Support to the development of methodologies for the certification of permanent carbon removals

Review of carbon removal by ocean alkalinity enhancement

25 July 2025

Submitted to:

Fabien Ramos

European Commission

Directorate General for Climate Action

Directorate C – Innovation for a Low Carbon, Resilient Economy

In association with:

Cerulogy

ecodiversity

climate ● people ● nature

ICF makes big things possible

ICF is a global consulting and technology services provider with more than 9,000 professionals focused on making big things possible for our clients. We are policy specialists, social scientists, business analysts, technologists, researchers, digital strategists and creatives. Since 1969 government and commercial clients have worked with ICF to overcome their toughest challenges on issues that matter profoundly to their success. Our five core service areas are described below. Engage with us at icf.com.

ICF Cerulogy ecodiversity climate • people • nature

Support to the development of methodologies for the certification of permanent carbon removals

Review of carbon removal by ocean alkalinity enhancement

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

Date: 25 July 2025

Job Number: 330301909

ICF S.A.
Avenue
Brussels
B-1000
Belgium
T +32 (0) 2 275 01 00
www.icf.com

Document Control

Document Title	Support to the development of methodologies for the certification of industrial carbon removals with permanent storage: Review of carbon removal by ocean alkalinity enhancement
Job No.	330301909
Prepared by	Martin Johnson, Zara Popstoyanova and Chris Malins
Checked by	Jonathan Lonsdale
Version	0_1 (draft)
Date	25 July 2025

Contents

Summary

Ocean alkalinity enhancement (OAE) is a potentially high capacity carbon dioxide removal (CDR) method utilising carbonate chemistry in the ocean to durably store CO_2 as dissolved inorganic carbon (DIC) in the ocean. The ocean already durably stores a huge quantity of DIC due to its high alkalinity, driven by natural rock weathering. The principles of this storage are well understood and not under question. Quantification and certification for OAE activities present particular challenges due to the large spatial and temporal scales on which CO_2 uptake from the atmosphere occur, the need for modelling to quantify removals and some complex potential second order feedbacks and side-effects which may need additional research to be fully understood after OAE activities begin.

Key messages:

- Storing atmospheric CO_2 as bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) in the ocean is a durable approach to climate mitigation. The ultimate residence time of alkalinity in the ocean is of the order of hundreds of millennia.
- The capacity of the ocean to store bicarbonate can be increased by increasing its alkalinity (alkalinity being the ability to 'mop up' acidity), resulting in additional absorption of CO_2 from the air, which is locked up as bicarbonate.
- OAE covers multiple approaches, delineated by the source of alkalinity (mineral solid/ dissolved or electrochemical) and the method and location of addition. Not all methods may be equally suitable for certification.
- The efficiency of OAE (i.e. moles of CO_2 removed per mole of alkalinity successfully added to the surface ocean) depends on the nature of the alkalinity addition, the state of the carbonate system in seawater (pH, baseline alkalinity), equilibration timescale between the alkalinity-enhanced water and the atmosphere (itself dependent on local conditions and ocean circulation) and any negative feedbacks, such as secondary precipitation of carbonates and biological response.
- In order to quantify the efficiency and therefore the net CO_2 benefit of an OAE action, numerical modelling will be an essential component of Monitoring Reporting and Verification (MRV), given the spatial and temporal scales of action as particles dissolve and/or alkalinity-enhanced water is circulated through the marine system and equilibrates with the atmosphere. Some components of this modelling are more mature than others and whether or not to certify will depend on an assessment of the maturity, suitability and uncertainty of these modelling tools (and the likely timeline of their development).
- OAE has both potential negative impacts and potential co-benefits on marine ecosystems, from release of toxic metal ions during the dissolution of some alkaline minerals to the amelioration of ocean acidification. The scale of the negative impacts may be small, but many knowledge gaps remain. Environmental co-benefits through reduced acidity are largely conferred by added alkalinity that has not (yet) resulted in CO_2 uptake – once full equilibration has occurred, pH has returned to a value close to the starting point.
- The scientific consensus is that OAE has potential to have a significant impact on climate, but that there are still some important unknowns and the models required to implement MRV need improvement to constrain uncertainty. However there is probably sufficient evidence and understanding to enable initial certifications of some OAE methods, as evidenced by Isometrics recently published standard for OAE from coastal outfalls. It would be beneficial if certification of carbon removals by early pilot schemes

is accompanied by open data sharing of efficiency and impacts data, to ensure lessons are learned and knowledge gaps filled while scaling the technologies involved.

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.[1]

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.

One carbon removal approach that has been identified as having potential is ocean alkalinity enhancement (OAE).

1.1 Ocean Alkalinity Enhancement

Ocean Alkalinity Enhancement (OAE) is a CDR strategy that aims to increase the ocean's capacity to absorb and store atmospheric CO_2 by artificially enhancing its alkalinity. This process involves adding alkaline substances to seawater – such as finely ground minerals like olivine or industrial byproducts like lime – or the electrochemical modification of seawater or brine streams to extract acidity, returning a strongly alkaline stream back into natural seawater. These additions shift the ocean's carbonate chemistry, converting dissolved CO_2 into stable bicarbonate and carbonate ions, thereby facilitating the net uptake of atmospheric CO_2.

OAE has the potential to remove significant amounts of CO_2 from the atmosphere and store it durably. However significant knowledge gaps exist, with ongoing studies examining its efficacy and efficiency, and its environmental impacts. At climate-relevant scales, the impact of negative feedbacks on the global marine carbon cycle may be important in limiting removals. Monitoring, Reporting, and Verification (MRV) frameworks will be essential to assess the effectiveness of this form of CO_2 removal and to manage potential environmental risks, with numerical modelling playing a key role for quantifying the effects of OAE over the wide spatial and temporal scales on which it acts. However, the tools and frameworks required are not yet mature. The next generation of MRV systems and protocols are already in development by various operators and independent bodies – though there are a number of pre-revenue commercial operators in the space and the first certification methodology for voluntary carbon markets was recently published.

[1] At the time of writing a consultation is ongoing on methodologies for DACCS, BioCCS and BCR, https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14573-Carbon-removals-and-carbon-farming-methodologies-for-certifying-permanent-carbon-removals_en.

1.2 Glossary of terms and key underpinning concepts

Here we address the background knowledge required to understand OAE and the topics presented in the following chapters. There is much commonality between OAE and enhanced rock weathering (ERW), both ultimately adding alkalinity to the ocean to store atmospheric CO_2 durably as dissolved inorganic carbon (DIC). There are also direct overlaps with mineral carbonation (in terms of mineral carbonate chemistry) and with direct ocean capture and storage of CO_2 (DOCS). The following sections are intended to be used as a reference to aid understanding across all of these related topics.

1.2.1 Chemical equilibrium

Thermodynamic equilibrium refers to a stable state in which a system shows no net change through time, unless subjected to external stimulus. In the context of a chemical reaction, this means that the forward and reverse reactions occur at the same rate, so the concentrations of reactants and products remain constant. This could apply to state changes (such as liquids turning to gases), to dissolution reactions (such as gases or solids dissolving in water) or to chemical reactions in solution (such as acid-base reactions). Thermodynamic chemical equilibrium indicates that the system has reached a point where there is no net energy or matter flow, but this can always be disturbed by external perturbations (temperature and pressure changes or addition of new reactants, for example). For any reaction the concentrations at equilibrium can be determined from the equilibrium constant, K.

For the hypothetical reaction where *b* moles[2] of B plus *a* moles of A are in equilibrium with *c* moles of C and *d* moles of D:

$$\mathrm{bB} + \mathrm{aA} \rightleftharpoons \mathrm{cC} + \mathrm{dD} \quad (1)$$

The equilibrium constant for the reaction is

$$\mathrm{K} = \frac{[\mathrm{C}]^{\mathrm{c}}.[\mathrm{D}]^{\mathrm{d}}}{[\mathrm{A}]^{\mathrm{a}}.[\mathrm{B}]^{\mathrm{b}}} \quad (2)$$

In the above equation, square brackets denote concentration[3], i.e. the amount (in moles) per unit volume; with units of moles per litre (mol l^{-1}), or commonly 'molar' or 'M'[4].

The value of K tells us the degree to which a reaction proceeds. Its value for a particular reaction is dependent on conditions (e.g. temperature, pressure) and can be determined empirically or can be calculated for any reaction from thermodynamic theory and data. For the

[2] Moles are a fundamental ' concept in chemistry that relates to the amount of matter... A mole represents a fixed number of atoms / molecules / ions, exactly 6.022×10^{23}, This is useful because, unlike mass, it is easy to relate the amount of the products of a reaction to the amount of reactants started with. For example in the chemical reaction, $CO_2 + H_2O \rightarrow H_2CO_3$,1 mole of CO_2 reacts with 1 mole of H_2O to form 1 mole of carbonic acid, H_2CO_3. The 'molar mass' *M* of an element or compound, expressed in g mol^{-1} is defined as the ratio between the mass (g) and the amount of substance (mol). It can be determined from the atomic mass of the compound's constituent elements, such that 1 mole of CO_2 weighs $M(C) + 2xM(O) = 12+2x16 = 44$ g mol^{-1}.

[3] For simplicity we refer to concentration throughout. For non-ideal solutions and gases these must be modified to activity (concentration * activity coefficient) and fugacity (e.g. fCO_2), respectively. For conceptual purposes activity ≡ concentration and $fCO_2 \equiv pCO_2$, but when measuring / modelling OAE/ERW and related processes the difference can be significant and must be accounted for (either in measurement processes or in data processing).

[4] In seawater, where salinity (salt content) affects density, it is common to use moles per kg, or molal units rather than molar (per unit volume) as this term is conservative i.e. when different water masses are mixed the molal concentration varies linearly with mixing ratio, whereas if the water masses are of different density the molar concentration does not. For the purposes of this document it is adequate to consider molar and molal units interchangeable.

reverse reaction (cC + dD ⇌ aA + bB), the equilibrium constant is the inverse of that in Equation (2).

For a reaction that goes to completion (i.e. where the reactants A and B are used up), K is very large; conversely where K is very small the reaction will not proceed and little or no products C and D are produced. K is however not directly related to reaction rate, so it is possible to have a reaction with large K that appears not to proceed because of rate limitation. For many reactions, the equilibrium point (where the forward and reverse reactions occur at the same rate, hence the ⇌ symbol) is such that there is an appreciable amount of both reactants and products coexisting. These principles are relevant to all chemical processes, from fuel combustion to biochemistry. Here we focus on those which are directly relevant to ocean alkalinity enhancement (and, therefore also to ERW and DOCS).

1.2.1.1 Acid-base equilibria

The simplest description of an acid is a compound that can donate H^+ ions (protons), and the corresponding description of a base is as a H^+ acceptor (which in practice can sometimes mean a donor of hydroxide ions, OH^-, which can react with H^+ to make water). The strength of an acid is represented by its acid dissociation constant, K_A (another equilibrium constant). For the generic acid dissociation reaction:

$$HX_{(aq)} \rightleftharpoons H^+_{(aq)} + X^-_{(aq)} \quad (3)$$

where “aq” stands for “aqueous”, i.e. in water.

The acid dissociation constant (as per Equation (2)) is

$$K_A = \frac{[H^+].[X^-]}{[HX]} \quad (4)$$

The stronger the acid, the greater the value of K_A. For example, hydrochloric acid, HCl, has a K_A of the order of 10^8, indicating that it is effectively fully dissociated into H^+ and Cl^- in solution and is therefore classified as a strong acid. Strong bases, like sodium hydroxide (NaOH) have similarly high base dissociation coefficients (K_B).

1.2.1.2 The dissociation of water

Water can act as both an acid and a base because it can dissociate into H^+ and OH^- ions:

$$H_2O_{(l)} \rightleftharpoons H^+_{(aq)} + OH^-_{(aq)} \quad (5)$$

The equilibrium constant for this reaction, K_W, is 10^{-14} under standard conditions[5]. In neutral solution (i.e. water with no other acids or bases), $[OH^-] = [H^+]$. We can consider the concentration of water (in water) to be unity (equal to 1), therefore

$$K_W = [OH^-][H^+] = 10^{-14} \quad (6)$$

Where their only source is pure water, the concentration of the two ions must be equal, hence:

$$[H^+] = [OH^-] = \sqrt{K_W} = 10^{-7} \quad (7)$$

[5] Along with many other so-called ‘constants’ in physical chemistry, equilibrium constants vary with temperature and pressure. Their characteristic values are typically quoted under standard conditions – 25 °C and 1 atmosphere.

pH, the measure of acidity or basicity is then defined:

$$pH = -\log_{10}[H^+] \quad (8)$$

Therefore, when the concentrations of OH^- and H^+ are equal, pH = -log[10^{-7}] = 7. This is why a pH of 7 corresponds to a neutral solution. As acidity (concentration of H^+) increases, pH decreases. Below pH 7, $[H^+] > [OH^-]$. At pH above 7, $[OH^-] > [H^+]$.

1.2.1.3 The solubility of ionic salts and their impact on pH

The degree to which solid ionic compounds (or salts) can dissolve in water is determined by the equilibrium constant of dissolution, K_{SP}, also known as the solubility product.

For the generic salt XZ:

$$XZ_{(s)} \rightleftharpoons X^+_{(aq)} + Z^-_{(aq)} \quad (9)$$

As with liquid water, the concentration of a solid is unity (=1), so

$$K_{SP} = [X^+][Z^-] \quad (10)$$

In a solution where $[X^+]*[Z^-]$ is less than K_{SP}, it is said to be undersaturated with respect to the salt, and dissolution of solid salt would be expected, notwithstanding kinetic limitations. Conversely, where$[X^+]*[Z^-]$ is greater than K_{SP} the solution would be oversaturated and net precipitation would be expected (again notwithstanding kinetics).

Sodium chloride, NaCl is the salt of a strong acid (HCl) and a strong base (NaOH). It dissolves in water as:

$$NaCl_{(s)} \rightleftharpoons Na^+_{(aq)} + Cl^-_{(aq)} \quad (11)$$

When dissolved in water, NaCl does not affect pH, because Na^+ will not react with OH^- and nor will Cl^- react with any H^+, because base and acid dissociation constants, respectively, are large. However, calcium carbonate ($CaCO_3$), whose dissolution reaction is:

$$CaCO_{3(s)} \rightleftharpoons Ca^{2+}_{(aq)} + CO_3^{2-}{}_{(aq)} \quad (12)$$

is the salt of a strong base (calcium hydroxide $Ca(OH)_2$) and a weak acid (bicarbonate, HCO_3^-). Therefore, whilst Ca^+ will not associate with OH^- in solution, CO_3^{2-} will accept H^+ to form HCO_3^- (at e.g. neutral or typical seawater pH). The net result of $CaCO_3$ dissolution is to reduce $[H^+]$ and increase the pH of the solution:

$$CaCO_{3(s)} + H^+_{(aq)} \rightleftharpoons Ca^{2+}_{(aq)} + HCO_3^-{}_{(aq)} \quad (13)$$

or, equivalently

$$CaCO_{3(s)} + H_2O_{(l)} \rightleftharpoons Ca^{2+}_{(aq)} + HCO_3^-{}_{(aq)} + OH^-_{(aq)} \quad (14)$$

$CaCO_3$ is therefore considered a basic, or alkaline, salt. This means that the solubility of calcium carbonate is greater at lower pH, with more acidic solutions (more H^+ ions) pushing the equilibrium in Equation (13) and Equation (14) to the right.

1.2.1.4 The dissolution of CO_2 in water

The reaction of CO_2 gas dissolving in water can be chemically described as:

$$CO_{2(g)} \rightleftharpoons CO_{2(aq)} \quad (15)$$

The equilibrium constant for this type of reaction is known as the Henry's Law constant, K_H, or the air-water partitioning coefficient; and directly relates the atmospheric concentration with the surface water concentration at equilibrium. In this case:

$$K_H = [CO_{2(aq)}] \,/\, pCO_{2(g)} \quad (16)$$

Where pCO_2 is the partial pressure of CO_2 in air[6], and the subscript $_{(aq)}$ denotes 'aqueous' i.e. dissolved in water (note the subscript $_{(sw)}$ is sometimes used to denote 'dissolved in seawater'). K_H can be expressed in a range of forms and with different units, the complexity of which is beyond the scope of this report; in Equation (16) the units of K_H are in moles per litre per atmosphere (or M atm^{-1}). In this case the value of this equilibrium constant under standard conditions is around 0.034 (Sander, 2023), indicating that 0.034 mol per litre of CO_2 in water would be in equilibrium with 1atm of CO_2; or that an air concentration of CO_2 of 420 µatm[7], would be in equilibrium with a water concentration of approximately 15 µmol l^{-1} (though the precise value is sensitive to factors such as temperature, salinity[8] and atmospheric pressure).

Rearranging Equation (16), the water phase CO_2 concentration that would be in equilibrium with a given gas phase CO_2 concentration is expressed as

$$[CO_{2(aq)}]/K_H = pCO_{2(g)} \quad (17)$$

If the value on right hand side of Equation (17) is larger than the value on the left (i.e. the air concentration is above the concentration that would be in equilibrium with the water) the system is not in equilibrium and there will be a spontaneous flow of CO_2 from air to water. Various natural processes tend to remove CO_2 from the surface ocean (biological activity, ocean circulation) and human activity is increasing the atmospheric concentration of CO_2, so the ocean is a natural CO_2 sink and is presently a sink for additional anthropogenic CO_2. Another way of saying this is that the ocean is *undersaturated* with respect to atmospheric CO_2. The basis of OAE and DOC as carbon removal activities is to reduce the concentration of CO_2 at the ocean surface and therefore to drive greater undersaturation (disequilibrium) and enhance net CO_2 uptake from the atmosphere.

The reverse situation where $[CO_{2(aq)}]/K_H > pCO_{2(g)}$ (supersaturation) would result in a flow of CO_2 from (sea)water to air. The rate of exchange (flux, F) between atmosphere and ocean of any gas is driven by the difference in the relative concentrations in air and water, and a kinetic term, k, known as the transfer velocity, which to first order is a function of wind speed.

$$F_{CO2\_atmosphere\text{-}ocean} = k * (pCO_{2\_atm} - [CO_{2(aq)}]/K_H) \quad (18)$$

Therefore, the greater the disequilibrium $(pCO_{2\_atm} - [CO_{2(aq)}]/K_H)$, the greater the ocean-atmosphere exchange flux for a given wind speed. The characteristic ocean-atmosphere

[6] 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' (hereon $pCO_{2(sw)}$), calculated as $[CO_{2(aq)}]/K_H$, is used to express the seawater concentration in atmospheric units.

[7] i.e. 420 parts per million CO_2 in air, roughly the current atmospheric CO_2 concentration.

[8] Salinity is the concentration of dissolved ions in seawater, or 'saltiness'.

equilibration time for CO_2 is much longer than for most gases due to the large concentration of bicarbonate in seawater, which can replenish the relatively small concentration of CO_2 as it is lost to the atmosphere.

CO_2 can dissolve in water (Equation (15)), and react with the water to form carbonic acid (H_2CO_3) and then dissociate into bicarbonate (HCO_3^-) and subsequently carbonate (CO_3^{2-}) ions according to Equation (19):

$$CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)} \rightleftharpoons H^+_{(aq)} + HCO_3^-{}_{(aq)} \rightleftharpoons 2H^+_{(aq)} + CO_3^{2-}{}_{(aq)} \quad (19)$$

Note that the concentration of undissociated carbonic acid is small[9] so Equation (19) can be simplified to:

$$CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H^+_{(aq)} + HCO_3^-{}_{(aq)} \rightleftharpoons 2H^+_{(aq)} + CO_3^{2-}{}_{(aq)} \quad (20)$$

Dissolved inorganic carbon (DIC) is the sum of the carbonate system species:

$$[DIC] = [CO_{2(aq)}] + [HCO_3^-{}_{(aq)}] + [CO_3^{2-}{}_{(aq)}] \quad (21)$$

The distribution - or *speciation* - of dissolved inorganic carbon (DIC) in seawater is strongly dependent on pH. As shown in the Bjerrum plot of the carbonate system (Figure 1.1), pH controls the relative proportions of these species: at typical seawater pH (~8.2), most DIC exists as bicarbonate.

1.2.1.5 Buffering capacity of seawater

Seawater has a high buffering capacity, meaning it can limit changes in pH when acids or bases are added. This capacity is primarily governed by the carbonate system, which can absorb or release hydrogen ions (H^+) to keep the pH relatively stable. For example, when H^+ is added to the system some carbonate will combine with H^+ to make bicarbonate, and a little bicarbonate will combine with H^+ to make CO_2 + H_2O (Equation (20)). Solid calcium carbonate provides a further reserve of alkalinity which can buffer extremes of low pH (relative to seawater's pH value of ~8.1).

Higher atmospheric CO_2 concentration means greater uptake of CO_2 by the ocean (Equation (18)) and therefore greater total DIC concentration. More CO_2 dissolving in the ocean means lower pH (ocean acidification, Equation (20) and therefore a shift in the carbonate system equilibria to increase the fraction of DIC present as CO_2. However, as pH decreases and bicarbonate shifts to CO_2, carbonate can then shift towards bicarbonate. Both of these changes mop up some of the additional H+, *buffering* against ocean acidification. This shift to the left in the carbonate equilibrium reactions (Equation (19)) in response to ocean acidification uses up some of the ocean's buffering capacity and its ability to absorb further CO_2.

At the same time, the carbonate system is the primary control on seawater pH itself. The relative concentrations of CO_2, HCO_3^-, and CO_3^{2-}, along with total alkalinity (defined below), determine the hydrogen ion concentration – and thus the pH – of the system. This bidirectional relationship between pH and DIC speciation means that external additions of alkalinity (such as through Ocean Alkalinity Enhancement) increase pH, which in turn shifts the carbonate equilibria to favour higher carbonate ion concentrations. The result is an increase in buffering

[9] There is very little free H_2CO_3 in seawater for 2 reasons. Firstly because it tends to dissociate into bicarbonate. Whilst a weak acid, at pH 8 it is mostly dissociated into H^+ and HCO_3^-. Furthermore the equilibrium constant for the hydration of CO_2 forming H_2CO_3 is very small, meaning that the equilibrium lies strongly in favour of the reactants.

capacity and enhanced potential for atmospheric CO_2 uptake, as the system re-equilibrates to maintain chemical balance.

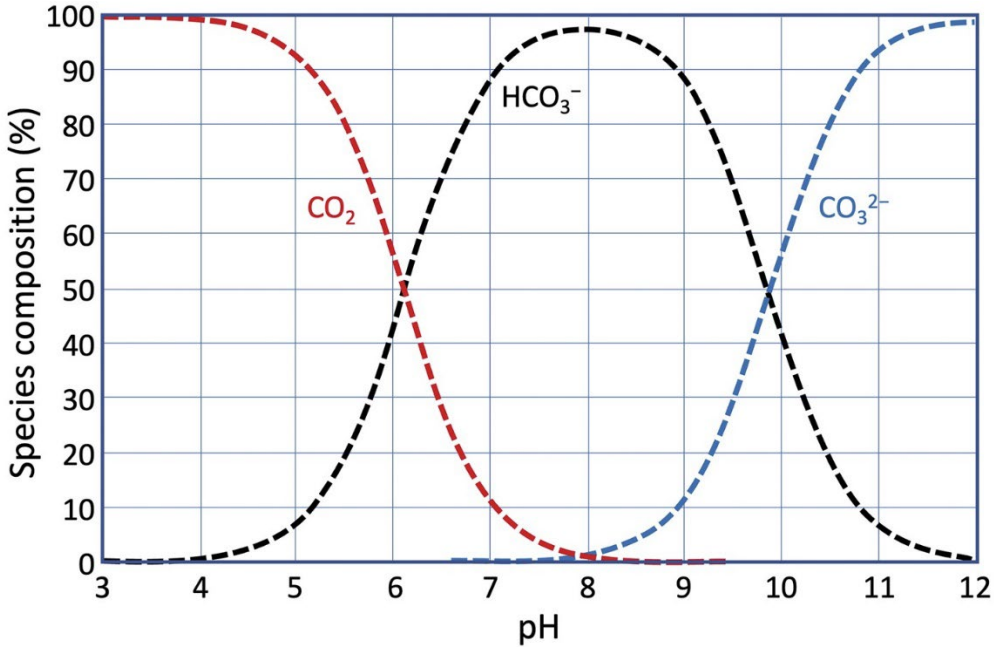


Figure 1.1 Bjerrum plot of the carbonate system in seawater.

Note: the 'CO_2' line in this plot should be understood as the sum of dissolved CO_2 and carbonic acid.
Source: Rohling (2023)

1.2.1.6 Alkalinity

Alkalinity can be generally considered as the capacity of an aqueous solution to 'mop up' (better: neutralize?), or buffer, acidity. Alkalinity is a concept that emerged from a recognition that natural waters (particularly seawater) required larger quantities of acid to be added to reduce the pH to a given value than would a simple system of water and strong base at the same starting pH (Rakestraw, 1949; Wolf-Gladrow et al., 2007). This empirical 'titration alkalinity' is a fundamental measurable property of (sea)water and is directly related to the formally-defined total alkalinity (TA) of a system.

Total alkalinity is defined as the excess of proton (H^+) acceptors (bases) over proton (H^+) donors (acids) (Dickson, 1992). Seawater is a complex mixture of proton acceptors and donors but the dominant control on alkalinity and pH is the carbonate system. Following Wolf-Gladrow et al. (2007) it is useful for illustrative purposes to consider a simple aqueous system of just dissolved NaCl and $NaHCO_3$, with the concentrations of Na^+ and DIC equal to that of typical seawater.

Here, the total alkalinity (excess of proton acceptors over donors) is expressed as:

$$TA = 2[CO_3^{2-}] + [HCO_3^-] + [OH^-] - [H^+] \quad (22)$$

Carbonate ions (CO_3^{2-}) count 'double' because they have the ability to accept two H^+ ions. At pH 8.2 and 25 °C, the concentrations of OH^- and H^+ are 10 µmol/kg and 6.3×10^{-9} µmol/kg respectively, with $[CO_3^{2-}]$ = 331 and $[HCO_3^-]$ = 1660 µmol/kg (Wolf-Gladrow et al., 2007). $[CO_2]$ is about 10 µmol/kg, (roughly in equilibrium with atmospheric CO_2) but is not included in the calculation of total alkalinity. In this simple system, bicarbonate is the dominant species in the carbonate system and also the dominant form of alkalinity in the system. The same is true in real seawater, however the total alkalinity equation then includes a wide range of other proton

acceptors and donors that separately and collectively play a minor role relative to the carbonate system.

1.2.1.7 Measuring the state of the carbonate system

In theory the carbonate system can be completely characterised by measuring any 2 of the core parameters DIC, TA, pH, $[CO_3^{2-}]$ and $pCO_{2(sw)}$ (i.e. the full state of the carbonate system including the other core parameters can be calculated from any measured 2). However, for real measurements uncertainty is reduced by measuring more than 2 parameters, and some combinations result in greater uncertainty in the unmeasured parameters than others (Schulz et al., 2023; Wolf-Gladrow et al., 2007). For example, measuring just $pCO_{2(sw)}$ and pH, which are both strongly dependent on H^+ concentration, and relatively or completely insensitive to TA, will lead to large uncertainties on TA, DIC and $[CO_3^{2-}]$.

1.2.1.8 Calcium carbonate minerals and saturation state, Ω

Calcium carbonate exists in multiple mineral phases, the most common of which are calcite and aragonite. All calcium carbonate minerals have the same ratio of calcium to carbonate ions (1:1) but they are arranged differently in their crystal structure. Some calcium carbonate minerals are hydrated, meaning that water molecules are fixed into their crystal structure. Figure 1.2 illustrates the differing structures of calcite and aragonite. As a result of their structural differences their solubility in water also differs ($K_{SP\_calcite} \neq K_{SP\_aragonite}$).

The saturation state of calcium carbonate (or any other ionic solid) tells us whether or not it will dissolve or precipitate spontaneously from seawater. In the case of calcium carbonate minerals:

$$\Omega = [Ca^{2+}_{(aq)}][CO_3^{2-}{}_{(aq)}] \,/\, K_{SP} \tag{23}$$

Where Ω >1, there is supersaturation, so precipitation will tend to occur. Where Ω <1 there is undersaturation and dissolution of solid phase will occur. Typically the ocean is supersaturated with respect to calcite and aragonite, but spontaneous precipitation is very slow, and precipitation is normally biologically mediated (Schulz et al., 2023; Zhong & Mucci, 1989).

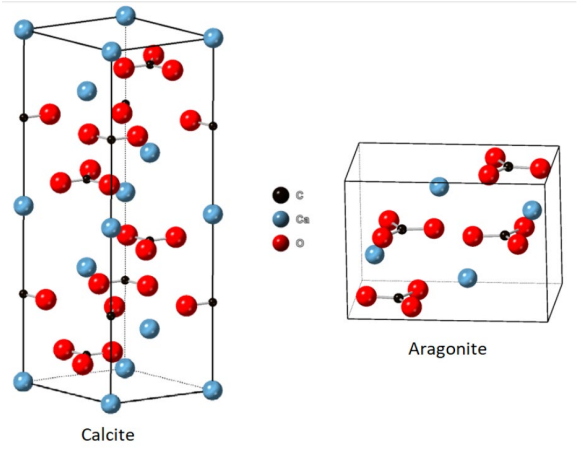


Figure 1.2 Atomic structure of calcite (rhombohedral) and aragonite (orthorhombic).

Source: Wikimedia Commons; CC BY-SA 4.0

1.2.1.9 Loss of alkalinity through $CaCO_{3(s)}$ formation

Just as dissolution of $CaCO_3$ adds alkalinity and increases the pH of a solution, precipitation of $CaCO_3$ out of solution removes alkalinity and will decrease the pH of the solution. Considering the net effect on the carbonate system:

$$Ca^{2+}{}_{(aq)} + 2HCO_3{}^{-}{}_{(aq)} \rightleftharpoons CaCO_{3(s)} + CO_{2(aq)} \quad (24)$$

Two moles of alkalinity (two moles of bicarbonate) are removed from solution for every mole of calcium carbonate precipitated. Just as addition of alkalinity reduces H^+ and therefore reduces $pCO_{2(sw)}$ and results in net additional uptake of CO_2 by the ocean, removal of alkalinity (e.g. through calcification) leads to an increase in H^+ and thus $pCO_{2(sw)}$ and leads to net loss of CO_2 to the atmosphere.

1.2.2 Ocean circulation and structure

The ocean's thermohaline circulation, or 'global ocean conveyor belt', is a vast, slow-moving set of ocean currents driven by density differences. Cold, salty, dense water sinks in high-latitude regions ('downwelling'), entering the deep ocean where it travels across basins before eventually returning to the surface through upwelling on a timescale of centuries or greater. Downwelling in cold regions which tend to absorb CO_2 is a strong sink for natural and anthropogenic CO_2 from the atmosphere to the deep ocean. Upwelling from the thermohaline circulation is slow and diffuse, but hotspots exist in the Southern Ocean and along continental margins, where winds drive deep mixing or divergence, bringing water up from depth.

Outside of the downwelling and upwelling zones, the ocean is vertically structured into layers, primarily by temperature and density. The surface mixed layer is well stirred by wind and waves and exchanges gases like CO_2 efficiently with the atmosphere. Beneath this lies the permanent thermocline, a zone of steep temperature (and therefore density) gradient that separates the surface from the deep ocean. Unlike the seasonal thermocline, which forms and dissipates annually with summer warming, the permanent thermocline is a stable, year-round barrier. Once water is mixed below this layer, it can be effectively isolated from the atmosphere for decades to centuries and so unable to affect atmospheric CO_2 at CDR-relevant timescales (Siegel et al., 2021).

Shelf seas are shallow coastal areas over continental margins that tend to remain well mixed due to tides and wind-driven mixing. In these regions, the water column is often entirely ventilated (mixed with the atmosphere with respect to gas exchange) year-round, and the permanent thermocline is either absent or significantly weakened. These dynamics make shelf seas potentially more effective sites for OAE: additions to surface waters in these zones are more likely to achieve higher efficiencies faster.

2 Carbon removals by Ocean Alkalinity Enhancement

Ocean alkalinity enhancement (OAE) relies on the modification of the acid-base equilibrium chemistry of seawater. The primary non-anthropogenic control of this equilibrium is the addition of mineral alkalinity via the hydrological cycle and its equilibration, over long timescales, with the acidic gas CO_2 in the atmosphere. By adding additional alkalinity to (or removing acidity from) seawater, the ocean's capacity to absorb and store atmospheric CO_2 as dissolved inorganic carbon (DIC) can be enhanced (Figure 1.1).

Natural weathering of silicate minerals on the land surface is responsible for an estimated uptake of 0.9 $GtCO_2$ yr^{-1} from the atmosphere in the present day (Hartmann et al., 2009). Mineral weathering is a major long-term natural control on atmospheric CO_2, providing a negative climate feedback; with warmer, wetter and more acidic conditions under elevated atmospheric CO_2 levels result in greater weathering rates (Renforth & Henderson, 2017; Walker et al., 1981). This natural feedback mechanism is slow. Various processes and timescales are involved, but natural carbonate and silicate mineral weathering feedbacks will ultimately transfer a large proportion of anthropogenic CO_2 emissions to the ocean on timescales of tens of thousands of years, although complete re-stabilisation could take millions (Lenton & Britton, 2006; Zachos et al., 2005).

Enhancement of the weathering rate of minerals or otherwise adding alkalinity to the surface ocean, could accelerate or augment this natural process. This could result in the uptake and durable storage of atmospheric CO_2 in climate-relevant quantities and on human-relevant timescales. Hence, OAE presents a potentially important CDR pathway for climate mitigation (Oschlies et al., 2023; Renforth & Henderson, 2017).

Even at climate-relevant scales of CO_2 removal the net global impact of OAE on ocean chemistry is likely to be small (Renforth & Henderson, 2017). However, negative feedbacks within the marine carbonate system may significantly reduce the efficiency of OAE (Renforth & Henderson, 2017; Schulz et al., 2023; Zhou et al., 2025). Secondary precipitation of calcium carbonate and impact of other mineral components added to the ocean are potentially significant and should be considered (Bach, 2024; Bach et al., 2019).

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). Although the seawater concentration of CO_2 in equilibrium with the atmosphere is only of the order of 10 µmol L^{-1}, total equilibrium concentration of DIC in the ocean is much higher, in excess of 2000 µmol L^{-1}. The total alkalinity of the ocean controls the equilibrium total DIC concentration for a given atmospheric CO_2 concentration, such that addition of alkalinity increases the DIC concentration, while the concentration of CO_2 remains the same (Figure 1.1).

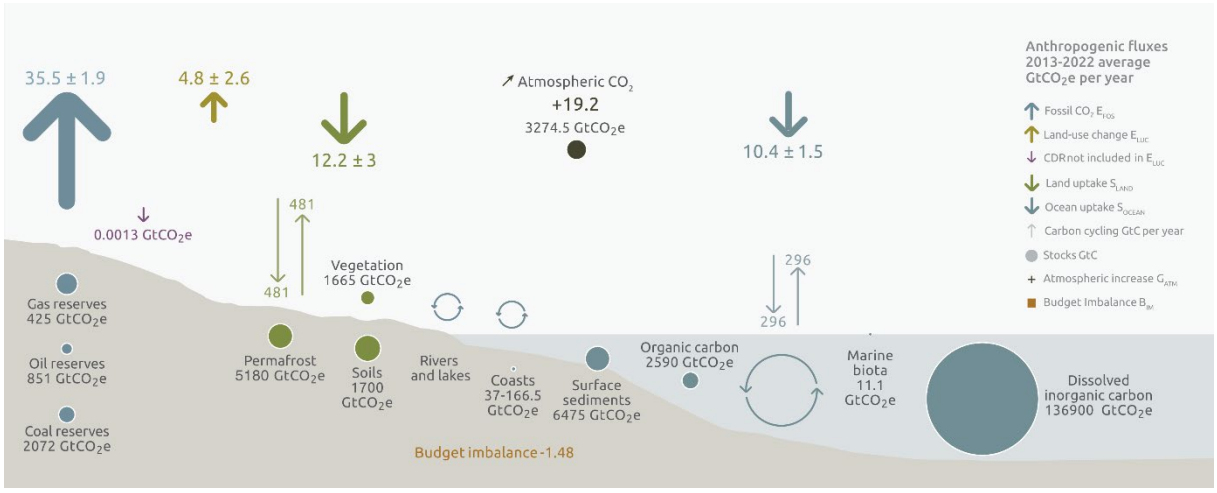
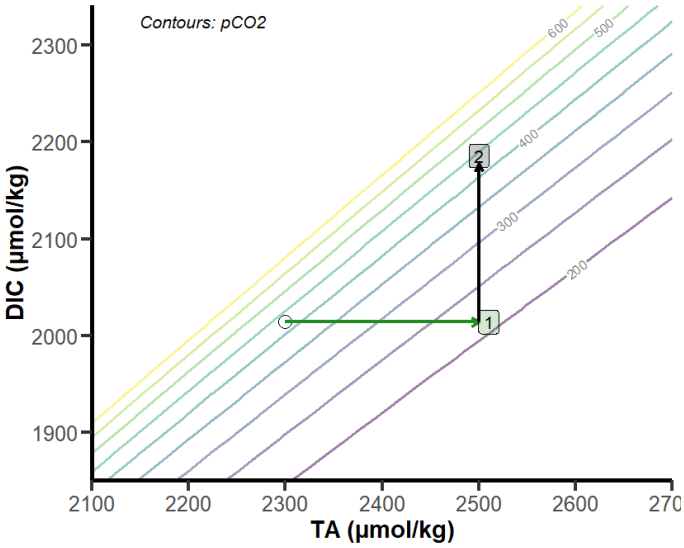


Figure 2.1 The present-day global carbon cycle.

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.



Step	Description	pH	pCO_2	CO_2	HCO_3^-	CO_3^{2-}	DIC
-	initial	8.02	425	12	1798	204	2014
1	add 200 µmol/kg of alkalinity	8.28	216	6	1663	345	2014
2	equilibrate	8.05	425	12	1930	236	2178

Figure 2.2 Deffeyes diagram (cf. Deffeyes, 1965) demonstrating the principle of Ocean Alkalinity Enhancement.

Starting from an initial state similar to the present-day surface ocean (pCO_2 = 425 ppm, TA = 2300 µM), initial DIC is calculated for the equilibrium state. Step 1: After addition of alkalinity, pH is increased and CO_2 concentration is decreased as the carbonate speciation changes in response to pH). Step 2: After equilibration with the atmosphere, DIC increases, leading to a decrease in pH as the new equilibrium state is reached, with most of the new DIC as bicarbonate ions. Calculated using SeaCarb package in R (Gattuso et al., 2024).

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 alkalinity addition. 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.

Enhanced alkalinity in the surface ocean can significantly increase its capacity to absorb and retain CO_2 by converting it into stable bicarbonate and carbonate ions. These dissolved forms of inorganic carbon are non-volatile and remain in solution for hundreds to thousands of years, even within the surface layer. As a result, ocean alkalinity enhancement (OAE) can deliver durable carbon storage without requiring the altered water to be transported to the deep ocean, since the chemical transformation itself stabilizes the carbon in long-lived forms.

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). In the present day the 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 could be affected equally by OAE activities that decrease a natural emission or that increase a natural sink.

2.1.2 Durability and reversals

The question of permanence, or durability, is a relatively simple one to first approximation, which applies equally to all CDR techniques which utilise ocean DIC as their terminal carbon store (i.e. OAE, ERW). Bicarbonate is stored durably on a timescale of many thousands of years unless or until:

i) some external source of acidity is added to the ocean or alkalinity is removed such that the pH of the ocean is shifted, or

ii) 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.

In the former case, external changes leading to a reduction in alkalinity will result in a shift in the carbonate system, increasing $pCO_{2(sw)}$ and potentially driving outgassing of CO_2 from the ocean – reversing the additional carbon storage delivered by the OAE activity. This raises a question of baselining, however. Any future reductions in ocean alkalinity would be independent of any OAE activity, and would occur whether or not the original OAE activity had taken place. We can consider scenarios with and without OAE activities: 1) OAE occurs in Year A, and at some point in the future ocean alkalinity is reduced, leading to CO_2 outgassing that returns the ocean to its original CO_2 Year A-storage level; 2) OAE does not occur in Year A, and at some point in the future ocean alkalinity is reduced, leading to CO_2 outgassing that leaves the ocean with a lower CO_2 storage level than in Year A.

It may therefore not be useful to consider such a case as a reversal – as the OAE can still have the net impact of reducing atmospheric CO_2 levels compared to a counterfactual without OAE. Therefore, the accounting for such apparent reversals in certifications may not be relevant, or at least requires a detailed consideration of the counterfactual situation. To put it differently, it might be more relevant to consider overall changes in ocean CO_2 storage than to focus on the specific fate of notional individual CO_2 molecules – and this implies a different monitoring approach than is possible for geological CO_2 storage, where the fate of specific molecules (or at least groups of molecules) can be known.

In the latter case where atmospheric CO_2 decreases below ocean $pCO_{2(sw)}$, due to some combination of emissions reductions, carbon uptake by natural processes in the Earth system, and human CDR action, the ocean will switch from being a sink to being a source of CO_2. Again, comparison with the counterfactual will be key to evaluating the magnitude of any reversal. At that point the OAE might be considered to have served its purpose, so that any reversals due to reduced atmospheric CO_2 levels might be considered the least problematic form of reversal, but still the relationship between atmospheric CO_2 levels and the effectiveness of OAE must be considered as certification methodologies are developed and evolve. This is addressed in more detail in Section 2.3.6.

2.2 Methods of achieving OAE

OAE interventions act to increase the alkalinity of seawater in contact with the atmosphere, either by addition of alkaline matter, or the addition of OH^- ions / removal of H^+ ions via electrochemistry. This reduces $pCO_{2(sw)}$ relative to atmospheric pCO_2, increasing the rate of uptake; and increases the capacity of the ocean to permanently store CO_2 as bicarbonate, as described above. Where methods for alkalinity production result in acidic byproducts (e.g. electrodialysis, Section 2.2.3.3) it is essential that these byproducts are safely stored or neutralised, as returning them to the ocean system would lead to reversal.

A range of techniques to achieve OAE have been proposed or piloted and the field continues to evolve. There is considerable commonality of method details, challenges and issues across the various techniques. There is also an overlap with enhanced rock weathering techniques. For example, addition of olivine mineral powders to the coastal zone has been referred to as “marine enhanced rock weathering” – mERW – in a recent paper (Geerts et al., 2025).

It’s notable that the list of techniques has changed considerably from the comprehensive review by Renforth & Henderson in 2017 to that conducted more recently by Eisaman et al., (2023), who, along with most more recent studies discount the application of finely ground alkaline minerals to the surface of the open ocean due to the high energy cost (and health risks) of grinding rock powders to the 1-10 µm range, or the transport costs of pre-dissolved minerals. Here we adopt the nomenclature from the review by Eisaman et al., (2023). The range of OAE methods can be delineated by i) the source of alkalinity; ii) the details of processing techniques, iii) the nature of the matter added to the ocean (i.e. Alkalinity Type) and iv) the location of the alkalinity addition (i.e. Dispersal) (Figure 2.3). Here we consider the key issues relevant to each method or set of methods.

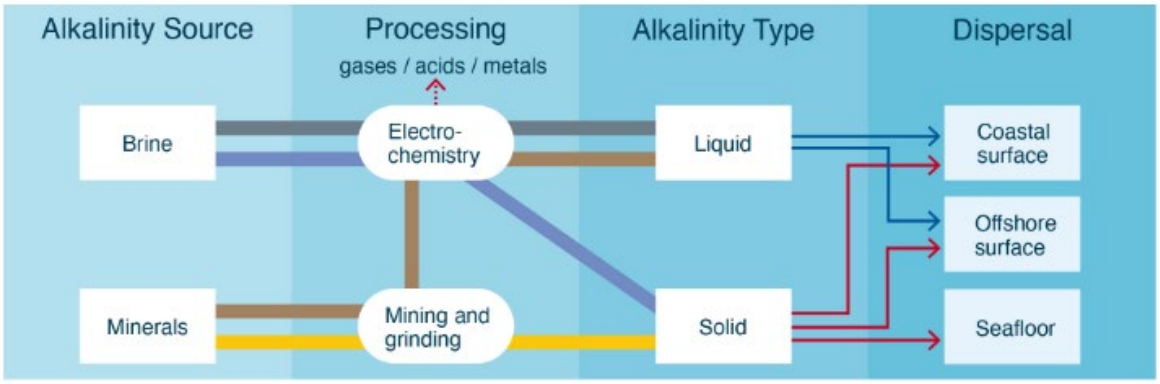


Figure 2.3 Summary of different types of OAE.

Each coloured pathway represents a unique approach, but within each pathway multiple potential variants exist based on specific technologies, mineral alkalinity sources, electrochemical methods and dispersal / delivery approaches. Reproduced from Eisaman et al., (2023)

2.2.2 Mineral alkalinity sources

Various minerals have been considered for OAE and have different potential methods and issues due to their differing chemical composition.

2.2.2.1 Carbonates: accelerated weathering of limestone (AWL)

In accelerated weathering of limestone (AWL), first proposed by Rau et al. (2007), carbonate rich rocks such as limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) are dissolved in a water stream that has artificially elevated $pCO_{2(sw)}$, producing bicarbonate ions that can then be discharged to seawater.

$$CaCO_{3(s)} + CO_{2(aq)} + H_2O \rightleftharpoons Ca^{2+}{}_{(aq)} + 2HCO_3^-{}_{(aq)} \quad (25)$$

The stoichiometry (reaction ratio) of this reaction is dependent on water temperature, atmospheric pCO_2 and other factors but under typical conditions, 3.5 tonnes of $CaCO_3$ is required to sequester net 1 tonne of CO_2 (Eisaman et al., 2023), notwithstanding secondary precipitation or other negative feedbacks (Section 2.3.4 - 2.3.5).

Given that a concentrated CO_2 stream is required, this technique was originally envisaged for use as an emissions reduction method at fossil fuel power plants (Eisaman et al., 2023, and references therein). However, where the CO_2 is atmospheric or biogenic or possibly extracted from upwelled seawater (Eisaman et al., 2023), this method would be relevant to CDR.

AWL adds both Ca^{2+} and CO_3^{2-} ions into solution, so it has a stronger effect on the saturation state of calcium carbonate than non-calcium alkalinity (e.g. magnesium silicate, sodium hydroxide). Therefore, compared to other OAE methods the risk of secondary precipitation (Section 2.3.4) is somewhat greater, and the amount of alkalinity that can be added 'at once' to a parcel of water without undue risk of secondary precipitation, is lower (Eisaman et al., 2023).

2.2.2.2 Silicate minerals: 'coastal enhanced weathering' (CEW)

Addition of silicate minerals to the ocean has been suggested as a form of enhanced rock weathering, called coastal enhanced weathering (CEW). The characteristic chemical equations for weathering are equivalent for silicate mineral weathering on land or in the ocean

(cf. review paper on carbon removals through ERW), although as ocean pH and alkalinity tend to be higher than in terrestrial waters (rain, soil water, streams and rivers), dissolution of the applied material is less thermodynamically favourable. Either way, the resulting bicarbonate ions end up eventually being stored durably in the ocean.

Originally conceived as a technique that could be applied anywhere in the surface ocean, more recent studies have focussed on near-shore application. In the open ocean it is essential for mineral powders to dissolve prior to sinking out of the surface layer of the ocean, otherwise the added alkalinity would be out of contact with the atmosphere and not contribute to CDR on useful timescales. The required size range for such rapid dissolution has been estimated to be <1 μm (Eisaman et al., 2023 and references therein). Grinding to this size is very energy intensive and the resulting powders potentially pose a respiratory risk to human operators. Shipping of solutions of pre-dissolved alkalinity may bypass this problem but the shipping emissions would be significant.

As an alternative to the open ocean, the coastal zone provides a highly dynamic environment relatively isolated from the deep ocean, where wave action and tides may accelerate the breakdown and dissolution of larger particles whilst maintaining contact with the atmosphere and reducing material transport costs vs delivery to the open ocean. Addition to the water column or the sediments of coastal and shelf environments have been proposed. In the surf zone, wave energy is sufficiently strong that millimetre-sized particles may break down and dissolve on relevant timescales, which makes this approach attractive. However, MRV in such environments is particularly challenging due to transport of minerals and their dissolution products away from the deployment location (though to some extent this is a common problem for all OAE). Application in shelf sediments (sandy and muddy environments) at depths below the wave base requires at least an order of magnitude smaller grain size (Eisaman et al., 2023). Here dissolution would rely on sediment biogeochemistry – where respiration leads to high local CO_2 concentrations and relatively low pH, favouring dissolution.

Figure 2.4 by Geerts et al. (2025) summarises the various approaches to silicate mineral application. Panel (a) shows a schematic overview of CEW: (1) particles of a fast-weathering silicate mineral (e.g. olivine) are spread in the coastal zone. (2) The silicate minerals are deposited onto or mixed into the sediment. (3) The silicate minerals dissolve, releasing alkalinity (here depicted as OH-) to the pore water. (4) Alkalinity is either transported from the sediment to the overlying water, leading to ocean alkalinity enhancement, or trapped in the sediment by secondary reactions. (5) the seawater carbonate system re-equilibrates with the atmosphere, leading to uptake of CO_2.

Panel (b) shows bedload application scenario in which silicate minerals are deposited on top of the sediment allowing bedload transport to naturally grind the grains to smaller sizes.

Panel (c) shows permeable sediment application where high through-flow of water flush the pore water and ensure the release of alkalinity to the overlying water.

Panel (d) shows cohesive (muddy) sediment application where benthic fauna irrigate the sediment to bring oxygen, lower the pH (via oxidative respiration of organic matter), increase the dissolution rate and release the alkalinity to overlying waters.

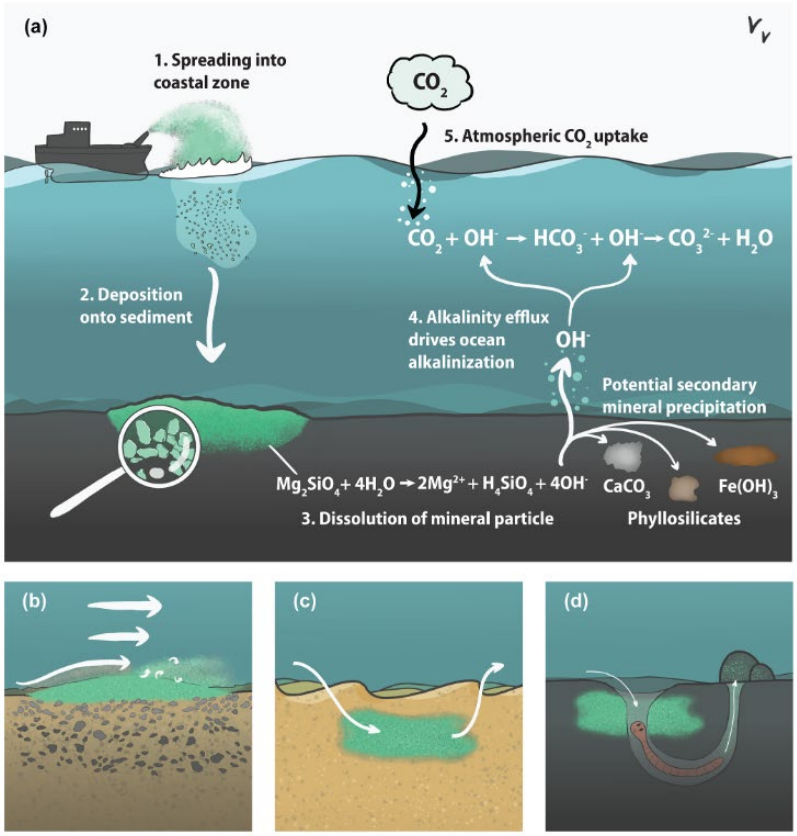


Figure 2.4 Overview of coastal enhanced weathering (also called marine enhanced rock weathering) techniques and processes.

Reproduced from Geerts et al. (2025) summarizing the principles and application scenarios.

2.2.2.3 Hydroxides – ocean liming

Ocean liming is the addition of calcium or magnesium oxides and hydroxides (either produced from carbonates through calcination, or mined from naturally occurring but rare mineral sources such as $Mg(OH)_2$) to surface seawater. The most likely large-scale application is the production of limes from calcium carbonate by heating, releasing CO_2 (calcination) to produce calcium oxide (quicklime). Quicklime is highly caustic and difficult to handle so most likely the additional step of hydrating to calcium hydroxide (slaked lime) would also be undertaken (noting the additional mass per unit of alkalinity affecting transport costs/emissions).

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)} \quad (26)$$

$$CaO_{(s)} + H_2O \rightarrow Ca(OH)_{2(s)}$$

$$Ca(OH)_{2(s)} \rightarrow Ca_2^+ + 2OH^-_{(aq)}$$

The efficiency of this method relies on the capture and durable storage of the CO_2 released during calcination. In the optimal full lifecycle case, over 1 tonne of atmospheric CO_2 could be stored in the ocean per 1.8 tonnes of $CaCO_3$ mined (Foteinis et al., 2022).

2.2.2.4 Hydrated carbonate minerals

Mineral forms of calcium and magnesium carbonate which include water in their crystal structure ('hydrated' carbonates) are undersaturated in seawater and therefore should spontaneously dissolve and add alkalinity (Eisaman et al., 2023). There are various minerals

identified, such as ikaite, $CaCO_3.6H_2O$ and hydromagnesite, $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$, many of which are naturally occurring, although in insufficiently large quantity to achieve climate-relevant scales of CO_2 removals. However, an industrial production process for ikaite from limestone has been proposed (Renforth et al., 2022), which would use considerably less energy than calcination (and not produce CO_2), which makes this approach potentially attractive, although it is very early stage (TRL 1 according to Eisaman et al., 2023). Ikaite is more soluble in colder waters so dispersal would be limited to higher latitudes.

2.2.3 Electrochemical alkalinity sources

Electrochemistry allows the manipulation of the acid-base chemistry of seawater through energy input, which provides an alternative, or complementary, method to alkaline mineral addition. Generally, electrochemical OAE removes hydrochloric acid (or in some cases H_2 and Cl_2 molecules) from a concentrated brine stream and the resulting OH^--rich brine is discharged to seawater to add alkalinity (Eisaman et al., 2023). A benefit of this technique compared to solid mineral addition is that a known amount of alkalinity is added to seawater, and so MRV need only focus on the equilibration of the alkalinity enhanced water with the atmosphere, secondary feedbacks (Section 2.3) and environmental impacts, and need not worry about (in)complete dissolution of mineral feedstocks. A full review of electrochemical methods was conducted by Eisaman (2024). For OAE, two main approaches with different energy costs and byproducts are relevant and these are outlined below.

Electrochemical alkalinity addition results in point sources of alkalinity to the surface ocean, unlike distribution of minerals (solid or dissolved) which are spread over more diffuse (larger?) areas. Therefore the impacts of high pH and alkalinity (Section 4.1.2) are likely to be more intense at electrochemical OAE release points. This requires either a) dilution prior to release and/or b) pre-equilibration with atmospheric CO_2 prior to release. Eisaman et al. (2023) suggests that b) is effectively a direct air capture technique, in which the stored CO_2 is directly quantifiable by measurement of the carbonate system in the outflow from the facility, and provides a "*tuneable knob to perform 'partial direct air capture' to the degree required to reach the target* [release] *pH… and the rest of the CO_2 removal can occur via OAE once it is returned to the ocean.*" The disadvantages of such pre-equilibration are the energy costs and volume limits to the achievable OAE.

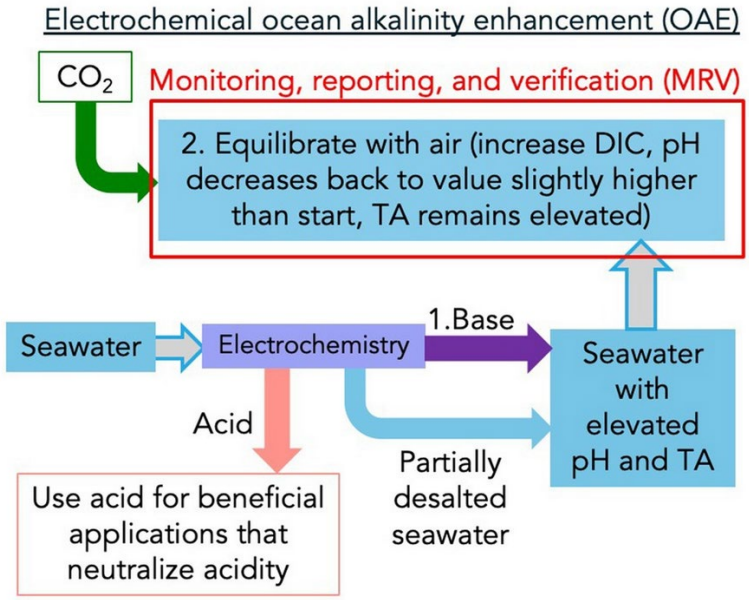


Figure 2.5 Summary of electrochemical OAE.

Figure reproduced from Eisaman (2024)

2.2.3.2 Electrolysis

Electrolysis of brines typically results in the oxidation of chloride ions to chlorine gas at the anode and reduction of water to H_2 gas and OH^- ions at the cathode, although other 'exotic' electrochemical reactions can also be employed (e.g. Iyapazham Vaigunda Suba et al., 2023; La Plante et al., 2023).

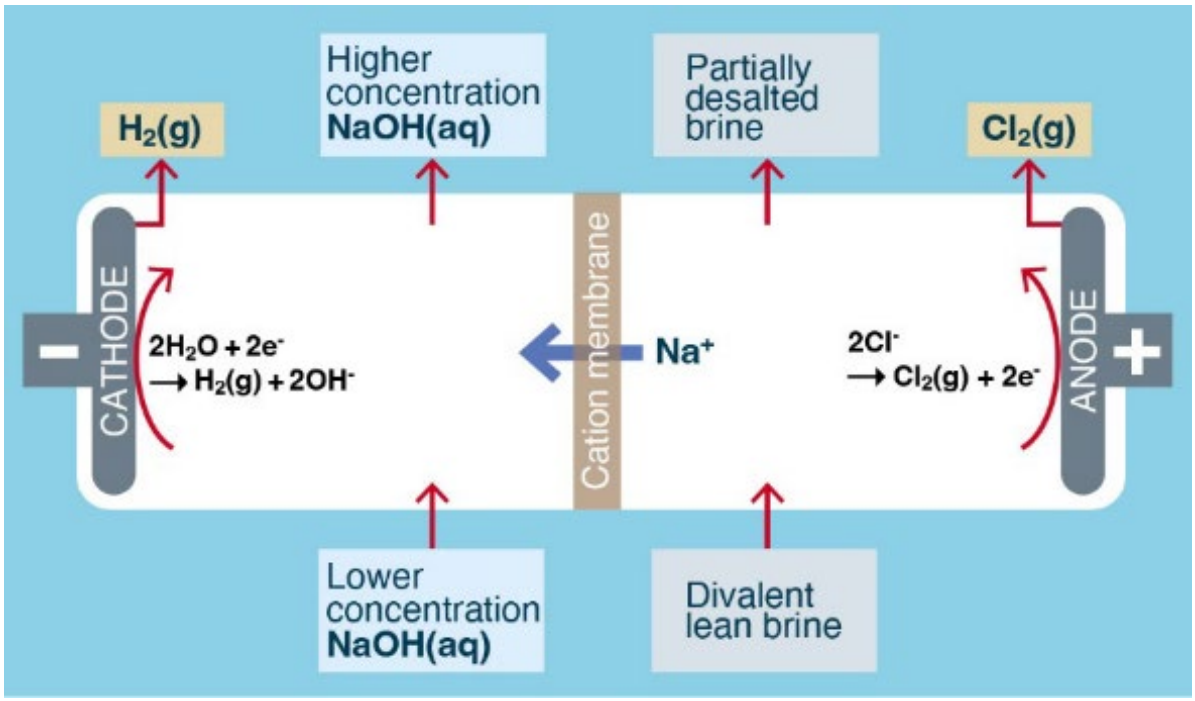


Figure 2.6 Typical process flow diagram for the production of NaOH from brine (with $H_2(g)$ and $Cl_2(g)$ as byproducts) using electrolysis via the chloralkali process.

Figure reproduced from Eisaman et al., (2023).

This process is used extensively in the chemical industry to produce NaOH and Cl_2. The NaOH can be discharged to seawater to increase alkalinity. Although produced in fixed ratios, demand for the two products is not coupled and there have been periods where demand for chlorine exceeded hydroxide [a good reference needed]. Currently demand for NaOH is greater than chlorine, and this is likely to remain the case for globally for the foreseeable future[10]. Additional chlorine production from this CDR method could potentially distort markets and exceed potential demand, and the energy cost of processing and disposal of the chlorine would have to be addressed within the CDR costs and lifecycle assessments. In a future market, if demand for chlorine exceeded that for sodium hydroxide, this excess NaOH could be disposed of by OAE as an additional benefit.

2.2.3.3 Electrodialysis

Electrodialysis is not capable of making such concentrated streams of NaOH, however the energy input per mole of alkalinity produced is lower as the method enhances the reversible dissociation of water into H^+ and OH^-, rather than fully splitting water molecules (i.e. the irreversible breaking of O-H bonds) (Eisaman et al., 2023). As with electrolysis, NaOH is produced and can be discharged to increase ocean alkalinity, but the byproduct of this reaction is hydrochloric acid rather than H_2 and Cl_2 (Eisaman, 2024). The fate of this produced acid is essential to delivering durable CO_2 storage, as its release into the natural environment would drive permanent CO_2 transfer from hydrosphere to atmosphere, just as alkalinity addition drives durable storage in the ocean (addition of acidity leads to a reduction in alkalinity – see the total alkalinity equation, Equation (22)). Some OAE schemes plan to react the acidity with alkaline minerals on land to neutralise the acidity, effectively 'shunting' the mineral alkalinity to NaOH for release to the ocean, with controlled and quantifiable mineral dissolution by acidity on land. Where the acidity leaves the electrochemical OAE facility, its fate must be certified

[10] Cf. https://www.gep.com/blog/mind/why-caustic-soda-can-be-the-next-major-shortage-in-the-chemical-industry

and validated or its release into the natural environment would need to be brought under MRV and reversals quantified.

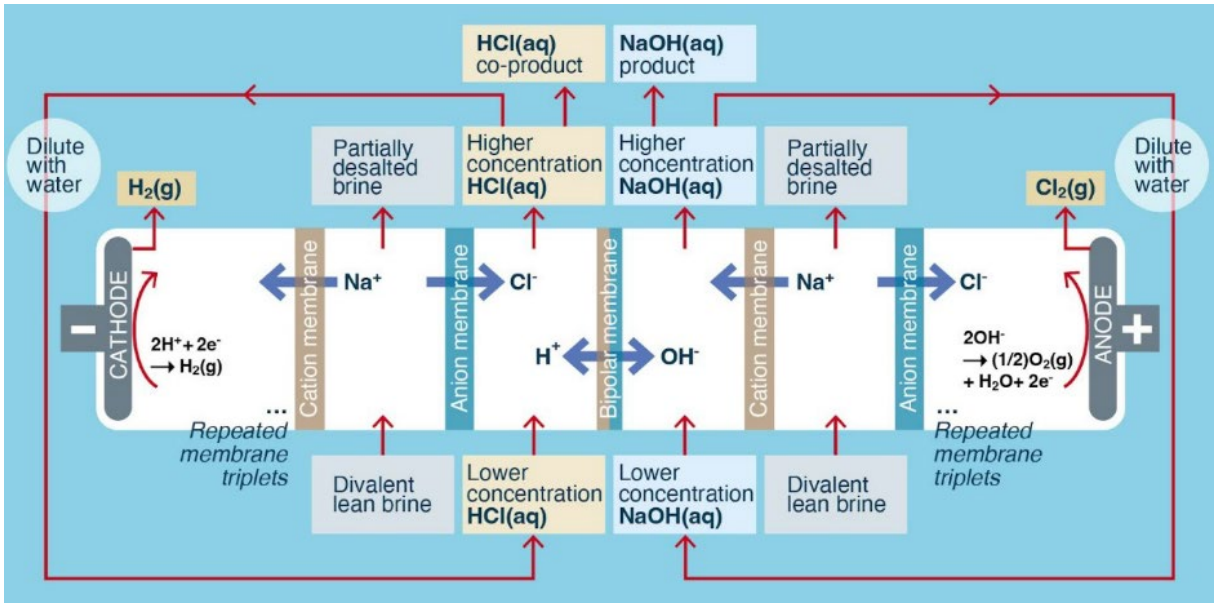


Figure 2.7 Typical process flow diagram for Electrodialysis of brine to produce NaOH and (as a by-product) HCl.

Note that only trace amounts of $H_2(g)$ and $Cl_2(g)$ are produced in this process when operating efficiently (Eisaman et al., 2023). Figure reproduced from Eisaman et al. (2023).

2.3 Efficiency of CDR by OAE

In order to evaluate the effectiveness of an OAE activity it is essential to be able to constrain the quantity of alkalinity added and the impact this added alkalinity will have on CO_2 uptake at the sea surface. Assuming complete equilibration with the atmosphere and no reversals this can be quantified from first principles. In practice, complete equilibration is unlikely on climate-relevant timescales and various negative feedbacks will act to reduce efficiency.

2.3.1 Quantifying alkalinity addition

Where mineral powders are added directly to the ocean, the rate and completeness of dissolution impacts the rate and absolute magnitude of the CO_2 sequestration. In particular, where powders are added to deep waters locations (i.e. offshore), the alkalinity added by any mineral powder that dissolves after sinking below the permanent thermocline (Section 1.2.2) will be isolated from the atmosphere for decades to millennia, depending on location (Siegel et al., 2021). In shallower waters, where particles remain in the surface ocean / sediments, there is a longer time for dissolution, but any fraction of alkalinity that remains undissolved will be ineffective. Given the complexities of carbonate chemistry in coastal waters (river inputs, sediment pore water chemistry, high biological productivity, human impacts) and the complexities in the kinetics of heterogenous mineral particle dissolution, this is difficult to predict, although laboratory-based studies can offer some constraint on likely dissolution dynamics (Renforth et al., 2015), and modelling of particle dissolution kinetics is identified as an important tool for quantification (Ho et al., 2023), although improvement in such models is needed before they will be fit for purpose (Fennel et al., 2023).

The application of alkalinity in the form of pre-dissolved minerals or through electrochemical techniques is directly quantifiable and avoids the uncertainties associated with mineral

dissolution. The following sections consider the CDR efficiency of a known amount of added alkalinity.

2.3.2 Capture efficiency of OAE, η

The (chemical) efficiency of OAE is defined as the change in DIC (i.e. the amount of CO_2 taken up from the atmosphere) per change in total alkalinity:

$$\eta = \Delta DIC / \Delta TA \quad (27)$$

The maximum theoretical efficiency, η_T can be determined from our knowledge of the seawater carbonate system (Section).Various different, broadly equivalent expressions have been presented to approximate this (e.g. Renforth & Henderson, 2017; Schwinger et al., 2024), which we will not explore in this report. η_T is variable with temperature and the pre-addition concentration of DIC and total alkalinity, and to a small extent, salinity (Renforth & Henderson, 2017; Schulz et al., 2023). In the present-day ocean η_T varies from 0.77 to 0.96 (Schulz et al., 2023) with higher values in colder, polar waters. Its value is not 1 (i.e. one mole of alkalinity added does not result in one mole of CO_2 uptake) because the buffering capacity of the carbonate system reacts to counter the alkalinity addition. The greater the baseline alkalinity, the lower the maximum theoretical efficiency, although the naturally-occurring total alkalinity in the ocean is so high that even climate-altering scales of OAE would be unlikely to significantly affect η_T.

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 (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).

2.3.3 Efficiency limits due to incomplete equilibration with the atmosphere

In practice, complete equilibration between added alkalinity and atmospheric CO_2 is unlikely to be achieved. Ocean waters are subject to vertical mixing and horizontal transport, which can remove alkalinity-enriched surface water from contact with the atmosphere before full equilibration occurs. As a result, the associated CO_2 uptake may be delayed by years to decades and may occur far from the original site of alkalinity addition. In cases where alkalinity is transported to the deep ocean (i.e. below the permanent thermocline) prior to equilibration, the corresponding CO_2 removal could be postponed by centuries or longer.

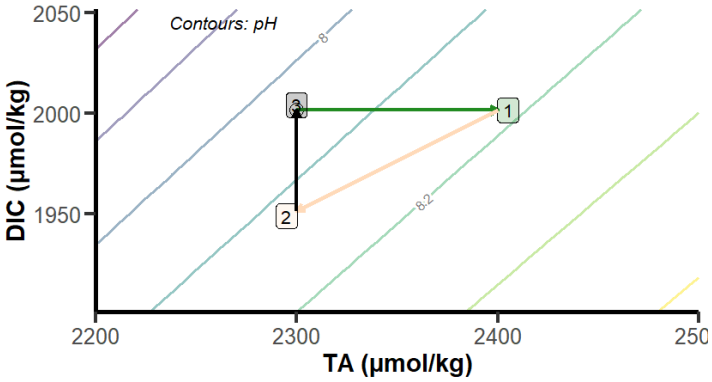
The rate of atmospheric CO_2 uptake following alkalinity addition is initially high, driven by a steep concentration gradient between the atmosphere and the surface ocean, but will slow down as the system re-equilibrates and the additional alkalinity is diluted by vertical and horizontal mixing. This means that while alkalinity-enhanced water may take many months or even years of contact with the atmosphere to approach complete equilibration, the majority of CO_2 uptake commonly occurs in the early stages, within weeks to months, thus this initial phase is critical.

Efficiency of OAE is thus governed by an equilibration factor, representing the proportion of added alkalinity that ultimately results in atmospheric CO_2 removal within a relevant timeframe. This factor is influenced by the season and location of deployment (Ho et al., 2023; Wang et al., 2023; Zhou et al., 2025) and can vary widely depending on local ocean dynamics. Because CO_2 uptake resulting from alkalinity addition is distributed over broad temporal and spatial

scales, direct observation is impractical; instead, estimates of equilibration efficiency must rely on ocean biogeochemical modelling (Fennel et al., 2023; Ho et al., 2023). This modelling plays a critical role in the MRV of OAE (see Section 2.4).

2.3.4 Efficiency losses due to secondary precipitation of carbonates

Although seawater is typically supersaturated with respect to $CaCO_3$, spontaneous abiotic precipitation is rare under natural conditions because it generally requires a nucleation site or "seed" crystal to initiate the process. However, when OAE raises the saturation state (Ω) far beyond typical background levels – especially in poorly mixed or high-alkalinity conditions – spontaneous or even "runaway" precipitation can occur. In some cases more alkalinity has been observed to be lost through carbonate precipitation than was initially added, reversing the intended CO_2 removal benefit (Moras et al., 2022). Runaway precipitation notwithstanding, it is interesting to note that if the addition of non-carbonate alkalinity results in the same amount of alkalinity loss through precipitation, there is still net carbon storage as solid $CaCO_3$ and thus a potential future alkalinity source if the ocean acidified (Figure 2.8).



Step	Description	pH	pCO_2	CO_2	HCO_3^-	CO_3^{2-}	DIC
-	initial	8.04	400	11	1778	212	2002
1	add 100 µmol/kg of alkalinity	8.18	280	8	1712	282	2002
2	precipitate 50 µmol/kg of calcium carbonate	8.12	317	9	1698	245	1952
3	equilibrate	8.04	400	11	1778	212	2002

Figure 2.8 Deffeyes diagram demonstrating the impact of a 1:1 ratio of non-carbonate alkalinity addition and secondary precipitation of calcium carbonate.

Step 1: Alkalinity addition (e.g. OH^-) increases alkalinity without impacting DIC. Step 2: Precipitation of calcium carbonate removes the added alkalinity but also DIC. Step 3: CO_2 is still taken up from the atmosphere (durable storage) to return the system to its initial state.

To mitigate the risk of secondary precipitation, it is essential to monitor and control key geochemical thresholds at the point of alkalinity addition – particularly pH and the saturation state of aragonite (Ω_{arag}[11]). Moras et al. (2022) propose maximum threshold values for safe deployment, beyond which the risk of unwanted precipitation rises sharply. While these general limits (pH < 8.8 or Ω_{arag} < 5) may be used as a guideline, in practice these limits are likely to vary depending on local seawater chemistry, temperature, and the specific alkalinity source; and the amount of a particular alkalinity source that can be added before reaching these limits

[11] Although aragonite is more soluble in seawater than calcite, it has been shown experimentally that it has a lower spontaneous precipitation threshold than calcite, so Ω_{arag} is the key saturation threshold to consider (Moras et al., 2022; Zhong & Mucci, 1989).

also depends on the local conditions. Therefore, site- and material-specific consideration will be important.

The effect of alkalinity addition on saturation state is not uniform across different materials. The saturation state of calcium carbonate depends on both the carbonate ion (CO_3^{2-}) and calcium ion (Ca^{2+}) concentrations, as well as on pH (Section 1.2.1.3). For example, adding 1 mol of alkalinity via magnesium hydroxide, $Mg(OH)_2$, increases pH alone, and thus has a more moderate effect on Ω than calcium hydroxide, $CaCO_3$, which adds both alkalinity, Ca^{2+} and CO_3^{2-}, leading to a greater rise in saturation state[12]. Figure This is particularly relevant to methods which pre-dissolve calcium carbonate to add alkalinity to the ocean i.e. AWL (Section 2.2.2.1).

2.3.5 Other carbon cycle feedbacks

OAE could potentially have feedbacks and impacts on the natural carbon cycle that could affect its efficiency (as well as other non-climate impacts on marine ecosystems discussed in Section 4.3).

2.3.5.1 Suppression of natural alkalinity fluxes from natural weathering in marine sediments

Suppression of natural sedimentary alkalinity fluxes could further reduce the effectiveness of OAE. Under current conditions, dissolution of carbonate and silicate minerals in marine sediments provide a constant natural source of alkalinity to the ocean. OAE will tend to decrease this natural alkalinity flux by increasing the saturation state of these minerals in the seawater and slowing their dissolution; thereby lowering the background flux of natural alkalinity. This could be viewed as reducing the efficiency of the OAE activity or as a reduction from the baseline rate of carbon removal. Laboratory experiments on beach sand by Bach (2024) demonstrated a strong reduction in natural alkalinity flux from sands after alkalinity addition.

2.3.5.2 Response of biogenic calcification

Changes in biological calcification (precipitation of solid $CaCO_3$) rates may influence the long-term efficiency of OAE. Marine calcifying organisms such as coccolithophores, corals, and molluscs produce calcium carbonate shells, a process that consumes alkalinity. By raising ocean pH and carbonate saturation states, OAE may stimulate increased calcification in some organisms (Bach et al., 2019; Gore et al., 2019). This enhanced biological precipitation could act as a counteracting sink for added alkalinity, reducing the net CO_2 removal benefit (although making coral ecosystems more resistant to ocean acidification could be seen as an environmental co-benefit). Conversely, where OAE leads to addition of iron or other micronutrients, it has been suggested that non-calcifying phytoplankton could out-compete coccolithophores, leading to a decrease in calcification by microorganisms (Bach et al., 2019). The direction and magnitude of this feedback depend on species responses and ecosystem context as well as the nature of the alkaline material added.

2.3.5.3 Response of the biological carbon pump

The biological carbon pump is a major natural mechanism transporting carbon from the surface to the deep ocean and thus maintaining natural CO_2 uptake at the ocean surface. Perturbations

[12] The saturation state of magnesium carbonate ($MgCO_3$) is much less than 1 in the surface ocean (it's much more soluble than $CaCO_3$) so secondary precipitation of magnesium carbonates is not a concern.

to the efficiency of the biological carbon pump may arise from large-scale OAE. Several mechanisms could contribute to this.

- Changes in plankton community structure due to pH shifts or nutrient availability could potentially alter the amount and type of organic matter exported (Bach et al., 2019; Guo et al., 2024). Different alkalinity sources may have different impacts (Guo et al., 2025).
- Increased calcification, which adds ballasting material to sinking organic particles, may enhance carbon export to the deep ocean, albeit at the cost of some alkalinity
- Impacts from elevated metal ion concentrations – such as Mg^{2+} or trace metals released during mineral dissolution – could affect microbial activity or toxicity thresholds (Bach et al., 2019).

These changes could either amplify or dampen the effectiveness of OAE, depending on ecological context and deployment scale, and are critical to understand in the broader assessment of climate intervention impacts.

2.3.6 Impact of future atmospheric CO_2 trajectory

The eventual integrated efficiency of OAE over time depends on the future CO_2 trajectory. Successful future reduction of CO_2 in the atmosphere will reduce the partial pressure of CO_2 in the atmosphere and therefore result in some of the CO_2 stored in the (surface) ocean being released back into the atmosphere (Schwinger et al., 2024). If that reduces the efficiency of previously undertaken OAE activities, then this would represent a partial reversal of the delivered carbon removal. At that point, further OAE could be undertaken to 'maintain' the efficiency of earlier OAE activities or some form of liability mechanism could be activated; but this would be a 'success problem', and it may be considered that the possibility of some future release of stored DIC in the context of stabilised atmospheric CO_2 concentrations would be acceptable. Nevertheless, quantifying and certifying permanent carbon removals through OAE requires that some assumption is made on future atmospheric CO_2 levels, either explicitly or implicitly.

This highlights the importance of considering both timescale and scope when evaluating the efficiency of different OAE deployments. A publicly available tool developed by Carbon Plan (Figure 2.9) (Zhou et al., 2025), based on first-order carbonate chemistry and ocean circulation, provides a 15-year efficiency assessment of OAE actions using an Earth-system model. The model does not account for biogeochemical feedbacks (Section 2.3.5) or secondary precipitation (Section 2.3.4).

Results from this tool highlight that both timing (season) and location of deployment significantly influence efficiency. Generally, summer is the best time for deployment (when wind speeds and vertical mixing are at a minimum), although this is not universal to all locations. Cold downwelling (deep water formation) regions in the North Atlantic are particularly inefficient, whereas shelf seas and regions with buoyant, upwelled water show greater efficiency. This appears at odds with the theoretical maximum efficiency being in colder waters (Section 2.3.2), but is related to the time during which the water remains in contact with the atmosphere and able to re-equilibrate added alkalinity before sinking to the deep ocean.

This tool offers valuable guidance and highlights the necessity for comprehensive spatio-temporal assessments to achieve accurate MRV. However, it relies on a single model run under specific conditions. Additional model development covering global, regional, and OAE method-specific variations is needed along with multi-model intercomparison to enhance confidence in model-based MRV for OAE and other marine CDR methods (Fennel et al., 2023; Zhou et al., 2025).

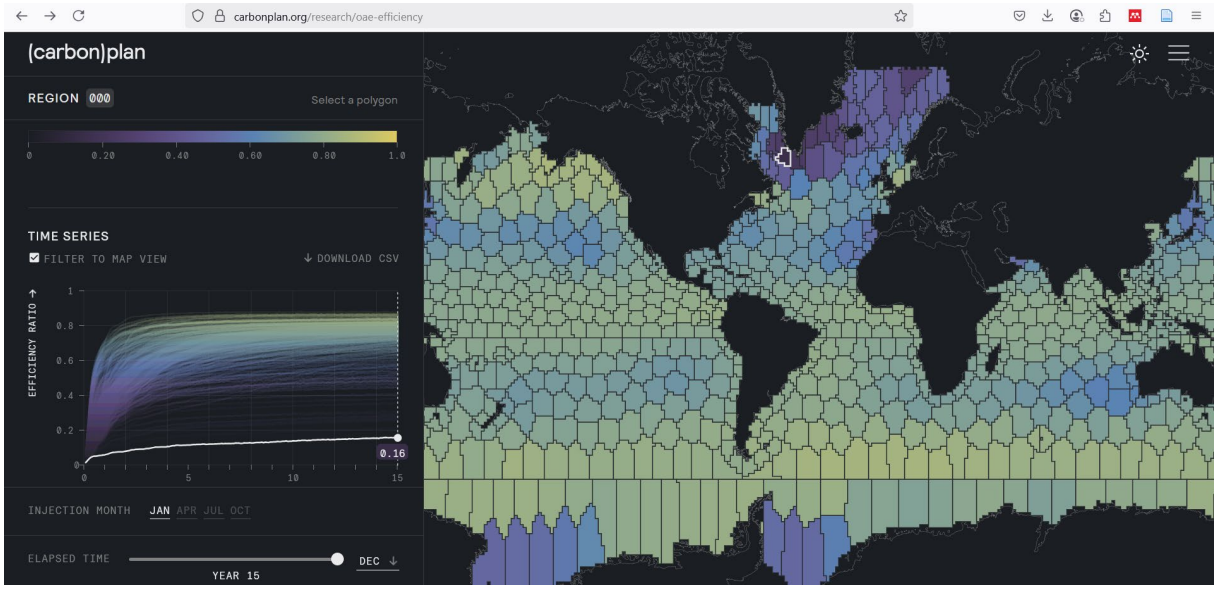


Figure 2.9 Screenshot of the OAE efficiency tool from Carbon Plan, after Zhou et al., (2025)

Accessible at https://carbonplan.org/research/oae-efficiency (last accessed May 2025).

2.3.7 Associated emissions

As with any CDR, full assessment of lifecycle emissions is necessary to evaluate the net carbon removal benefit. LCA emissions associated with OAE arise from mining, grinding and transport for mineral OAE and energy input to and dealing with the byproducts from electrochemical OAE. Such associated energy requirements and emissions have been evaluated as being comparable to those for land-based CDR (BECCS and DAC) by Renforth and Henderson (2017).

2.4 Monitoring OAE outcomes

Given that efficiency and impacts of OAE will be specific to location and OAE method, a hierarchy of observations and modelling can be envisaged, including detailed process studies at various scales to establish location-specific effects and efficiencies and calibrate models with routine ongoing local measurements to ensure the non-exceedance of established threshold values. As models for predicting OAE efficiency and impact improve, there may be less requirement for reliance on site-specific process studies in future.

2.4.1 Observations

As OAE activities, MRV and certifications develop, observations will play multiple important roles. There is a hierarchy of monitoring and measurement requirements to meet baselining and certification needs.

- Baseline conditions prior to OAE activity at the addition site and/or at a parallel site not impacted by the OAE activity but otherwise comparable
- Measurements for quantification including mineral dissolution rates, threshold monitoring (e.g. pH, saturation state)
- Measurements to support the set-up and to check and validate models used for MRV, including hydrodynamics (water mixing and dissolution of the alkalinity signal) and CO_2 equilibration (air-sea gas exchange).

- Process studies to quantify location- and method-specific issues, feedbacks and environmental safety which are likely one-offs per location or deployment and may become less necessary as site-specific knowledge and/or models and understanding improve.
- Experiments and longitudinal studies to fill knowledge gaps around OAE, which will be particularly important in early deployments but inform knowledge globally.

The Isometric standard (Section 3) outlines monitoring requirements in some detail for OAE from coastal outfalls, most of which is directly relevant for all OAE activities. They require monitoring in the outfall pipe and in the near-field mixing zone (Figure 2.10.)

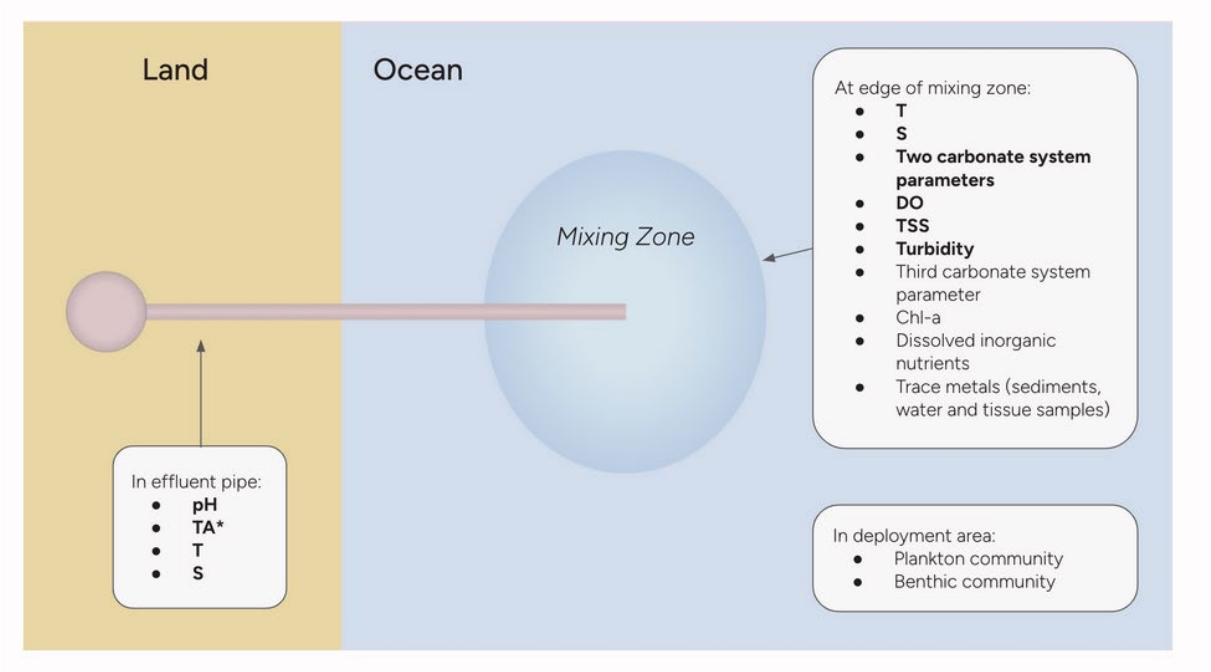


Figure 2.10 Isometric monitoring plan diagram for OAE from coastal outfalls.

Essential parameters to meet minimum requirements under the Isometric standard are shown in bold. Non-essential recommended parameters in normal weight type. DO: dissolved oxygen; TSS: total suspended solids; Chl-a: chlorophyll-a. DO, TSS and turbidity are required by the Isometrix standard as routine water quality indicators. Source: Isometric Standard for Ocean Alkalinity Enhancement from Coastal Outfalls (v1.0)

2.4.1.2 Baseline conditions at application site.

In order to predict the alkalinity addition that is appropriate at a particular site without triggering unwanted secondary effects (on efficiency or ecosystem impacts) the baseline condition would need to be established over a representative period. Given the strong seasonality in most marine systems, this probably entails at least a year of baseline monitoring at sufficient frequency. Core parameters of the carbonate system and core oceanographic parameters will be measurements, summarised in Table 2.1.

Table 2.1 Key baseline parameters to be considered over an annual cycle

Baseline parameter	Details
Seawater temperature, salinity	Standard oceanographic measurements allow quantification of carbonate system state, Ω_{arag} etc from other measured variables and are a key underpinning of all other parameters. Except in shallow, well mixed waters, depth profiles would be beneficial
Carbonate system in seawater / sediment pore waters	Necessary to understand optimal application season, and alkalinity addition possible without exceeding Ω_{arag} limit. Measurement of at least 2 carbonate system parameters, constraining uncertainty to appropriate value (Section 1.2.1.6)
Ω_{arag}	Carbonate system plus calcium ion concentration can be used to calculate Ω_{arag} baseline and therefore quantify potential alkalinity addition within limits (also accounting for dilution – see below). Calcium ion concentration is generally conservative with salinity so can in most cases be determined with reasonable certainty from salinity.

Other baseline observations may be necessary, for example quantifying biogenic calcification rates and natural mineral dissolution (alkalinity addition) rates, or monitoring plankton community structure to quantify efficiency impacts of second order feedbacks described in Section 2.3.5. This might also be achieved simultaneously with OAE release by means of a nearby 'baseline site' unaffected by the OAE activity although some pre-OAE comparisons and baselining of the two locations would then likely be required.

2.4.1.3 Process study measurements to constrain models and confirm safe alkalinity addition rates.

Intensive process studies will be necessary in early OAE activities to quantify alkalinity addition / dilution / CO_2 uptake in order to constrain models for quantification. Additionally, intensive measurement of ecosystem response variables at early application sites will allow ongoing impact evaluation from a more limited subset of local measurements. What's needed for the latter will depend on local conditions / ecosystems and type of alkalinity addition. Constraining the natural alkalinity budget to the greatest extent possible will minimise uncertainty from secondary effects.

For example quantifying the rate of dilution is essential to understand the amount of alkalinity in the short-to-medium term that remains available for uptake of CO_2 at the sea surface. Dual tracer techniques, where one tracer is able to degas to the atmosphere and another cannot, can be used to simultaneously constrain dilution and air-sea exchange from a release site. However, as time progresses the area and depth coverage of measurements required to constrain the tracer budget grows exponentially, and the signal to noise ratio decreases accordingly. Therefore i) such dual tracer approaches could not be used routinely for alkalinity additions but rather to better constrain models of the same processes and ii) even in process study mode there is a time- and spatial scale limit to the extent of such observations, which will vary depending on local conditions.

Experiments such as those undertaken by Bach (2024), where mineral alkalinity sources are incubated along with natural sediments, could be used to quantify the impacts of inhibition of natural mineral dissolution. This could be undertaken to both predict the magnitude of this

effect prior to OAE activity or, with some modification to experimental design, to quantify the magnitude of the effect during an OAE activity.

Other process-specific monitoring for quantification of removals or assessment of impacts may be required or desirable depending on the specific local conditions and requirements of future certification.

2.4.1.4 Quantification measurements at application sites

Routine measurements are likely to be required for all OAE applications, to ensure pre-defined thresholds (of pH, Ω_{arag}) are not exceeded. The threshold values may be determined from baseline observations or pre-deployment process studies, or it may be found that universal threshold values are sufficient (Section 2.3.4). It is not likely that direct quantification of CO_2 uptake will be feasible for OAE due to the time- and space- scales and limits, rather these will rely solely on modelling, but with measurements or discrete process studies for model validation.

2.4.1.5 Impacts monitoring at application sites.

Monitoring the local conditions at alkalinity release sites is essential to ensure impacts on local ecosystems do not exceed acceptable levels. Such measurements might include chlorophyll, turbidity, suspended solids, nutrients, heavy metals and dissolved oxygen (as suggested by the Isometric standard, cf. Section 3.1) and additionally phytoplankton species composition, biogenic calcification rates, macrofauna populations and sediment biogeochemistry.

The type and extent of appropriate measurements will depend on the site characteristics, the nature of the alkalinity added and the application technique. For example, monitoring toxic metal or micronutrient increases would not be necessary for addition of pure NaOH or electrochemical OAE. These may be required at each addition, or at the first addition in each season at a new addition location, or at representative addition sites to demonstrate level of impact which, if found to be low-to-zero, may mean such observations would not be needed routinely thereafter.

2.4.2 Modelling

Modelling how added alkalinity dissolves, disperses, and drives CO_2 uptake, using both physical ocean models and coupled biogeochemical models, is critical for assessing the effectiveness and potential ecosystem impact of OAE. These models will play a key role from early planning through long-term MRV.

At the planning end, there are already tools emerging, developed by the MRV community to evaluate medium term (15 year) OAE efficiency based on physical models of alkalinity dispersal and equilibration with the atmosphere (https://carbonplan.org/research/oae-efficiency-explainer).

Thanks to efforts in climate science and weather prediction over recent decades, global and regional ocean biogeochemical modelling is no longer in its infancy. However, uncertainties in the current generation of ocean biogeochemical models remain large, both in terms of their fundamental ability to reproduce the behaviour of the marine biogeochemical system and the specific process representation (e.g. natural alkalinity sources and sinks, secondary precipitation), variable spatial detail and tuning and validation required for OAE assessment specifically (Fennel et al., 2023; Ho et al., 2023). There is much ongoing effort to improve these models – projects that implement OAE activities in practice and implement measurement programmes would help to constrain these uncertainties significantly.

The biggest challenge in improving model skill is a lack of tuning and validation data, particularly measurements to constrain the state of the carbonate system and for parameterising air-sea gas exchange, as well as fundamental physical oceanography data (temperature, salinity) and data on ocean currents (Fennel et al., 2023).

Ho et al. (2023) envisage functional MRV for OAE based on statistical parameterisation of trusted ocean biogeochemical models to allow cost-effective prediction of OAE efficiency based on model output and local validation measurements. They suggest that this is achievable in a 5-10 year timescale, taking into account the recommendations in their paper and Fennel et al. (2023), summarised here:

- Development of **validated particle-fluid interaction models** to constrain dissolution kinetics and secondary precipitation, nested within small-scale hydrodynamic models to predict near-field processes and effects. Parameterisation of these models to extend prediction into the wider domain will also be beneficial
- Empirical research on the impacts of OAE on and **response of the plankton community** will be essential to improve representation in models and constrain feedbacks on and impacts of OA.
- **Sediment–water exchanges** (DIC from organic remineralization, $CaCO_3$ dissolution/burial and associated alkalinity fluxes) must be included in models on timescales from hourly, decadal or longer.
- **Riverine inputs** of both alkalinity and DIC (including from land-based CDR) need accurate, up-to-date flux estimates – ideally tied to field trials and tracked in a central registry.
- **Data assimilation** (DA) and model experiments to design optimal observational strategy are essential to model fidelity and help quantify uncertainty; ensemble DA and multi-model intercomparisons (MIPs) will provide robust uncertainty estimates.
- **Field trials and MRV** should be co-designed with modelers/observers, adhere to FAIR data principles in a public registry, document both obvious risks (e.g. secondary precipitation) and longer-term ecosystem impacts, and include a comprehensive uncertainty budget to guide future research.
- **Model validation:** Employ a two-step approach – first verify the unperturbed model baseline against natural variability, then assess its response to alkalinity addition – using multiple, complementary metrics across space, time, and variable types.
- **Tackling uncertainties:** Develop a comprehensive uncertainty budget combining known measurement and mapping errors with expert estimates of unmeasurable risks, and use ensemble data-assimilation alongside multi-model intercomparisons to capture model spread.

3 Assessment of relevant methodologies from private standards

3.1 Isometric Ocean Alkalinity Enhancement from Coastal Outfalls

Isometric released its protocol for certifying carbon removals through ocean alkalinity enhancement in June 2024, version v1.0. 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 OAE protocol follows the Isometric Standard as the main guiding document and complies with ISO 14064-2:2019. The protocol is further informed by ISO standards (ISO 14064-3: 2019, ISO 14040: 2006, ISO 14044: 2006).

Additional reference standards and protocols for OAE that were reviewed with attempts to align with best practice include:

- Criteria for High-Quality Carbon Dioxide Removal (Carbon Direct, Microsoft, 2023)
- Guide to Best Practices in Ocean Alkalinity Enhancement Research (Copernicus Publications, State Planet, 2023)
- Measurement, Reporting and Verification (MRV) Protocol for OAE Carbon Removal (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.

3.1.1 Scope

The protocol applies to projects enhancing total alkalinity in the surface ocean via discharge from coastal outfalls through:

- Mineral or solid feedstock: alkaline materials can originate from natural rocks and minerals, synthetic production, or industrial waste sources. These materials may be introduced into the ocean as dissolved substances, solids, or slurries.
- Electrochemical methods (e.g. electrolysis or electrodialysis): splitting or separation of seawater into acid and base streams, with the alkaline stream (NaOH), returned to the ocean.

The methodology treats reduced ocean outgassing and increased ocean uptake symmetrically, i.e. both increased ocean uptake and reduced ocean outgassing are treated as removals.

Isometric states that credits for removal from OAE projects are issued after net removal has been achieved (ex-post). These credits may be issued incrementally over time based on the incremental air-sea equilibration, or they may be issued all at once after full or near-complete air-sea equilibration. For the latter option, there is no specific requirement regarding the percentage of equilibration achieved; any net removals up to the chosen time point can be credited. The timeline for crediting, corresponding reporting periods, and allocation of emissions to reporting periods must be agreed with Isometric.

The quantification framework is designed for OAE projects that increase total alkalinity without directly introducing additional mineral carbon to the ocean. Consequently, projects using carbonate feedstocks as their primary source of alkalinity (which can increase DIC in the ocean without delivering CO_2 removal) require modifications to the quantification method. These modifications must be approved by Isometric. Uncertainty at each step of the quantification model must be determined.

3.1.2 Quantification

OAE is a marine CDR technique that adds alkalinity to the ocean surface and involves ocean mixing, requiring a different quantification method than closed systems.

Isometric states that measuring air-sea CO_2 fluxes is currently challenging due to rapid dilution and various spatial and temporal scales involved in OAE. Quantification is presently dependent on biogeochemical ocean models that are validated through observational data.

The reporting period pertains to the duration within which total net carbon removals ($\boldsymbol{CO_2e_{Removal,RP}}$) are assessed and documented for verification purposes. For OAE projects adhering to the Isometric protocol, the reporting period may encompass a singular dosing interval or may be divided into multiple reporting intervals.

3.1.2.1 Net carbon removals

The total net carbon removal is calculated for each reporting period as follows with all units in tCO_2e:

$$CO_2e_{Removal,RP} = CO_2e_{Stored,RP} - CO_2e_{Counterfactual,RP} - CO_2e_{Emissions,RP} \quad (28)$$

Or (a shorter version of the same)

$$CO_2e_{Removal,RP} = \Delta CO_2e_{AirSeaFlux,RP} - CO_2e_{Emissions,RP}$$

Where:

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

$\boldsymbol{CO_2e_{Stored,RP}}$ is the total CO_2 removed from the atmosphere and stored in a reporting period and it is equal to the $\boldsymbol{CO_2e_{AirSeaFlux,Intervention,RP}}$. It is calculated by quantifying the air-sea CO_2 fluxes i.e. the total amount of CO_2 that is exchanged across the air-sea boundary resulting from the OAE project activity for the reporting period.

$\boldsymbol{CO_2e_{Counterfactual,RP}}$ refers to the total counterfactual CO_2 removed from the atmosphere and stored in the absence of the OAE project. This represents the CO_2 removal calculated in the baseline scenario. It equals the air-sea CO_2 fluxes in the baseline ($CO_2e_{AirSeaFlux,Counterfactual,RP}$).

$\boldsymbol{CO_2e_{Emissions,RP}}$ 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), emissions from the transportation of products and equipment (Transportation Emissions Accounting Module) and embodied emissions (Embodied Emissions Accounting Module).

$\Delta CO_{2^e AirSeaFlux,RP}$ includes both the gross removal term and the counterfactual term. The methodology specifies that the net ocean uptake of atmospheric CO_2 (or a reduction in ocean outgassing) is defined by the difference in air-sea fluxes between the OAE intervention and counterfactual scenarios written as $\Delta CO_{2^e AirSeaFlux,RP}$.

3.1.2.2 Associated emissions

The methodology stipulates that all GHG emissions associated with project activities during the reporting period 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 OAE project activity. This includes emissions related to project establishment (e.g. construction, installation and initial surveys), emissions occurring within the reporting period (e.g. emissions from energy used, feedstock manufacturing and transport, consumables, waste processing, 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 ERW project activity must be identified including any emissions outside the defined categories, which are referred to as miscellaneous emissions.

Emissions from project establishment must be allocated to carbon removals by one-time deduction from the first removal; annual emissions over the project's anticipated lifetime; or per tonne of CO_2 removed based on estimated total production over the project's duration. The allocation of project establishment emissions must be reviewed at each crediting period, with adjustments made to the allocation schedule for future removals if necessary. If the allocation schedule cannot be adhered to, Isometric would initiate the protocol's reversal process and utilise the project's buffer pool for compensation. Reversals would be classified as either avoidable or unavoidable by Isometric.

Emissions resulting from operational activities are assigned to the reporting period in which they occur. The neutralization and disposal of acid waste for electrochemical OAE projects must also be accounted for. Allocation of these emissions may be allowed, but only with prior approval from Isometric.

For end-of-life emissions occurring after the reporting period, these directly related to each deployment must be quantified as part of that reporting period, while indirect emissions may use the same allocation method as for project establishment emissions.

The methodology stipulates that emissions induced by processes that would not occur without the OAE process, such as subsequent transportation and refining, must be fully included within the system boundary. Activities that were already occurring and would continue without the OAE project can be excluded from the system boundary, provided evidence is presented. This approach aims to ensure that only emissions directly associated with the OAE project are considered in the carbon removal calculations.

Furthermore, "ancillary activities" which are activities associated to a project but not directly or indirectly related to credit issuance[13], may be excluded from the system boundary. Possible secondary climate effects impacting GHG emissions, such as CO_2 uptake from increased primary production and biological carbon export, or higher dimethylsulfide production due to increased pH, are currently not included in the system boundary.

[13] Ancillary activities include supplementary R&D and corporate administration.

3.1.2.3 Uncertainty

The methodology requires accounting for uncertainty in the estimate 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.

The gross CO_2 removal via OAE occurs across various spatial and temporal scales. The Isometric quantification framework for this process requires defining four specific spatiotemporal regimes, i.e. alkalinity dosing location, mixing zone, coastal dynamic domain and air-gas exchange domain. The process involves three main steps to characterise the spatiotemporal regimes of alkalinity addition and its impact on air-sea CO_2 exchange.

- **Step 1 Effluent measurements**: The alkalinity dosing rate must be determined through continuous measurement at the outflow before a release into the ocean, or at the input location of the ocean outfall when justified. The quantity of total alkalinity must be determined before discharge. Total time-duration of discharge, timeseries of mass flow rate and timeseries of volumetric flow rate are continuously observed throughout the dosing period for both electrochemical and mineral OAE approaches. The upper limit of the alkalinity dosing rate is achieved only if complete dissolution takes place within the mixing zone. However, the increase in alkalinity due to particle dissolution and sinking requires further quantification in the coastal dynamics domain in Step 2. Isometric requires measuring or estimating of the fraction of solid and dissolved alkalinity in the outflow pipe. Project developers are asked to validate particle dissolution kinetics with samples from the effluent pipe and report the uncertainty in the feedstock released to the ocean for each reporting period.
- **Step 2 Alkalinity upscaling**: This step characterises the transport and mixing of alkalinity to support the quantification of air-sea CO_2 fluxes. In the mixing zone and coastal domain, the release of alkalinity must be scaled up to serve as a forcing function in the air-sea CO_2 uptake model. Any alkalinity losses must be quantified and subtracted. For mineral OAE, feedstock sinking and dissolution impact how much total alkalinity is added, when it increases, and its distribution. Full mineral dissolution in the water column maximizes dissolved alkalinity addition. However, this addition decreases if particles sink out of the mixed layer or interact with natural fluxes on the seabed. Thus, unless the feedstock dissolves quickly, its dissolution and sinking must be validated through coastal modelling or measurements.

  Isometric presents three approaches to choose from for determining the time-variable alkalinity forcing function 1) a validated coastal model (1D, 2D, 3D[14] and nested hydrodynamic models) to simulate alkalinity dispersal and particle dissolution (preferred for mineral OAE but not fast-dissolving feedstocks) ; 2) seasonal tracer studies to measure depth profiles of tracers in the coastal domain (used for electrochemical OAE or fast dissolving feedstock); 3) sensitivity studies to demonstrate the air-sea CO_2 uptake ocean model insensitivity to different alkalinity distributions and temporal variability (used for electrochemical OAE or fast dissolving feedstock). Isometric is open to considering and accepting innovative and hybrid approaches on a case-by-case basis, provided they are

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

well-supported. Most projects involve a density difference between effluent and marine waters, so it is recommended to use both a mixing zone model and a coastal model.

- **Step 3 Air-sea CO_2 uptake**: 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. The alkalinity forcing function is determined in Step 2 and implemented into the ocean model, which computes the $\Delta CO_{2^{e}AirSeaFlux,RP}$. 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 alkalinity 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 two "sense checks" for the model, 1) that the moles of carbon removed via air-sea gas exchange must be less than the moles of alkalinity added; 2) that the total alkalinity increase in the model does not exceed the alkalinity added by the project, as measured in Step 1.

3.1.2.4 Alkalinity losses

Isometric acknowledges that that the net CO_2 removals can be impacted by processes that may reduce the total alkalinity added to the ocean and thus the $\Delta CO_{2^{e}AirSeaFlux,RP}$. These are termed as "alkalinity losses," and they must be accounted for in the net carbon removal quantification to reflect a more appropriate quantity of total alkalinity represented in the air-se gas exchange models as mentioned in Step 2 above. The Isometric protocol outlines three main processes that contribute to alkalinity losses and reduce the effectiveness of OAE:

- Secondary precipitation involves the formation of calcium carbonate minerals in seawater due to alkalinity enhancement, 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 secondary precipitation risk is highest in coastal areas and mixing zones where there are significant changes in pH and total alkalinity from OAE, as well as high total suspended solids (TSS) levels. 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.
- Biotic calcification refers to the process where marine organisms use alkalinity to form calcium carbonate shells and skeletons. The carbonate chemistry conditions promoted by OAE 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.
- Added alkalinity interacting with ocean sediments could reduce natural sediment alkalinity fluxes, affecting project effectiveness, especially in mineral OAE projects. The protocol suggests using fast-dissolving feedstocks, appropriate dosing rates, and sites with full water column mixing or sufficient resuspension to mitigate this. Quantification

and monitoring methods include sediment sampling, measuring particle settling and accumulation rates, numerical modelling of particle transport, assessing benthic alkalinity fluxes, analysing net calcification changes, and sediment diagenesis modelling.

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 treat alkalinity losses:

- Avoiding losses by identifying strategies to mitigate conditions causing non-negligible loss terms, with monitoring for adherence;
- Estimating a conservative upper limit of alkalinity loss using scientific literature, calculations, or experiments;
- Conducting process-based modelling studies;
- Taking direct measurements;
- Employing justified alternative methods.

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 feedstock and consumables replacement considered.

A framework is provided to identify market leakage emissions from waste input products to be excluded from the system boundary if no payment or only a nominal "tipping fee" is made for the material, there is no alternative use for the waste product by another sector, and payments for the waste product are not a ‘significant share’ of revenue for the material producer.

3.1.4 Additionality and baselining

Projects must demonstrate additionality by showing that the carbon removal would not have occurred without the project intervention. The Isometric general standard (Isometric, 2025) 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 verification and is to be reviewed every two years or 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 OAE project activities are absent, and infrastructure is not installed. The calculation for this 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 OAE 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 $\Delta CO_{2^e AirSeaFlux,RP}$. 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

The protocol requires that OAE projects provide long-term storage, estimated to last over 1000 years, of removed atmospheric CO_2 or reduced ocean outgassing as dissolved inorganic carbon (DIC) in seawater.

Isometric discusses durability and reversal risks of the DIC storage reservoir in a separate module "Dissolved Inorganic Carbon Storage in Oceans". 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 alkaline 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 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's OAE projects are categorised as having a very low level of reversal, however, it is acknowledged that changes in the global ocean DIC reservoir cannot be directly observed through measurements and attributed to a specific project. Isometric allocates a buffer pool of 2% for such projects.

3.1.6 Sustainability

Environmental and socio-economic safeguard plans must be included into all major project phases, with comprehensive reports made available to stakeholders. These safeguards encompass environmental protection, social equity, community involvement, and the respect for cultural values. All crediting projects are obligated to adhere to and verify these environmental and socio-economic safeguards. Isometric references the *Guide to Best Practices in Ocean Alkalinity Enhancement Research* (Chapters 10 and 11) and the *Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration* (Chapters 2.1 and 2.2) for legal, social, and justice considerations pertinent to OAE projects.

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 coastal 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 international conventions such as the London Protocol; Convention on Biological Diversity; 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.

Potential feedstock risks include land use impacts from sourcing, production, preparation, storage, and distribution (e.g. land degradation, land occupation, dust pollution, deforestation, localised watershed contamination). Project developers are required to select feedstocks as per Isometric's Rock and Mineral Feedstock Characterisation Module.

Potential marine environmental risks include rapid changes in alkalinity dosing; changes in carbonate chemistry impacting calcification and ecological regime shifts; increased pH affecting aquatic life; removal of inorganic nutrients due to secondary precipitation, leading to nutrient limitation and decreased biological productivity.

Additional marine risks depending on the type of the OAE project can include:

- Impacts on marine biota from seawater intake pipes;
- Increased suspended solids affecting ambient light, filter feeders, and flocculation;
- Turbidity and turbid plumes affecting water quality and benthic habitats;
- Changes in silicate concentrations altering diatom growth rates;
- Metal contamination from feedstock dissolution and potential bioaccumulation in the food chain.

The protocol recognises that expecting a project to demonstrate zero impact on the ocean ecosystem is "unrealistic". Instead, it emphasises that project impacts should be evaluated holistically, considering climate change risks, attribution challenges, and the establishment of an appropriate baseline.

In terms of socio-economic safeguards, the protocol mandates an environmental justice review designed to account for historical advantages and disadvantages before selecting a site. There are requirements for engaging with local stakeholders who have 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

OAE 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 every two years at each dosing location. These site visits must comply with the requirements of ISO 14064-3.

The protocol outlines **pre-deployment requirements** which include: 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 alkalinity dispersal supported by a sensitivity analysis to ensure adherence to water quality limits; selection of safe alkalinity dosing rates through modelling. For mineral OAE projects, feedstock must be characterised according to the Rock and Mineral Feedstock Characterisation Module. This includes determining major and trace elemental abundances, mineralogy, particle size distribution, surface area, and the dissolution rate of the feedstock. For electrochemical OAE, the protocol requires details regarding the neutralization and disposal of acid by-products, as well as the identification of storage and disposal methods for hazardous by-products.

The monitoring plan must be established before the project activities and includes details on monitoring duration, frequency, location, sample collection methods, analytical methods, thresholds, data reporting, and quality assurance. 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 10.6 of the protocol and notes it is a challenge to establish a control site to isolate the OAE impact from baseline).

Isometric methodology involves **monitoring before, during, and after dosing**. Pre-deployment monitoring requires a baseline characterization of water chemistry and ecological parameters. The duration and frequency of the monitoring should align with the timescales of risks identified in the environmental risk assessment, dosing period, residence time, natural variability, and availability of historical data. Similarly, post-dosing monitoring requires the timescales of risks, residence time, and dissolution time. The monitoring frequency must be such that it provides sufficient information about the effluent and receiving waters. It is influenced by factors such as operational capacity, location of the discharge, dosing schedule, seasonality, and nature of the discharge.

This methodology does not specify precise monitoring locations. 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 i.e. in effluent pipe, at the edge of the mixing zone where initial dilution takes place and in the deployment area where a broader area is affected by the project. The protocol requires a diagram of monitoring locations to be included in the project design document. Parameters monitored at these locations include pH, alkalinity, temperature, and salinity at the effluent site. In the mixing zone, temperature, salinity, carbonate chemistry parameters, dissolved oxygen, turbidity, and total suspended solids are measured. In the deployment area, plankton and benthic communities and trace metal concentration are observed. Monitoring in the

deployment area is focused on ecosystem health and documenting any shifts in the baseline ecology.

Isometric outlines **minimum monitoring requirements** for all OAE projects credited under the protocol.

In the effluent prior to discharge monitoring location, temperature and salinity determine the physical conditions of the effluent while the pH and alkalinity ensure compliance with the set pH threshold of the dosing rate and mineral dissolution rates. Alkalinity can be calculated using two carbonate system variables (e.g., pH and $pCO_{2(sw)}$). Routine bottle samples should verify these calculations. A third carbonate system variable ($pCO_{2(sw)}$ or DIC) to assess the initial state of carbonate system disequilibrium at the point of discharge is recommended. Isometric will not issue credits for time periods lacking adequate in-pipe effluent measurements.

The mixing zone is the area surrounding the discharge infrastructure where water quality criteria can be exceeded. Permits which allow for a mixing zone require water quality criteria to be met at the edge of a mixing zone. Small-scale deployments may struggle to detect signals beyond the mixing 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 alkalinity addition. Therefore, monitoring should focus on the edge of the mixing zone. 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.

The methodology also outlines **additional monitoring requirements** for OAE projects. For projects with intake pipes it requires to assess the impact on marine biota via demographic and conditional mortality approaches. Biological and ecological monitoring via periodic surveys to assess functional diversity, taxonomic diversity and trace metal concentration in tissues are required in the deployment area. OAE mineral projects must evaluate feedstock accumulation on the seabed and monitor heavy metals and trace elements in water and sediments, complying with local or US EPA standards.

In summary, Isometric lists the required and recommended measurements for monitoring. Required measurements are the minimum needed for all projects. Additional measurements depend on the project's specifics, site, alkalinity loss strategy, and environmental risk plan. The project design document must describe the exact monitoring plan.

Isometric requires measurements for both validating models and providing inputs for models used in OAE 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.

4 Review of known and potential issues

4.1 Quantification

Quantification of carbon removals by ocean alkalinity enhancement requires numerical modelling to assess diffuse effects over large areas and multiple years, which can be supported by local measurements to quantify local and short-term effects (Section 2.4.2). For certification, a key decision will be what the minimum measurement requirements should be (parameters, geographic scale and frequency).

4.1.1 (In)complete dissolution of mineral powders

Where solid minerals are added to the marine environment, the quantity of alkalinity added depends on the fraction of the added minerals which dissolve. Particle dissolution rates and alkalinity release through time (which may not be linear with dissolution), vary depending on the source mineral and particle size distribution. Certification methodologies will need to either

i) Require that any mineral alkalinity sources are 'pre-dissolved' so that a known quantity of alkalinity is added, or

ii) ensure that particles dissolve rapidly (i.e. within days or weeks) so that the OAE activity can be considered as a near-instantaneous alkalinity addition for the purposes of downstream modelling of efficiency (Section 2.3.3) or

iii) accurately model the dispersal and dissolution of added particles and alkalinity release through time.

The latter is a complex problem, particularly where particles are added to dynamic coastal environments where wave action will break down and resuspend particles and currents will redistribute the particles.

4.1.1.1 Key knowledge gaps

There is little scope for quantifying long-term particle dissolution from direct observations except where particles are added into cohesive sediments and allowed to react in situ with minimal disturbance (Section 2.2.2.2). In other situations, locating and measuring a sufficiently representative sample of added particles is likely to be impossible. Therefore multi-scale coupled models of particle dissolution and transport encompassing seawater and sediment physical and chemical dynamics are needed (Fennel et al., 2023; Ho et al., 2023). This will need to be supported by laboratory and field measurements to parameterise and (separately) validate the models. There is certainly extensive ongoing work in this area but such models are currently immature relative to the requirement, making OAE by mineral addition without pre-dissolution the least certifiable of the OAE methods currently. Overall, to constrain the uncertainty in alkalinity release from mineral additions, comprehensive field trials linked to multi-scale modelling efforts will be necessary (Fennel et al., 2023; Ho et al., 2023).

Relying on modelled rates of particle dissolution also introduces a moral hazard if the calculated nominal removals from an activity are not directly dependent on the actual quality of appropriate feedstock and on its successful dissolution, which would need to be carefully managed.

4.1.2 Secondary precipitation

Secondary precipitation and inhibition of natural alkalinity inputs from mineral dissolution in coastal sediments are potentially important efficiency issues for OAE deployments. Threshold

limits for pH and $\Omega_{aragonite}$ are proposed in the literature and avoidance of these secondary effects by ensuring these thresholds are not breached is the main method of addressing these issues, including in the Isometric standard. However, it is reasonable to assume that any increase in alkalinity will have an effect on some or all of these processes, even if not readily detectable. Future observations and experiments may give certification systems opportunity to adapt to our developing understanding of secondary dynamics.

As per the Isometric standard (Section 3.1.2) the current most sensible approach to secondary precipitation and mineral dissolution is to take mitigation measures to minimise the risk of inhibiting dissolution fluxes in sediments (e.g. avoiding overloading sediments with slow dissolving alkalinity sources) by avoiding exceedance of thresholds. General thresholds of pH and Ω have been suggested (Section 2.3.4), but location-specific thresholds may need be established for baseline conditions at each OAE site. Monitoring of pH and Ω at release locations would allow secondary precipitation to be avoided.

4.1.2.1 Key knowledge gaps

Biological precipitation of calcium carbonate, for instance by bivalves, calcifying plankton or corals is known to be enhanced by increased alkalinity (Section 2.3.5.2). The longer-term diffuse effect of non-equilibrated alkalinity on increased calcification will likely be small for any individual OAE activity but also very difficult or impossible to quantify. If and when OAE activities scale such that the compound effect of many deployments increases baseline alkalinity to the point where this is a potentially significant feedback this will need to be considered further, particularly how to address this in certifications in the context of ocean acidification, which would otherwise be decreasing calcification rates.

4.1.3 Equilibration with atmospheric CO_2

As alkalinity-enhanced seawater 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. It can take years to more than a decade for the carbon removal to be completed, and the degree to which alkalinity remains unequilibrated (i.e. the proportion mixed out of reach of the atmosphere) is a major control on the overall efficiency of the carbon removal per unit alkalinity added (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. This is probably the best constrained of the modelling needs for MRV for OAE, given that ocean circulation and air-sea exchange are key parts of the carbon cycle that have been studied relatively intensively for decades. 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 alkalinity enhancement, 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.

4.1.3.1 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 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.

4.1.4 Quantification of other biogeochemical / marine carbon cycle feedbacks and reversals

For the purposes of development of a certification methodology, these issues should be considered knowledge gaps in the short-to-medium term, but will need to be addressed as knowledge and understanding improve. Enhancement of alkalinity may directly or indirectly (e.g. through secondary impacts of mineral dissolution) affect the marine carbon cycle via a range of potential mechanisms (Section 2.3.5), such as altering the efficiency of the biological carbon pump. Neither the direction or potential magnitude of most such effects are known with any certainty (Bach et al., 2019; Johnson et al., 2024). It is important that research is undertaken into these 'known unknowns', and also currently unforeseen 'unknown unknowns' as they emerge, to ensure that large scale manipulation of Earth's alkalinity budget is both safe and a truly durable carbon store on the timescales that climate action requires.

4.1.5 Acid disposal

Electrochemical alkalinity addition processes (electrolysis, electrodialysis) involve the generation of either HCl or of Cl_2 – and if this acidity was allowed to return to the ocean system, it would counteract the carbon removal delivered by alkalinity enhancement (Section 2.2.3.3). The best case for projects would be that these products could be sold on existing markets and productively utilised. Currently, however, it is understood that because demand for NaOH exceeds demand for chlorine, there is already an excess of Cl_2 production from the chloralkali process. If these products cannot be utilised then they must be otherwise disposed of, incurring disposal costs and environmental risks.

One possible solution for HCl is to use alkaline mineral feedstocks to neutralise the acid produced. This can be seen as shifting the use of mineral alkalinity from the ocean, where it is uncontrolled and suffers from potential side-effects and inefficiencies (Section 2.3.1, Section 4.3), into a more controlled on-land environment. Overall this is probably the most constrainable OAE approach we have come across.

If, however, the acidity leaves the boundaries of an OAE activity without being neutralised, consideration would need to be given to whether some or all of that acidity could be returned to watercourses, either in disposal or at end of life after productive use.

4.1.6 MRV 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 OAE studies. It will be important to recognise that early OAE 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 OAE deployments. This highlights the importance of transparency and openness in OAE activities. Indeed, the Isometric protocol makes clear that the gathering and availability of data is critical for understanding the potential and limitations of OAE and for developing the technology. Isometric requires that modelling and observations undertaken in support of any OAE 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 Oschiles et al. (2023).

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

4.1.7 Complementary value

In some circumstances, alkalinity addition 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, in particular if the complementary value is so high that it would justify the activity without the need for carbon markets.

4.1.7.1 Shellfish aquaculture

Shellfish aquaculture may benefit from increased alkalinity. Artificially increasing the alkalinity of waters in shellfish hatcheries and nurseries is common practice (Alma et al., 2024) and the addition of carbonate shells to seawater in the area of shellfish farms has also been considered as a practice to mitigate the effects of ocean acidification (Scigliano, 2012). Therefore, OAE may benefit shellfish aquaculture and some OAE is already being undertaken at least at small scale for the purposes of increasing aquaculture yield, particularly in hatcheries and juvenile tanks prior to deployment (Gaines et al., 2022). Existing alkalinity deployment should be reflected in the project baseline.

As discussed in Section 2.3.5.2, the presence of shellfish and the increased calcification resulting from alkalinity addition will decrease the efficiency of the OAE activity with respect to CO_2 removal, due to the removal of alkalinity during calcification (Morris & Humphreys, 2019). It is therefore important that the presence of any local aquaculture should be disclosed during certification.

4.1.7.2 Electrochemical OAE byproducts

Where there is strong local demand for Cl_2 e.g. in chemical plants, there may be excess NaOH produced by the chloralkali process (Section 2.2.3.2). Given the global current excess of Cl_2 vs NaOH, transport and sale of the alkali is probably profitable, but if this is not the case, alkalinity 'disposal' to OAE is a possible pathway. In this case, OAE would be a byproduct of chlorine production by the chloralkali process.

4.1.7.3 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 electrochemical OAE costs, as brine creation has already been undertaken. 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 OAE 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.

4.1.8 Baselining feedstocks

As in the case of ERW feedstocks, some candidate OAE feedstocks are byproducts of other industries: quarry dust, fly ash, steel slag, crushed concrete, etc. Candidate feedstocks which are likely to have significantly weathered under typical conditions (i.e. those which would be exposed to water and CO_2 anyway) may experience a comparable amount of weathering in the baseline to that which would be delivered by an OAE application. The expected baseline removals may not be static, in which case this categorisation may have to be updated as time

goes on to reflect changing disposal practices. This is discussed in more detail in the section on ERW.

4.2 Long-term (durable) storage

As established above, 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 the short-to-medium term CO_2 storage resulting from OAE (and ERW and DOCC) 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.

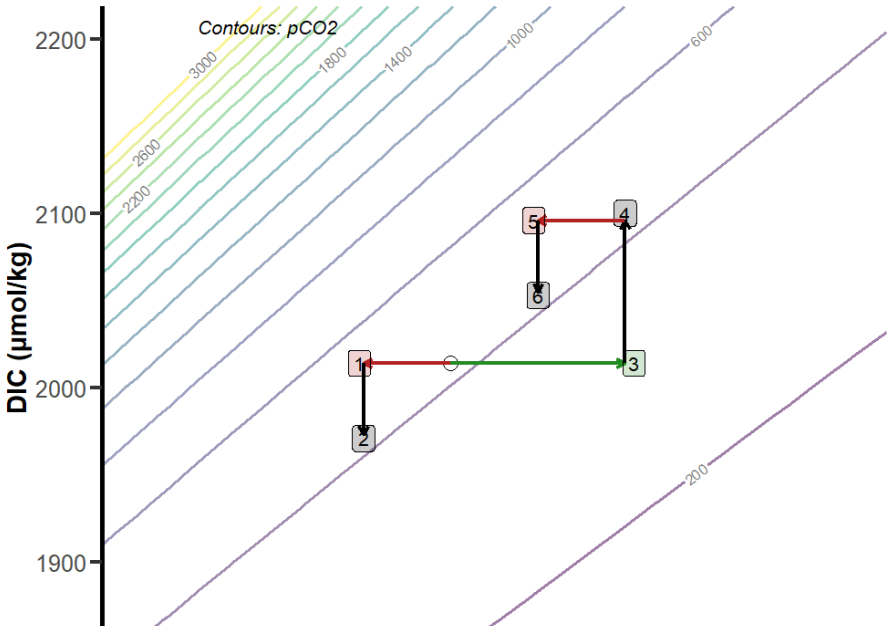
4.2.1 Relevance to long-term emissions trajectories

Future changes to atmospheric CO_2 on 100-200 year timescales will impact the long-term efficiency of OAE, 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). Certification approaches would need to consider whether a reduction or increase in modelled CO_2 removal due to differences between the expected and observed atmospheric CO_2 concentration over time should be treated as a reversal, or lead to the issuance of additional units.

4.2.2 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 (NOx, SO_2) will alter the alkalinity balance of the ocean and therefore the equilibrium point between the surface ocean and the atmosphere.

Two competing factors govern the CO_2 emission from the ocean for a given amount of acidification in the OAE vs counterfactual situations – the alkalinity prior to the acidification and the total DIC prior to the acidification. In the scenario where OAE has been practiced there is both more alkalinity and greater DIC than in a scenario without. So, a larger quantity of DIC is available to be released, but the buffering against acidification is greater. Figure 4.1 shows the Deffeyes process diagram for the addition of acidity with or without a preceding alkalinity enhancement. The net impact on DIC of the acidification is very similar whether or not it is preceded by OAE. In a full exploration of realistic values of starting conditions, alkalinity additions and acidity additions, the effect of an alkalinity addition is always to reduce the magnitude of the resulting CO_2 loss following acidification relative to the counterfactual where acidification was not preceded by OAE. Furthermore, in the typical situation where OAE-derived alkalinity is not fully equilibrated with the atmosphere, the non-equilibrated alkalinity will exert a greater buffer capacity against acidification and therefore provide a greater benefit. The net CO_2 benefit of OAE in the case of external acidity input (vs the counterfactual) is small; and given that quantifying such external acidity inputs is difficult or impossible, the pragmatic conclusion of this analysis is that external acidification leading to release of otherwise durably stored DIC from ocean acidification may be ignored.



Step	Description	pH	pCO_2	CO_2	HCO_3^-	CO_3^{2-}	DIC
-	initial	8.02	425	12	1798	204	2014
1	add 50 µmol/kg of acidity	7.94	525	15	1828	171	2014
2	equilibrate	8.01	425	12	1764	197	1973
-	initial	8.02	425	12	1798	204	2014
3	add 100 µmol/kg of alkalinity	8.16	295	8	1732	273	2014
4	equilibrate	8.04	425	12	1864	220	2096
5	add 50 µmol/kg of acidity	7.96	520	15	1895	186	2096
6	equilibrate	8.03	425	12	1831	212	2055

Figure 4.1 The impact of external acidity input (50 µM) on CO_2 emissions in a fully equilibrated OAE case vs counterfactual situation (pCO_2 = 425ppm, T=25 °C, S=35).

Steps are defined in the table above. 1-2 (counterfactual) leads to emission of 40.75 uM of CO_2, whereas 5-6 (response to acidification after fully equilibrated OAE) leads to emission of 40.59 uM CO_2. Therefore OAE confers a marginal additional CO_2 benefit under external acidification. The magnitude of this benefit varies depending on conditions, but is almost universally positive and increases with greater acidity addition, even when acidity addition >> alkalinity addition. Note that the $pCO_{2(sw)}$ contours are imperceptibly curved, leading to the slight differences in CO_2 uptake between 1>2 and 5>6, despite starting and finishing at the same pCO_2. pCO_2 in the diagram and table refer to $pCO_{2(sw)}$.

4.3 Sustainability

Where OAE is undertaken, the chemistry of seawater is altered, which has the potential to impact marine organisms and ecosystems, and potentially the marine carbon cycle and thus be a feedback on efficiency or usefulness of OAE (Section 2.3.5). Here we address the non-CO_2 impacts of the changes in seawater caused by OAE. Such impacts are poorly quantified 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.

4.3.1 Impacts of increased alkalinity

Increased alkalinity leads to a change in DIC speciation, favouring bicarbonate and carbonate and reducing the concentration of dissolved CO_2 (Section1.2.1.5) and an increase in pH, both of which can affect the marine ecosystem. In particular, calcifying organisms will be favoured by increased alkalinity (Bach et al., 2019). As well as impacts for the biological carbon pump (Section 2.3.5.3) this may also affect ecosystem structure at the expense of other phytoplankton types and potentially impact function of higher organisms. Given the progression of ocean acidification, it is reasonable to expect that, other than locally to application sites, the impact increased alkalinity from OAE has is likely to be small and in large part can probably be considered an amelioration of ocean acidification.

4.3.2 Other impacts

Dissolution of silicate minerals will increase silicate concentration in the surface ocean. This may lead to a change in community structure from calcifying to silicifying plankton, potentially altering the alkalinity balance (in favour of greater CO_2 uptake due to reduced calcification) but also may impact ecosystem structure and function, for example leading to a change in dominant phytoplankton species (Bach et al., 2019).

Increased concentrations of calcium and magnesium ions will impact calcification rates, with Ca^{2+} favouring calcification, but Mg^{2+} tending to inhibit calcification (increased Mg content inclusion in $CaCO_3$ increases solubility, again leading to alkalinity impacts but also community structure changes) (Bach et al., 2019).

Impurities in alkaline minerals will tend to release toxic (e.g. nickel) and micronutrient (e.g. iron) metal ions. The former may impact total algae growth or potentially impact health of marine organisms more broadly. Iron, conversely, may enhance the growth of algae, particularly favouring non-calcifying plankton, affecting alkalinity budget and community composition.

For all of the impacts listed here, baselining and monitoring marine ecosystems in the locations of OAE actions, and the monitoring of concentrations of silicate, calcium, magnesium and other metal ions could be done if necessary, as knowledge develops. Such monitoring is likely to be more important in early OAE deployment to help build knowledge and understanding.

4.3.3 Legality under the London convention

There are questions raised in the literature about the legality of OAE, along with other marine CDR methods, in the context of the London convention on dumping at sea (Steenkamp & Webb, 2023). These relate in particular to mineral addition approaches, which may be considered ‘dumping at sea’. A recent paper suggests that there is an important role for national / federal-scale legislation in addressing this uncertainty for marine CDR methods, which can supersede the slow process of international law (Johnson et al., 2024).

5 References

Alma, L., McElhany, P., Crim, R. N., Newton, J. A., Maher, M., Mickett, J. B., & Padilla-Gamiño, J. L. (2024). Phenotypic plasticity and carryover effects in an ecologically important bivalve in response to changing environments. *Frontiers in Marine Science*, *11*. https://doi.org/10.3389/fmars.2024.1178507

Bach, L. T. (2024). The additionality problem of ocean alkalinity enhancement. *Biogeosciences*, *21*(1), 261–277. https://doi.org/10.5194/BG-21-261-2024

Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S., & Renforth, P. (2019). CO_2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems. *Frontiers in Climate*, *1*(7), 476698. https://doi.org/10.3389/FCLIM.2019.00007/PDF

Deffeyes, K. S. (1965). Carbonate Equilibria: A Graphic and Algebraic Approach. *Limnology and Oceanography*, *10*(3), 412–426. https://doi.org/10.4319/lo.1965.10.3.0412

DeVries, T. (2022). The Ocean Carbon Cycle. *Annual Review of Environment and Resources*, *47*(Volume 47, 2022), 317–341. https://doi.org/10.1146/annurev-environ-120920-111307

Dickson, A. G. (1992). The development of the alkalinity concept in marine chemistry. *Marine Chemistry*, *40*(1), 49–63. https://doi.org/10.1016/0304-4203(92)90047-E

Eisaman, M. D. (2024). Pathways for marine carbon dioxide removal using electrochemical acid-base generation. *Frontiers in Climate*, *6*, 1349604. https://doi.org/10.3389/FCLIM.2024.1349604/BIBTEX

Eisaman, M. D., Geilert, S., Renforth, P., Bastianini, L., Campbell, J., Dale, A. W., Foteinis, S., Grasse, P., Hawrot, O., Löscher, C. R., Rau, G. H., & Rønning, J. (2023). Assessing the technical aspects of ocean-alkalinity-enhancement approaches. *State of the Planet*, *2-oae2023*, 1–29. https://doi.org/10.5194/SP-2-OAE2023-3-2023

European Union. (2024). Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products. *Official Journal of the European Union*. https://eur-lex.europa.eu/eli/reg/2024/3012/oj/eng

Fay, A. R., Munro, D. R., McKinley, G. A., Pierrot, D., Sutherland, S. C., Sweeney, C., & Wanninkhof, R. (2024). Updated climatological mean ΔfCO_2 and net sea–air CO_2 flux over the global open ocean regions. *Earth System Science Data*, *16*(4), 2123–2139. https://doi.org/10.5194/essd-16-2123-2024

Fennel, K., Long, M. C., Algar, C., Carter, B., Keller, D., Laurent, A., Mattern, J. P., Musgrave, R., Oschlies, A., Ostiguy, J., Palter, J. B., & Whitt, D. B. (2023). Modelling considerations for research on ocean alkalinity enhancement (OAE). *State of the Planet*, *2-oae2023*, 1–29. https://doi.org/10.5194/SP-2-OAE2023-9-2023

Foteinis, S., Andresen, J., Campo, F., Caserini, S., & Renforth, P. (2022). Life cycle assessment of ocean liming for carbon dioxide removal from the atmosphere. *Journal of Cleaner Production*, *370*, 133309. https://doi.org/10.1016/j.jclepro.2022.133309

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., … Zeng, J. (2025). Global Carbon Budget 2024. *Earth System Science Data*, *17*(3), 965–1039. https://doi.org/10.5194/essd-17-965-2025

Gaines, E., Sturmer, L., Anderson, N., Laramore, S., & Baker, S. (2022). *The Role of pH, Alkalinity, and Calcium Carbonate in Shellfish Hatcheries*. University of Florida.

https://shellfish.ifas.ufl.edu/wp-content/uploads/pH-and-Alkalinity-Fact-Sheet-for-Hatcheries-Final-Draft.pdf

Gattuso, J.-P., Epitalon, J.-M., Lavigne, H., Orr, J., Gentili, B., Hagens, M., Hofmann, A., Mueller, J.-D., Proye, A., Rae, J., & Soetaert, K. (2024). *seacarb: Seawater Carbonate Chemistry* (Version 3.3.3) [Computer software]. https://cran.r-project.org/web/packages/seacarb/index.html

Geerts, L. J. J., Hylén, A., & Meysman, F. J. R. (2025). Review and syntheses: Ocean alkalinity enhancement and carbon dioxide removal through marine enhanced rock weathering using olivine. *Biogeosciences*, *22*(2), 355–384. https://doi.org/10.5194/BG-22-355-2025

Gore, S., Renforth, P., & Perkins, R. (2019). The potential environmental response to increasing ocean alkalinity for negative emissions. *Mitigation and Adaptation Strategies for Global Change*, *24*(7), 1191–1211. https://doi.org/10.1007/S11027-018-9830-Z/TABLES/6

Guo, J. A., Strzepek, R. F., Swadling, K. M., Townsend, A. T., & Bach, L. T. (2024). Influence of ocean alkalinity enhancement with olivine or steel slag on a coastal plankton community in Tasmania. *Biogeosciences*, *21*(9), 2335–2354. https://doi.org/10.5194/bg-21-2335-2024

Guo, J. A., Strzepek, R. F., Yuan, Z., Swadling, K. M., Townsend, A. T., Achterberg, E. P., Browning, T. J., & Bach, L. T. (2025). Effects of ocean alkalinity enhancement on plankton in the Equatorial Pacific. *Communications Earth & Environment*, *6*(1), 1–8. https://doi.org/10.1038/s43247-025-02248-7

Hartmann, J., Jansen, N., Dürr, H. H., Kempe, S., & Köhler, P. (2009). Global CO_2-consumption by chemical weathering: What is the contribution of highly active weathering regions? *Global and Planetary Change*, *69*(4), 185–194. https://doi.org/10.1016/j.gloplacha.2009.07.007

Ho, D. T., Bopp, L., Palter, J. B., Long, M. C., Boyd, P. W., Neukermans, G., & Bach, L. T. (2023). Monitoring, reporting, and verification for ocean alkalinity enhancement. *State of the Planet*, *2-oae2023*, 1–12. https://doi.org/10.5194/SP-2-OAE2023-12-2023

Isometric. (2025). *Isometric Standard v1.7.2*. https://registry.isometric.com/standard

Iyapazham Vaigunda Suba, P., Gopalakrishnan, A., Radović, J. R., Tutolo, B. M., Larter, S., Karan, K., & Thangadurai, V. (2023). Electrochemical ocean alkalinity enhancement using a calcium ion battery. *International Journal of Greenhouse Gas Control*, *130*, 104012. https://doi.org/10.1016/j.ijggc.2023.104012

Johnson, M., van Doorn, E., Hilmi, N., Marandino, C., McDonald, N., Thomas, H., Allemand, D., Algarin, L. D., Lebleu, L., Ho, D. T., & others. (2024). Can coastal and marine carbon dioxide removal help to close the emissions gap? Scientific, legal, economic, and governance considerations. *Elem Sci Anth*, *12*(1).

La Plante, E. C., Chen, X., Bustillos, S., Bouissonnie, A., Traynor, T., Jassby, D., Corsini, L., Simonetti, D. A., & Sant, G. N. (2023). Electrolytic Seawater Mineralization and the Mass Balances That Demonstrate Carbon Dioxide Removal. *ACS ES&T Engineering*, *3*(7), 955–968. https://doi.org/10.1021/acsestengg.3c00004

Legge, O. J., Bakker, D. C. E., Johnson, M. T., Meredith, M. P., Venables, H. J., Brown, P. J., & Lee, G. A. (2015). The seasonal cycle of ocean-atmosphere CO_2 flux in Ryder Bay, west Antarctic Peninsula. *Geophysical Research Letters*, *42*(8), 2934–2942.

Lenton, T. M., & Britton, C. (2006). Enhanced carbonate and silicate weathering accelerates recovery from fossil fuel CO_2 perturbations. *Global Biogeochemical Cycles*, *20*(3). https://doi.org/10.1029/2005GB002678

Moras, C. A., Bach, L. T., Cyronak, T., Joannes-Boyau, R., & Schulz, K. G. (2022). Ocean alkalinity enhancement – avoiding runaway $CaCO_3$ precipitation during quick and hydrated

lime dissolution. *Biogeosciences*, *19*(15), 3537–3557. https://doi.org/10.5194/bg-19-3537-2022

Morris, J. P., & Humphreys, M. P. (2019). Modelling seawater carbonate chemistry in shellfish aquaculture regions: Insights into CO_2 release associated with shell formation and growth. *Aquaculture*, *501*, 338–344. https://doi.org/10.1016/j.aquaculture.2018.11.028

Oschlies, A., Bach, L. T., Rickaby, R. E. M., Satterfield, T., Webb, R., & Gattuso, J.-P. (2023). Climate targets, carbon dioxide removal, and the potential role of ocean alkalinity enhancement. *State of the Planet*, *2-oae2023*, 1–9. https://doi.org/10.5194/SP-2-OAE2023-1-2023

Rakestraw, N. (1949). The conception of alkalinity of excess base of sea water. *Journal of Marine Research*, *8*(1). https://elischolar.library.yale.edu/journal_of_marine_research/699

Rau, G. H., Knauss, K. G., Langer, W. H., & Caldeira, K. (2007). Reducing energy-related CO_2 emissions using accelerated weathering of limestone. *Energy*, *32*(8), 1471–1477. https://doi.org/10.1016/J.ENERGY.2006.10.011

Renforth, P., Baltruschat, S., Peterson, K., Mihailova, B. D., & Hartmann, J. (2022). Using ikaite and other hydrated carbonate minerals to increase ocean alkalinity for carbon dioxide removal and environmental remediation. *Joule*, *6*(12), 2674–2679. https://doi.org/10.1016/j.joule.2022.11.001

Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, *55*(3), 636–674. https://doi.org/10.1002/2016RG000533

Renforth, P., Pogge von Strandmann, P. A. E., & Henderson, G. M. (2015). The dissolution of olivine added to soil: Implications for enhanced weathering. *Applied Geochemistry*, *61*, 109–118. https://doi.org/10.1016/j.apgeochem.2015.05.016

Rohling, E. J. (2023). Marine methods for carbon dioxide removal: Fundamentals and myth-busting for the wider community. *Oxford Open Climate Change*, *3*(1). https://doi.org/10.1093/oxfclm/kgad004

Sander, R. (2023). Compilation of Henry's law constants (version 5.0.0) for water as solvent. *Atmospheric Chemistry and Physics*, *23*(19), 10901–12440. https://doi.org/10.5194/acp-23-10901-2023

Sartor, A., Maesano, C., & Clark-Sutton, K. (2025, June 25). *Harnessing Carbon Removal Opportunities in Desalination*. Rocky Mountain Institute. https://rmi.org/harnessing-carbon-removal-opportunities-in-desalination/

Schulz, K. G., Bach, L. T., & Dickson, A. G. (2023). Seawater carbonate chemistry considerations for ocean alkalinity enhancement research: Theory, measurements, and calculations. *State of the Planet*, *2-oae2023*, 1–14. https://doi.org/10.5194/SP-2-OAE2023-2-2023

Schwinger, J., Bourgeois, T., & Rickels, W. (2024). On the emission-path dependency of the efficiency of ocean alkalinity enhancement. *Environmental Research Letters*, *19*(7), 074067. https://doi.org/10.1088/1748-9326/AD5A27

Scigliano, E. (2012). *Sweetening the Waters: The Feasibility and Efficacy of Measures to Protect Washington's Marine Resources from Ocean Acidification* (p. 59). National Fisheries Conservation Center. https://www.eopugetsound.org/sites/default/files/features/resources/SweeteningtheWatersOptimized.pdf

Siegel, D. A., DeVries, T., Doney, S. C., & Bell, T. (2021). Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environmental Research Letters*, *16*(10), 104003. https://doi.org/10.1088/1748-9326/ac0be0

Steenkamp, R. C., & Webb, R. M. (2023). Legal considerations relevant to the research of ocean alkalinity enhancement. *State of the Planet Discussions*, *2023*, 1–30. https://sp.copernicus.org/preprints/sp-2023-8/sp-2023-8.pdf

Walker, J. C. G., Hays, P. B., & Kasting, J. F. (1981). A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. *Journal of Geophysical Research: Oceans*, *86*(C10), 9776–9782. https://doi.org/10.1029/JC086iC10p09776

Wolf-Gladrow, D. A., Zeebe, R. E., Klaas, C., Körtzinger, A., & Dickson, A. G. (2007). Total alkalinity: The explicit conservative expression and its application to biogeochemical processes. *Marine Chemistry*, *106*, 287–300. https://doi.org/10.1016/j.marchem.2007.01.006

Zachos, J. C., Röhl, U., Schellenberg, S. A., Sluijs, A., Hodell, D. A., Kelly, D. C., Thomas, E., Nicolo, M., Raffi, I., Lourens, L. J., McCarren, H., & Kroon, D. (2005). Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum. *Science*, *308*(5728), 1611–1615. https://doi.org/10.1126/science.1109004

Zhong, S., & Mucci, A. (1989). Calcite and aragonite precipitation from seawater solutions of various salinities: Precipitation rates and overgrowth compositions. *Chemical Geology*, *78*(3), 283–299. https://doi.org/10.1016/0009-2541(89)90064-8

Zhou, M., Tyka, M. D., Ho, D. T., Yankovsky, E., Bachman, S., Nicholas, T., Karspeck, A. R., & Long, M. C. (2025). Mapping the global variation in the efficiency of ocean alkalinity enhancement for carbon dioxide removal. *Nature Climate Change*, *15*(1), 59–65. https://doi.org/10.1038/s41558-024-02179-9