitation or the carbon cycle are unknown.

4.1.3 Acid / base imbalance and acid disposal.

DOCCS relies on the production of acid and base streams from seawater, where one unit of acid is made for every unit of base. Under the acid route, DOCCS will tend to use acid and base in equal quantities to drive the pH swing for CO_2 removal and subsequently to return the seawater to its original alkalinity, although extraction efficiency could lead to small imbalances in either direction (Section 2.2.2). In the case of incomplete removal of CO_2, the result will be a net loss of alkalinity from the seawater being returned to the ocean, which could either be accounted for as a loss term (if small) or may need to be remedied by further addition of base, yielding an excess of acid to be disposed of. In the case of over-extraction of CO_2, the seawater will have a gained alkalinity after adding back the base in the process and therefore a small amount of ocean alkalinity enhancement will have been co-delivered, or an excess of base could be accumulated within the facility. Whether dealt with in accounting or physical remediation (or avoidance through careful process control), addressing potential acid-base imbalances in acid pathway DOCCS will be essential.

Under the base route, alkalinity is removed in the form of solid carbonates so more base will always need to be added than acid (Section 2.2.3), and an excess of acid will be a by-product of the process. In theory this could be neutralised by reacting with the solid carbonates and therefore closing the alkalinity budget (notwithstanding small imbalances as per the acid route). Alternatively, the acid could be used in other industrial processes or safely neutralised in another way. Any acidity that escapes into the natural system, however, will lead to a reversal and therefore must be dealt with and accounted for carefully (Section 4.15 of the OAE report).

4.1.4 Model refinement

Direct validation of model-based MRV will be needed from detailed field experiments covering a range of baseline conditions, site characteristics etc., which necessarily relies on pilot DOCCS studies[9]. It will be important to recognise that early DOCCS activities will have greater uncertainties around carbon removed but will add the greatest value to the process of constraining and improving model-based MRV for future DOCCS deployments. This highlights the importance of transparency and openness in marine CDR activities. Indeed, the Isometric protocol makes clear that

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[9] Given the strong overlap between MRV modelling methods for DOCS and OAE, pilots of both can contribute to the same development and improvement effort.

the gathering and availability of data is critical for understanding the potential and limitations of DOCCS and for developing the technology. Isometric requires that modelling and observations undertaken in support of any deployment should be fully documented, open-access and adhere to FAIR data principles (findable, accessible, interoperable and reusable; e.g. (Jiang et al., 2023)), as well as complying with the best practice guidelines put forward for OAE research by (Oschlies et al., 2023).

As our knowledge and modelling capability improves, the need for comprehensive observations for model validation will be reduced for known addition locations and release rates. Care will always be needed, however, to avoid over-reliance on assumptions, rules of thumb and models that not validated for the specific DOCCS application in question.

4.2 Additionality and baselining

4.2.1 Complementary value

In some circumstances, it is conceivable that DOCCS could provide additional financial value to project operators alongside the value delivered by the generation of carbon removal units. This complementary value could affect the assessment of whether an activity would meet a standard for financial additionality, however in most cases this is unlikely to be a concern.

4.2.1.1 Use of water pumped for cooling or desalination

Where large volumes of water are being pumped from and returned to the ocean (for cooling e.g. power stations), and where concentrated seawater brines are produced (e.g. desalination plants) there is the potential to reduce DOCCS costs associated with pumping and brine production. For example the disposal of the brine produced by desalination plants is costly and / or environmentally damaging. Integrating CO_2 removal may provide process efficiencies for both DOCCS and desalination processes simultaneously (Sartor et al., 2025). There are challenges however, such as managing the density of desalination waste streams to avoid rapid sinking out of alkalinity, removing the opportunity for equilibration with the atmosphere.

4.2.1.2 By-products

Hydrogen produced as a by-product of electrolysis may be used to provide power to a DOCCS facility as a cost-saving, or be sold. Chlorine gas may have local value, as transport is a challenge, but globally it is in excess (OAE Report, Section 2.2.3.2). Excess hydrochloric acid may have a value where it can replace existing acid production, but if new markets are created and the net result is more acidity entering the environment at some point, then losses will need to be quantified proportional to the resulting additional alkalinity removal.

Calcium carbonates from base pathway DOCCS could be used to add alkalinity to the ocean, or to neutralise the acidity produced in the process and then returned to the ocean as pre-equilibrated alkalinity. Overall, careful by-product accounting is more likely to be important for quantification of losses than for financial additionality.

4.3 Long-term (durable) storage

As established in the OAE report the storage of CO_2 as dissolved inorganic carbon in the ocean should be considered durable on a timescale of at least several centuries. In some cases the storage is durable on geological timescales, but in the context of changing atmospheric CO_2 over the coming century or so, the durable fraction of CO_2 storage resulting from DOCCS may increase or decrease, with changes in CO_2 in the atmosphere and subsequent re-equilibration with the surface DIC pool. Furthermore other anthropogenic activities may impact the durable fraction through external changes in alkalinity.

4.3.1 Relevance to long-term emissions trajectories

Future changes to atmospheric CO_2 on 100-200 year timescales will impact the long-term efficiency of OAE/DOCCS, and how it interacts with other CDR along the way. While higher peak emissions mean greater long-term-integrated efficiency due to greater atmospheric CO_2 and therefore greater equilibrium DIC, successfully meeting Paris agreement targets reduces the long-term efficiency (Schwinger et al., 2024). It might be decided that as such variations to delivered long-term storage would be beyond the control of the operator that it would not be useful to create a liability system for such variations, but a certification approach could be designed that would treat a reduction in modelled CO_2 removal due to differences between the expected and observed atmospheric CO_2 concentration over time as a reversal, or conversely where an increase would lead to the issuance of additional units.

4.3.2 Reversals due to other anthropogenic activity

Other anthropogenic activity which affects the alkalinity balance of the marine system will alter the fraction of stored DIC which is durable on a given timescale. Increasing or decreasing acidic (e.g. nitrate) nutrient inputs from agricultural runoff via rivers and changing atmospheric deposition of acidic species from fuel combustion and agriculture (NO_x, SO_2) will alter the alkalinity balance of the ocean and therefore the equilibrium point between the surface ocean and the atmosphere, driving some DIC from the ocean to the atmosphere until the new equilibrium point is reached. In the case of OAE we have demonstrated that, relative to the counterfactual, a more alkaline ocean responds with marginally less CO_2 release for a given acidity addition (Section 4.2.2, OAE report).

In the case of DOCCS, if fully equilibrated there is no difference in surface ocean chemistry between DOCCS and the counterfactual (absence of DOCCS). Therefore there is no differential response of the system because of DOCCS and so reversals do not appear to be relevant. In the case of incompletely equilibrated DOCCS, surface ocean DIC would be marginally reduced relative to the counterfactual and thus the equilibrium point would slightly favour ocean DIC storage in the presence of DOCCS, making a marginal benefit (but probably not one that could or should be quantified). The conclusion of this analysis is that external drivers of DIC release from the ocean should not be considered as reversals for DOCCS. The exception to this is the situation where e.g. acidity is added to the ocean as a direct or indirect result of the DOCCS process. In this case it is not the fraction of DOCCS DIC that is driven back into the atmosphere that should be considered as a reversal, but the total loss of DIC as a result of the acidity addition. All in all this suggests the 'counting individual molecules' approach is inappropriate for CDR involving ocean DIC.

4.4 Sustainability

Where DOCCS is undertaken, the chemistry of seawater is *temporarily* altered (under OAE it is permanently altered, e.g. (Halloran et al., 2025)). This has the potential to impact marine organisms and ecosystems over an area of effect which might range from sub-tenths to tens of km^2 depending on local conditions and the volume and intensity of sustained DOCCS-treated water release (Section 2.3.6). This may lead to carbon cycle changes which could constitute a feedback on efficiency or usefulness of DOCCS (Section 2.3). Here we address the non-CO_2 impacts of the changes in seawater caused by DOCCS. Such impacts are poorly quantified (Hooper et al., 2025) and it would be beneficial to monitor and conduct research into potential negative side effects in order to ensure that OAE is a sound method for CDR prior to application at large scale. The main characteristics of DOCCS-treated water are i) reduced DIC, ii) raised pH, and iii) raised Ω_{arag}. For all of the below, impacts can be minimised by selection of sufficiently high flow / well mixed locations such that dilution rates are maximised. In any case, definition of and adherence to safe threshold values of key parameters (pH, Ω_{arag}) will be the main approach to ensure ecosystem impacts are minimal to zero. For all of the below impacts on marine ecosystems the risks are probably low but the uncertainty is high, so there is an urgent need for coordinated research into impacts of DOCCS (and similarly, OAE).

4.4.1 Impact of reduced DIC

Reduced DIC availability can reduce the biomass growth of photosynthesising organisms that require CO_2 to grow, and reduction of the growth rate of calcifying plankton and molluscs has been observed under low DIC conditions (Hooper et al., 2025). The impact of reduced DIC on biological calcification will vary depending on the degree of DIC removal (or location along the dilution pathway of treated water – Section 2.3.6). At very low DIC, saturation state is at a minimum due to effectively zero carbonate availability, despite high pH. Therefore, inhibition of biological calcification would be expected. This would be in a very limited space around the outflow. At intermediate treatment or dilution levels where saturation state is elevated relative to background seawater, enhanced calcification would be expected (Figure 2.6). Understanding the ecosystem level response to decreased DIC over different spatial scales under continuous DOC activities will be important in future assessment and monitoring of the impacts of the method on local ecosystems. DOCCS (and OAE) in high flow environments will present a lower risk to natural systems than in poorly flushed enclosed locations.

4.4.2 Impact of elevated pH

The direct impacts of elevated pH are poorly studied, but may include changes to intra-cellular ammonia toxicity or other additional energy costs to maintaining pH balance (Hooper et al., 2025). pH also has an indirect impact on organisms through DIC speciation – with higher pH favouring carbonate over free CO_2 and bicarbonate. This is likely to compound the impacts of reduced DIC in reducing photosynthesis (Hooper et al., 2025). High pH in DOCCS outflow is a direct consequence of the low DIC, so these two impacts will strongly co-vary and dilution will rapidly mitigate potential impacts in the near field.

4.4.3 Impact of elevated Ω_{arag}

In particular, calcifying organisms will be favoured by increased alkalinity (Bach et al., 2019). As well as impacts for the biological carbon pump this may also affect ecosystem structure at the expense of other phytoplankton types and potentially impact function of higher organisms. As a localised, transient effect under DOCCS, and given the progression of ocean acidification, it is reasonable to expect that, other than locally to application sites, the impact of elevated saturation state of carbonate minerals is likely to be small and in large part can probably be considered a (local, transient) amelioration of ocean acidification.

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