Ocean alkalinity enhancement - evidence on potential environmental impacts and social implications

Chief Scientist's Group report

September 2025

SC230003/R11

We are the Environment Agency. We protect and improve the environment.

We help people and wildlife adapt to climate change and reduce its impacts, including flooding, drought, sea level rise and coastal erosion.

We improve the quality of our water, land and air by tackling pollution. We work with businesses to help them comply with environmental regulations. A healthy and diverse environment enhances people's lives and contributes to economic growth.

We can't do this alone. We work as part of the Defra group (Department for Environment, Food & Rural Affairs), with the rest of government, local councils, businesses, civil society groups and local communities to create a better place for people and wildlife.

Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

Further copies of this report are available from our publications catalogue: www.gov.uk/government/publications or our National Customer Contact Centre: 03708 506 506

Email: research@environment-agency.gov.uk

Author(s):

David Kesner
Katharine Rowland
Laura Williams
Rebecca Southall
Rob Daniel
Dr. Tom Raven
Vita Ellis
David O'Connor (Royal Agricultural University)

Keywords:
ocean alkalinity enhancement, greenhouse gas removal technology, environmental, social, impacts

Research contractor:
Eunomia Research & Consulting
37 Queen Square, Bristol, BS1 4QS
+44 117 917 2250

Environment Agency's Project Manager:
Dr. Catherine Bayliss

Project number:
SC230003/R11

Citation:
Environment Agency (2025) Ocean alkalinity enhancement - evidence on potential environmental impacts and social implications. Environment Agency, Bristol.

Research at the Environment Agency

Scientific research and analysis underpins everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

This report is the result of research commissioned by the Environment Agency's Chief Scientist's Group, as part of SR21 Net Zero funded research.

You can find out more about our current science programmes at https://www.gov.uk/government/organisations/environment-agency/about/research

If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Dr Robert Bradburne
Chief Scientist

Contents

Introduction

This research is part of a series of reports, which aim to collate and review current evidence on the potential environmental impacts and social implications of five greenhouse gas (GHG) removal technologies: ocean alkalinity enhancement, enhanced rock weathering, biochar, bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS). This report synthesises the evidence relating to ocean alkalinity enhancement (OAE) and highlights the evidence gaps. The carbon removal efficacy of each GHG removal technology, and the economic impacts of their implementation, are not explored in this research.

The structure of the report is as follows:

- A description of how the OAE technological process functions and the various forms of OAE
- Synthesised evidence on potential environmental impacts of application of OAE
- Synthesised evidence on potential social implications of application of OAE
- A summary of the evidence and identification of evidence gaps

The findings in this report are based on a review of the published and grey literature. The approach to identifying, collating, and synthesising the available information is described in the Appendix.

A non-technical short summary of this research is also provided as a separate document.

Overview of ocean alkalinity enhancement

This section provides an overview of OAE, describes the various forms of the proposed technology, the spatial constraints on their implementation, and context on their current commercial maturity in the UK and globally.

Description

Ocean alkalinity enhancement is intended to be a deliberate, large-scale action aimed at counteracting climate change through the direct removal of carbon from the atmosphere and storing it within the oceans. The process involves enhancing the alkalinity of seawater (increase the pH level) through the introduction of alkaline OAE materials, such as carbonate or silicate compounds. The resulting change in seawater alkalinity causes more atmospheric carbon dioxide (CO_2) to transfer into the ocean through in-gassing, via a series of reactions shown in Figure 1. These reactions convert dissolved CO_2 into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, which in turn causes the ocean to absorb more CO_2.

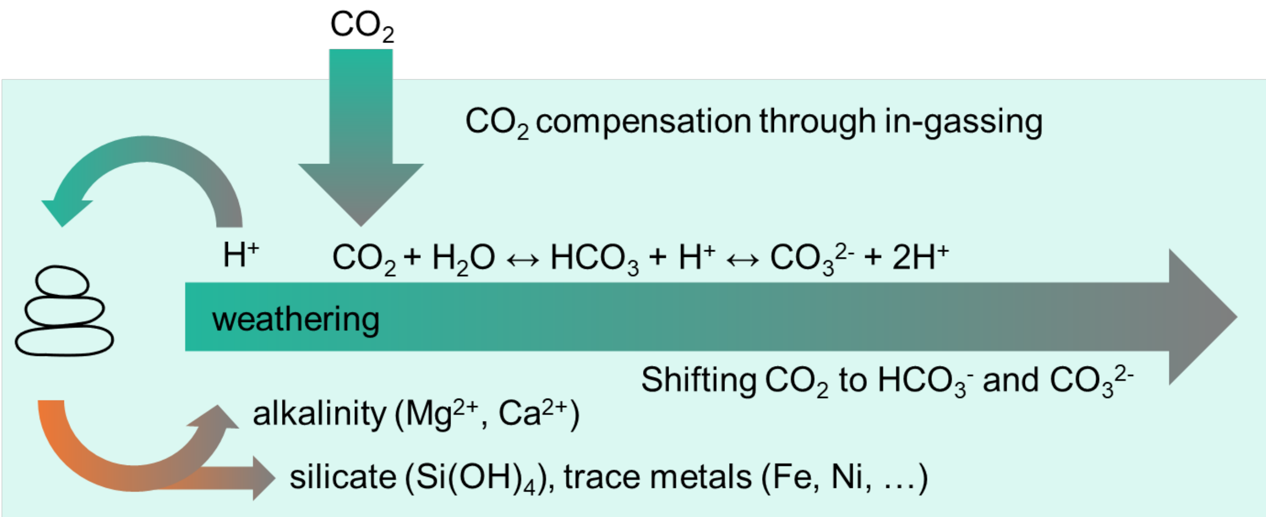

Figure 1 Carbon dioxide removal from the atmosphere through in-gassing to the ocean. The process is enhanced by the dissolution of OAE minerals (e.g., calcium oxide, olivine) which consume hydrogen ions (H+). This shifts the carbonate chemistry equilibrium from CO_2 to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. This facilitates additional CO_2 absorption to maintain the chemical equilibrium, due to CO_2 undersaturation relative to the atmosphere (Figure adapted from Bach et al. 2019).

Enhancement of seawater alkalinity for OAE purposes is achieved through the introduction of alkaline minerals. These can include: silicate; carbonate; the oxide and hydroxide forms of alkali metals like sodium and potassium; or alkaline earth metals such as calcium (Ca) or magnesium (Mg). The OAE process can sequester carbon but also combat ocean acidification – the observed trend in rising global seawater pH due to higher levels of atmospheric CO_2. OAE has similar principles to enhanced rock weathering, which involves spreading rock dust containing silicate and/or carbonate minerals onto land to accelerate the rock weathering processes that consume CO_2 (Bach et al., 2019). OAE differs from the concept of ocean fertilisation, which is another marine-based GGR technology involving the addition of nutrients (often iron) to the ocean to boost marine photosynthesis, increasing carbon dioxide removal from the atmosphere (Strong et al., 2009).

Technical process

Once atmospheric CO_2 is absorbed by the ocean, it reacts with water to form carbonic acid (H_2CO_3). This process acts as a source of seawater acidity by releasing protons (H^+), as the carbonic acid dissociates into bicarbonate (HCO_3^-) and hydrogen (H^+) ions, and then eventually into CO_3^{2-} and $2H^+$ (Figure 1). The oceans naturally regulate the increase in acidity, as hydrogen ions (protons) are consumed by alkaline inorganic compounds in the seawater column. These minerals, such as calcium carbonate, are introduced into the ocean through processes like rock weathering and hydrological cycles over geological timescales. Moreover, the resulting chemical imbalance from the relative proton deficit, causes the equation in Figure 1 to favour the production of more H^+ by consuming additional CO_2 (Bach et al., 2019; see Figure 1). This creates a deficit in dissolved CO_2, which causes more CO_2 to be absorbed from the atmosphere (Bach et al., 2019). In this way, the ocean acts as both a natural sink for CO_2 and acidity, playing a crucial role in global carbon cycling.

However the increased atmospheric CO_2 levels due to anthropogenic emissions have resulted in a declining trend in ocean pH levels – a process known as ocean acidification. This acidification causes a decrease in the saturation level of calcium carbonate in the ocean (Ma et al., 2023), a mineral essential for marine organisms like phytoplankton. Many plankton rely on calcium carbonate for constructing shells and for their overall health. Furthermore, phytoplankton play a vital role in atmospheric carbon fixation through photosynthesis and facilitate carbon storage in the deep ocean. Thus, ocean acidification has serious implications for marine ecosystems and the global carbon cycle (Honjo et al., 2013).

The OAE process leverages the natural acidity buffering capacity of the ocean to accelerate the removal of carbon from the atmosphere. It does so by boosting the supply of reactive alkaline inorganic compounds in the seawater environment. Furthermore, the reactivity of the rock minerals used can be enhanced artificially through methods such as reducing their particle size via grinding, converting them to more reactive compounds, or by using dissolved forms in solution.

To achieve overall net carbon removal, the CO_2 deficit in seawater from OAE must be compensated by CO_2 transfer from the atmosphere (Bach et al., 2019). Ideally, an equivalent amount of CO_2 that could react with the alkali OAE agent is absorbed from the atmosphere to the ocean, thereby reducing atmospheric CO_2 (Figure 1). However, this process can take several years to achieve, depending on the ocean context (e.g. mixing rates) and the OAE technology used (Bach et al., 2019; Foteinis et al., 2023) – though the rate of reaction can be accelerated by the introduction of concentrated CO_2 sources, such as the outputs of BECCS or DACCS processes.

Forms of OAE

There are various forms of OAE, separated based on distinct chemical principles that rely on different industrial processes, and they have different environmental and socio-economic implications. The methods of distributing OAE agents to the ocean include injecting alkaline liquids into the water surface, spreading solid alkaline particles from ships, pipes or other platforms, dispensing minerals to coastal environments, and removing acid from seawater electrochemically (Eisaman et al., 2023). Most forms of OAE have a Technology Readiness Level (TRL) of between 4-6 (Eisaman et al., 2023) on the 1-9 TRL scale (1 being basic principles observed and 9 being a proven system). In the UK, OAE projects are currently being researched at the trial stage (e.g., in south-west of England) and have not yet reached technological maturity required for full deployment.

Forms of OAE include:

- Crushed Mineral Application (TRL 4-5)
- Accelerated Weathering of Limestone (AWL) (TRL 5-6)
- Ocean Liming (TRL 5)
- Hydrated Carbonate Minerals (TRL 1)
- Electrochemical Brine Splitting (EBS) (TRL 6)
- Waste Metal Slag (TRL 3-4)

Crushed mineral application

Silicates

The chemical breakdown (e.g., natural weathering) of silicate rocks, like basalt, releases base cations (e.g. Ca^{2+} and Mg^{2+}) that react with atmospheric CO_2 to form secondary minerals. In nature, this process occurs over geologic timescales, and effectively traps, or sequesters, carbon in rocks (Renforth & Henderson, 2017). For example, olivine reacts with CO_2 to form magnesium carbonate:

$Mg_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2MgCO_3 + H_4SiO_4$

The divalent cations (e.g., Mg^{2+}) released must be compensated by two negative charges for the reaction chemistry to balance. If silicates are transported to the ocean, this is achieved through the production of bicarbonate ($2HCO_3^-$) via a reaction between CO_2 and water (H_2O). Stoichiometrically, two CO_2 molecules are required for each divalent cation introduced, though in reality the efficiency would be slightly lower (Renforth and Henderson, 2017). This oceanic process is more favourable than weathering in the terrestrial environment, where only one CO_2 molecule is sequestered for each cation (according to the balanced equation above). This means that silicate used for OAE in oceans have greater carbon sequestration potential than if used on land (Renforth & Henderson, 2017).

Other factors that control the rate of silicate weathering and the availability of cations to take up CO_2, include the temperature, the rate at which reaction products are introduced and their specific surface area (Renforth & Henderson, 2017). Dynamic ocean waters may facilitate faster reactions than on land where runoff water may not be readily available. Also, the surface area of crushed silicates can be increased further in energetic coastal environments, due to wave and tidal action. Exploiting natural ocean energy to achieve silicate particle comminution, a process known as Coastal Enhanced Weathering (CEW) (Eisaman et al., 2023; Figure 2), has been proposed to reduce the amount of grinding needed (i.e., lower energy consumption). In 2022, the world's first trial of CEW was undertaken in New York, USA, by incorporating olivine silicate material into a beach environment.

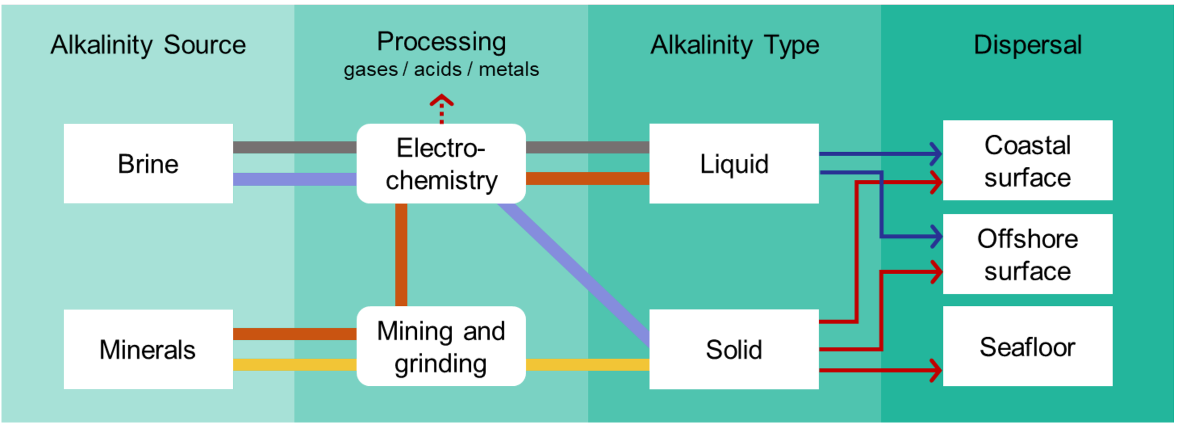

Figure 2 Categorisation of different OAE approaches by alkalinity source, processing method, alkalinity type, and dispersal location. Each pathway colour represents a unique approach. Dispersal location options are determined by alkalinity type. Liquid alkalinity is likely to be dispersed from the coastline due to its relatively low value per unit volume and mass, whereas solid alkalinity would likely be dispersed nearshore, offshore, or directly on the seafloor in shallow water, e.g., <100 m depth (Eisaman et al., 2023).

Carbonates

Applying carbonate minerals in the offshore surface ocean, as an alternative to silicates, offers the advantage of faster dissolution rates in water (Eisaman et al., 2023). However, ocean surface waters are naturally supersaturated with calcium carbonate (Orr et al., 2005, Renforth and Henderson 2017), meaning that limestone (calcite and dolomite forms of calcium carbonate) applied for OAE would likely remain in a solid form and not suitably dissolve (Eisaman et al., 2023). This problem may be addressed by applying the limestone to the deep ocean, where calcium carbonate is undersaturated. However, this entails technical challenges, including the part of the water column receiving the carbonates not being in contact with the atmosphere, thus not equilibrating with CO_2 (Eisaman et al., 2023). Alternatively, there are ways to convert carbonate minerals into more reactive species, as outlined below.

Accelerated weathering of limestone (AWL)

Accelerated weathering of limestone (AWL) involves the faster conversion of limestone to calcium bicarbonate ($Ca(HCO_3)_2$). This is achieved by dissolving limestone in seawater with high concentrations of dissolved CO_2 to produce calcium and bicarbonate ions (Eisaman et al., 2023). However, only a handful of AWL systems have been demonstrated so far and only at the feasibility of case-study or pilot scale. The largest of these currently is at a coal-fired power plant in Germany, where approximately 55% of flue gas CO_2 could be removed (Kirchner et al., 2020). The technological readiness level of AWL technology means that it is scoped out of further consideration within this report.

Ocean liming

Ocean liming (OL) overcomes the dissolution limitation of limestone by first calcining it at a high temperature (>800 °C) to produce CaO (lime). In order for CaO to deliver alkalinity to the ocean, it first needs to react with water to produce hydrated lime ($Ca(OH)_2$) (Moras et al., 2022). While this reaction happens naturally in the water column, it can also be industrially controlled so that the hydrated lime is added to the ocean directly (Moras et al., 2022; Eisaman et al., 2023). Other rapidly dissolving products have been suggested as liming agents, such as brucite ($Mg(OH)_2$) and magnesium oxide (MgO) (Fakhraee et al., 2023), which are also alkaline metal oxides with properties similar to CaO for delivering alkalinity to the ocean (Fakhraee et al., 2023). It should be noted that the production of lime from limestone releases CO_2 as a by-product of the reaction, necessitating its capture through carbon capture and storage (CCS) technology. If the CO_2 is released to the atmosphere, the life cycle carbon removal efficacy of OL will be substantially lower (Foteinis et al., 2022). In 2020, the first OL field experiment took place in Florida, USA (Voosen, 2022) and is thus considered to be at TRL 5 (Eisaman et al., 2023).

Hydrated carbonate minerals

Hydrated carbonate minerals, like the naturally occurring mineral Ikaite ($CaCO_36H_2O$), are an alternative to limestone that are undersaturated in the surface ocean (Eisaman et al., 2023), and could be dispersed at coastal or offshore locations (Figure 2). The use of naturally occurring hydrated carbonates is potentially more cost effective than other forms of ocean liming (OL), as they dissolve in their natural form and do not require energy-intensive chemical processing. However, they are relatively scarce in the natural environment, and stocks are insufficient to meet the feedstock demand of a scaled-up OAE industry (Eisaman et al., 2023). It has been suggested that hydrated carbonates could instead be industrially created and still be less energy demanding than the production of lime (Renforth et al., 2022; Eisaman et al., 2023). Currently this OAE method is only at the initial stage of basic principles, without a clear concept of the technological platform to deliver it (Renforth et al., 2022; Eisaman et al., 2023). Hydrated carbonate minerals are, therefore, scoped out of further consideration in this report.

Electrochemical brine splitting (EBS)

Electrochemical brine splitting (EBS) involves the production of hydroxide (OH^-) (e.g., NaOH) from seawater and brines (usually from desalination, hence derived from seawater), that act as an alkali agent for OAE purposes (see Figure 2). The advantage of this approach is the rapid delivery of alkalinity to the ocean with no solid phase to be dissolved and with the Na^+ and OH^- ions derived from the seawater itself. The net effect is to remove H^+ and Cl^- ions from the ocean directly during the production of NaOH (Eisaman et al., 2023). In this approach, the alkalinity is delivered through the OH^- ions, while the Na^+ and Cl^- ions provide the conductivity and charge balance needed for the process (Eisaman et al., 2023). This process is effective at reducing dissolved CO_2 due to reacting with CO_2 via two chemical pathways: 1) the OH^- ions react with CO_2 to form bicarbonate (HCO_3^-) and CO_2 reacts again with HCO_3^- to form H_2O and carbonate (CO_3^{2-}) ions; 2) when seawater equilibrates with atmospheric CO_2, the CO_2 reacts with H_2O and CO_3^{2-} in the first pathway to form HCO_3^-. As a relatively advanced OAE method, EBS achieves technology readiness level (TRL) scores of 5-6, with successful lab demonstrations having been carried out (Sharifian et al., 2021) and several start up companies deploying pilot demonstrations (Eisaman et al., 2023).

The EBS process produces hydroxides either via electrolysis or electrodialysis (removing ions from a solution by creating an electric field around the substance). Electrolysis is more energy intensive than electrodialysis and produces a more concentrated alkalinity source (Eisaman et al., 2023). The by-products of electrolysis are Cl_2 and H_2 gas. Whilst the H_2 is a valuable energy source, and would abate carbon emissions from industrial hydrogen production (NASEM, 2022), the Cl_2 produced is hazardous and difficult to dispose of, though it may be valuable for some industrial processes. The primary product of electrodialysis is hydrochloric acid (HCl) (Eisaman et al., 2023), which could be valuable, for example, for neutralising alkaline waste ponds in gravel and sand operations (Eisaman et al., 2023). One challenge to scaling-up EBS to provide gigatons of CO_2 removal per year will be finding large-scale uses of the by-products. Its use in pre-treating silicate rocks to enhance their CO_2 mineralisation capacity in enhanced weathering or OAE has also been noted (Eisaman et al., 2023).

Waste metal slag

Waste metal slag (e.g., blast furnace slag) from the iron and steelmaking industries is high in alkaline minerals (silicates and carbonates) and Ca and Mg ions, which could be beneficial for OAE purposes (NASEM, 2022; Li et al., 2020; Guo et al., 2023). However, slags require extra processing to remove their potentially toxic elements and other contaminants (Guo et al., 2023) before it can be safely applied to the ocean environment. We have found three experiments that investigated steel slag in the context of OAE, with one investigating the basic principle of higher CO_2 solubility in seawater enhanced with steel slag (Li et al., 2020), and two involving laboratory incubation experiments (Guo et al., 2023; Bach, 2024). This places waste metal slag OAE at TRL 3-4. No literature was found that focused on the environmental or social implications of repurposing slag for OAE. For this reason, this method is scoped out of further discussion.

Resources

The limiting factor among OAE alternatives is not typically resource abundance but rather the energy and engineering requirements to extract, process, and transport them to ocean waters. Limestone, for example, is a widely distributed and commonly extracted resource that is frequently used by various existing industries, with many tens of thousands of tonnes of reserves available for extraction globally (Caserini et al., 2022). Similarly, magnesium and iron-rich olivine minerals are abundant in many places (Caserini et al., 2022). Seawater for EBS is easily available and can be obtained as industrially produced desalination waste or harvested from geological fluids (Eisaman et al., 2023).

It is advantageous for OAE resources to be situated near coastlines where they are utilised, reducing energy consumption and transportation requirements. Nonetheless, spatial constraints can arise. For example, existing construction sites, recreation areas, nature reserves, and transport infrastructure that may also rely on the land area (Caserini et al., 2022). Moreover, sea level rise due to climate change poses a threat, potentially decreasing the available coastal area. However, there are extensive carbonate resources at various distances from the coast (Caserini et al., 2022), which makes it possible for resource operations to relocate and maintain proximity to the coast.

Proximity to other required resources or infrastructure is another consideration. For example, lime production from limestone requires kilns for calcination, along with carbon capture and storage (CCS) for optimal carbon removal efficiency (Foteinis et al., 2022). Long distances between mining sites and these facilities can increase the associated energy costs. Overland transportation has been identified as a key factor in Life Cycle Assessment (LCA) of OAE, emphasising the necessity for low-carbon transport infrastructure. The use of railways near the mining site are recommended to minimise the carbon footprint (Foteinis et al., 2022).

For mineral-based OAE to be ultimately successful as a carbon removal technology, mining operations will need to be significantly expanded (NASEM, 2022). A rough estimate suggests that to remove 1 gigaton (Gt) of CO_2 per year using any OAE mineral type, approximately 7Gt of extracted feedstock would be needed. For scale, this is roughly equivalent to the output of the global cement industry (NASEM, 2022; Renforth & Henderson, 2017). Additionally, Renforth & Henderson (2017) estimated it would take 20-50 years to develop a mining industry capable of producing 1Gt of feedstock annually based on growth of the cement industry.

For olivine deposits, although there are potentially hundreds of billions of tonnes of resources, most are situated far from coastlines, presenting transportation challenges (Caserini et al., 2022). Moreover, silicate rocks dissolve more slowly than carbonates (Eisaman et al., 2023), necessitating processing before application (Hangx and Spiers, 2009; Strefler et al., 2018; Eisaman et al., 2023). Grinding the minerals, for example, requires significant energy input which poses a practical and economic problem and a significant source of carbon emissions (Oppon et al., 2023). Coastal Enhanced Weathering (CEW) uses wave energy to break down the material into smaller particles, which avoids energy consumption and can be incorporated into coastal management schemes, such as beach nourishment (Foteinis et al., 2023). However, larger particles take longer to dissolve and the rate of CO_2 removal is decreased (Foteinis et al., 2023). These constraints render silicate use less suitable than other options for large scale OAE.

Another factor making silicate use less favourable is that it is potentially less efficient in delivering alkalinity to the ocean compared to other feedstocks. Fakhraee et al. (2023) investigated two silicates (Olivine and Basalt), MgO, and CaO, using a biogeochemical model, showing that alkalinity release in the upper 80m of the ocean was <10% for basalt, regardless of application rate. Alkalinity release from olivine was >20% and increased with higher application rates, but did not increase above 50%, even with high application rates and very small grain sizes. MgO was >80% effective regardless of application rate, while alkalinity release from CaO was effectively 100% for all application rates. Fakhraee et al. (2023) used these estimates to assess the impacts that OAE could have on global CO_2 removal at three application rates. They found that under a moderate emissions projection to 2100, basalt application would have virtually no effect on atmospheric CO_2 levels, while olivine sequestered roughly 1-7 Gt CO_2/year, MgO 7-23 Gt/year, and CaO 6-20 Gt CO_2/year. This suggests that silicate application is relatively ineffective at delivering alkalinity at a scale that can deliver climate-relevant carbon removal rates, while in contrast, the potential for MgO and CaO is more promising.

Environmental impacts

Successful OAE delivery requires the development of a complex industrial supply chain from source to the eventual ocean sink, encompassing multiple operational stages that are each associated with potential environmental impacts. The first operational stage is the sourcing of feedstocks. Secondly, the raw feedstock must then be transported to a processing plant where it is chemically or mechanically processed into an appropriate form, for example, by grinding or removing impurities. For minerals, overland transport is required, but for liquid feedstocks or slurries it can be transported via pipelines. Thirdly, the OAE material must then be transported to the application site via pipelines or ships. Finally, the processed feedstock is applied to the ocean where it can affect the oceanic ecosystems (NASEM, 2022). This section reviews the existing evidence on actual and potential environmental impacts associated with these four stages. While there are two transport stages, one before and one after industrial processing, these are considered together in the transport section.

As a technology that has not yet been widely implemented, research into the long-term environmental impacts for different forms of OAE has a limited evidence base. Hence, some sections below are limited in scope.

Sourcing feedstocks

Carbonates

The environmental consequences of expanding the mining industry to produce the feedstock required for mineral-based OAE are potentially very significant. For example, in India limestone mining has caused the destruction of thousands of hectares of woodland, heavy metal contamination of the soil environment and caused deterioration of local water quality (Lamare & Singh, 2016). Foteinis et al. (2022) conducted a life cycle impact assessment of producing hydrated lime from limestone incorporating 18 environmental impact categories. Limestone mining processes, including blasting, drilling and machinery use, only contributed ~1.5% of the GHG emissions (carbon footprint) and 13% of the overall environmental impacts. However, it dominated the land use impact as well as contributing to ozone formation, fine particulate matter formation, and terrestrial acidification associated with diesel powered machinery, dust emissions, and emissions from blasting. Hence the establishment of limestone-based OAE will need to ensure that the overall climate benefit (and any co-benefits) outweigh the environmental costs, either locally or abroad. The LCA by Foteinis et al. (2022) found that the overall impact of ocean liming had a net positive environmental impact due to the importance given to CO_2 sequestration for mitigating climate change.

Creating a limestone mining industry for OAE also requires substantial amounts of resources. For example, based on an inventory of inputs at five quarries in Algeria (Bendouma et al., 2020), producing 7 Gt of limestone feedstock would require 350-840 km^2 of land, equivalent to 22%-54% the area of Greater London. Renforth et al. (2013) estimated that this level of production would require an additional 23.9 km^2 of land per year, for 36 years to a total of 840 km^2. In terms of water usage, the Bendouma et al. (2020) findings imply that 10.9 to 31.6 billion litres of water would be required, approximately equal to the yearly consumption of 200-600 thousand people in England and Wales (Salas, 2023). In terms of energy consumption, based on the life cycle inventory of inputs presented by Foteinis et al. (2022), the energy required to produce 7Gt of crushed limestone is ~220 TWh, equivalent to ~70% of the UK's electricity generation in 2022. Each of these scaling issues could have wider environmental impacts.

Assuming 7 Gt of feedstock is required for each Gt of CO_2 sequestration, achieving 25 Mt of CO_2 per year by OAE would require ~175 million tonnes of limestone feedstock annually. A recent LCA study suggests that, when converted to hydrated lime, only 1.8 tonnes of limestone is needed for each tonne of CO_2 removal (Foteinis et al., 2022). However, this still equates to 44.65 million tonnes of limestone annually, approximately three times the 14.9 million tonnes of limestone and dolomite produced by the UK in 2021 (Mineral Products Association, 2023), to sequester 25 Mt of carbon by OAE. The energy required to produce 44.65 Mt of crushed limestone would be ~1400 Gwh and for 175Mt it would be ~9,800 GWh, approximately 3% of UK electricity generation. Most (77%) of this energy is required for grinding, while the remainder is mostly associated with diesel used in mining operations (Foteinis et al., 2022).

In the UK, it is estimated that the pure carbonate rock resource within 10 km of the coastline and to 25 m depth is ~373 Gt, and to a 200 km distance it is ~1,585 Gt (Caserini et al., 2022), which is likely an underestimate (Renforth et al., 2013). Assuming 5% of this resource is available for extraction, given land use limitations, there is ~79 Gt of limestone available for use in OAE in the UK alone. This could theoretically supply the global yearly requirement of 7 Gt for 11 years. The UK thus has a substantial and abundant limestone resource potentially available. Expansion of extractions at this scale is likely to increase local environmental implications, such as those mentioned at the start of this section.

Silicates

Total UK reserves of silicate rocks that can be extracted, is approximately 489 million tonnes (Madankan & Renforth, 2023). It has been estimated that silicates sequester ~0.8 kg CO_2 per kg of rock (Foteinis et al., 2023). In practice, however, there are additional inefficiencies (Renforth & Henderson, 2017; Foteinis et al., 2023). Nonetheless, using this conversion ratio equates to a maximum of ~391 Mt CO_2 sequestration from UK-mined silicates. Assuming the 7:1 ratio of rock per unit CO_2 sequestered, the CO_2 sequestration potential is ~70 Mt.

Regarding energy usage, if the silicates are used for Coastal Enhanced Weathering (CEW), relatively large particle sizes could be applied to coastlines, thereby, avoiding the need for energy intensive grinding. Assuming grinding to a 1 mm particle size, delivering 25 Mt CO_2 sequestration would require 220-1,510 GWh of energy, which is favourable compared to the equivalent figure for limestone (1400-9,800 GWh) (Foteinis et al., 2022; 2023). Over half (~55%) of this energy is diesel use by heavy machinery for mining, which is unlikely to be replaced by cleaner fuel alternatives in the near future. Moreover, if a 100 µm particle size is needed for CEW, as per limestone production, the total energy consumption would increase by a factor of three. For 10 µm, it increases by a factor of 11, making it substantially more energy intensive than crushed limestone production under a 7:1 rock:CO_2 removal ratio (Foteinis et al., 2023).

The LCA by Foteinis et al. (2023) assumed a 10 µm particle size, finding that the environmental impacts were initially net negative (i.e., the costs were greater than the benefits). This was mainly associated with power consumption for grinding (~54% of the overall footprint) using the European energy grid as a reference. Quarrying contributed ~17%, associated with ozone formation, fine particulate matter formation, and terrestrial acidification. However, within months the benefit of CO_2 sequestration by OAE outweighed the overall environmental costs. Furthermore, a scenario assuming a hydropower energy source halved the overall environmental footprint and lowered the contribution of feedstock grinding to only 7.1%. Another consideration is that while the adoption of a larger particle size would substantially reduce the electricity consumption, it would require ~37 years to negate the environmental cost. This is due to the longer time taken for the natural weathering processes to sequester carbon.

One case study looking at potential environmental impacts of crushed silicate production for eight countries, including the UK (Oppon et al., 2023). They found that for the UK to produce 1 unit of crushed silicate feedstock, 30% of the total energy and materials consumption would need to be imported, which was the highest of all countries investigated. This suggests that developed countries, and specifically the UK, might transfer their negative environmental externalities associated with the production of silicate feedstocks to other countries.

Electrochemical brine splitting (EBS)

Assuming EBS were to process a similar volume of seawater as the current global level of desalination, amounting to 16,876 desalination facilities, and an energy consumption of 50-1,600 GWh per year (Eke et al., 2020), it could remove ~90 Mt of CO_2 per year (NASEM, 2022). These figures are favourable to CEW and OL, though a comprehensive LCA on EBS has not yet been completed (NASEM, 2022), and the full life cycle environmental impacts of EBS cannot be compared to other OAE methods. Nonetheless, energy consumption is the main factor of the carbon footprint of EBS (NASEM, 2022;

Campbell, 2023), implying that the carbon impact of EBS would be highly efficient compared to other forms of OAE.

Summary: There is a high abundance of mineral feedstocks for OAE in the UK. However, the establishment of a mining industry to exploit these resources for climate relevant OAE is likely to require energy, water and land resources on the scale of the consumption of a small country. An EBS industry would use considerably less energy than a mineral-based OAE industry.

Transportation of feedstocks and OAE materials

Carbonates

While there are abundant limestone resources near coastlines in the UK (Caserini et al., 2022), the potential need to deliver raw limestone to processing plants where can be calcined into lime, is a factor that could increase transportation distance (Eisaman et al., 2023). The repurposing of the spare capacity of the cement production industry for calcination has been discussed in literature (Renforth et al., 2013; Campbell et al., 2023). There are 12 cement production plants in the UK (MPA Cement, 2024) co-located with limestone quarries, of which eight are located <55 km from the coast, and 3 of the remaining inland plants are accessible by rail (MPA Cement, 2024; BGS, 2014). This raises the possibility of exploiting potential spare cement capacity for OL purposes in the UK. However, the CO_2 produced by the calcination process needs to be captured and stored, e.g., in a geologic reservoir (Renforth et al., 2013). This may influence the location of calcination plants and hence transport distances since there are spatial constraints on the location of available CCS and CO_2 reservoirs.

Studies looking at the impacts of transporting carbonate feedstocks to the ocean suggest that this will have a relatively minor environmental impact compared to the wider impacts of carbonate-based OAE (Renforth et al., 2013; Harvey et al., 2008; Caserini et al., 2021; Foteinis et al., 2022). Sea freight provides an opportunity for large scale distribution of lime into the surface ocean by augmenting existing vessels (Renforth et al., 2013). Assuming lime delivers CO_2 sequestration at a ratio of 1:1 (Paquay & Zeebe, 2013; Foteinis et al., 2022), the energy needed to distribute enough lime to sequester 25 million tonnes of CO_2 is ~692.5 GWh (Renforth et al., 2013). Additionally, Renforth et al. (2013) estimated that 101 dedicated ships would be needed to deliver 1 Gt of lime to the ocean per year, however, another study estimated 1000 ships are required for delivering 1.3 Gt of slaked lime per year (Caserini et al., 2021). For the addition of the 1 Gt of pure limestone powder, it has been estimated that 750 ships would be required (Harvey, 2008), with the difference between lime and limestone being largely associated with solubility differences of the two feedstock types (Renforth & Henderson, 2017). Nonetheless, all estimates represent a minor impact on transportation demand given that there are tens of thousands of active ships globally with a very high potential for discharging slaked lime (Caserini et al., 2021). The removal of 1 Gt of CO_2 per year implies the use of 20-40% of the existing fleet of bulk carrier and container ships when repurposed for slaked lime distribution (Caserini et al., 2021).

An LCA of OL by Foteinis et al. (2022) found that transportation contributed 4% of the total life cycle GHG emissions, which was related mainly to road transport (3%) including low-sulphur diesel used by trucks. Ship transport made up 1% of emissions, mainly due to electricity consumed in loading and other dockside operations, rather than ferrying at sea. To achieve 25 Mt of CO_2 removal with OL, the total energy consumption from trucking and ship loading, dockside operations, and ship transport is ~395-2,800 GWh (Foteinis et al., 2022). Transportation contributed 5% to the overall environmental impacts, the majority being impact to human health from the combustion of fossil fuels. This highlights the relatively low expected impact of transportation in the overall environmental impact of an OL industry, with the potential to be reduced further by transitioning from fossil-fuel based electricity grids and diesel consumption, towards renewable energy sources.

Foteinis et al. (2022) also conducted a sensitivity analysis to explore the effect of varying the transport distance and replacing truck-based overland transport with trains. Mining at or near to the port reduced carbon and environmental footprints by 3.1 and 4.2%, respectively, while switching from truck to train transport reduced these by 2.2 and 2.8% respectively. Increasing the transport distance from 65 km in the base scenario to 520 km using trucks for transport increased the carbon and environmental footprints by 22% and 25.3% respectively, In the UK context, it is unlikely that road transport distances would reach this extended value, unless calcining plants were located far from both the coastline and the limestone mining sites creating an inefficient supply chain.

Silicates

Similar to carbonate-based OAE, the distance from the coast to where silicates are mined influences the overall environmental impact due to overland transportation. Foteinis et al. (2023) investigated the life cycle impact of Coastal Enhanced Weathering (CEW) using an olivine feedstock, following a method similar to Foteinis et al. (2022). The energy required for 25 Mt CO_2 sequestration was estimated at ~50-348 GWh. This is a relatively low figure compared to OL, which is related to the fact that olivine was assumed to be spread via marine vessels nearshore, limiting the need for bulk carrier shipping across open ocean (Foteinis et al., 2023). Further, this figure may be an overestimate because it was noted that olivine could be spread on land at the coastal zone, negating the need for maritime transport altogether. However, the logistics, associated energy and environmental costs of terrestrial spreading remains unclear.

A life-cycle assessment by Foteinis et al., (2023) found that the overall environmental impact was dependent on transportation distance, finding that an increase in distance from 50 km to 250 km or 500 km would increase the total environmental footprint by 22.6% and 50.84%, respectively. However, at 50 km distance from the coastline, transportation contributed only 5.6%. In the UK, most available silicates fall within 100 km of the coastline (Madankan & Renforth, 2023). Hence the impact of transportation is only a minority of the overall environmental impact of a potential CEW operation in the UK, unless locations used for comminution are for some unforeseeable reason located far from the mining sites. Indeed, the LCA by Foteinis et al (2023) assumed a 10 km transport distance from the mine to the rock crushing plant as a base assumption.

EBS

Energy is required to transport EBS inputs, including seawater or waste brine from desalination plants, to EBS processing plants via pipelines and then to pump the processed alkaline solution to the ocean. However, the amount of energy consumed is unlikely to be significant in terms of environmental impact or energy demand since desalination plants are favourably located near to coastlines. Indeed, ~80% of desalination brine is produced within 10 km of the coastline (Jones et al., 2019). Furthermore, ocean disposal of waste brine from desalination is the dominant disposal method of current desalination operations (Jones et al., 2019), providing an opportunity to exploit the existing infrastructure for OAE purposes. Waste brine could be transported to an EBS plant and existing submerged pipes for brine disposal used for final dispersion of alkalinity to the ocean (Campbell et al., 2023).

Summary: A key theme amongst all OAE methods is that minimising overland transportation is favourable for the overall transport related environmental impacts. Hence, co-locating feedstock sourcing and processing operations together, and locating these close to ports, is beneficial for this purpose. In the UK, potential OAE feedstock inputs are located close to coastlines, so this should be feasible to achieve.

Processing of feedstocks

Carbonates

A LCA by Foteinis et al. (2022) found that calcination of limestone to produce lime was the main driver of GHG emissions in OL, with gas (methane) burning contributing 66% of the total life cycle GHG emissions. Calcination also had the largest environmental impact score (42% of the environmental footprint), which was mainly associated with damage to human health primarily due to methane combustion. As discussed, the existing UK cement industry could be repurposed to produce lime for OAE, which could avoid additional impacts. The annual limestone processing capacity of UK cement plants is currently ~17.1 Mt (BGS, 2005; 2014). By unrealistically assuming that all this capacity is used for limestone calcination, this would still only account for ~10-39% of the input required for 25 Mt CO_2 removal under OL. Hence, significant additional calcination facilities would be needed along with their associated environmental impacts.

Foteinis et al. (2022) also found that CCS was the next highest impact category for OL due to its energy intensity, contributing 23% to the overall carbon footprint and 32% to the environmental footprint which also mostly came from damage to human health due to fossil fuel combustion for electricity.

To capture 25 Mt of CO_2 by OL would require 5,270-37,000 GWh of energy to process crushed limestone into lime, a further 4,370-31,000 GWh of electricity for CCS, and 190-1,340 GWh for the hydration of lime (Foteinis et al., 2022). It is important to note that these higher estimates assume a 7:1 ratio of rock:CO_2 removal, which may not be the case in a UK context given an abundance of high purity limestone (Caserini et al., 2022). A ratio of 1.786:1 crushed limestone:CO_2 removal conversion was used in Foteinis et al. (2022).

In total, 11,600-82,000 GWh (3.6%-26% of UK electricity production in 2022) would be needed to produce 25 Mt of CO_2 sequestration from OL when accounting for the mining, crushing, lime production, hydration, CCS energy, and transportation energy.

CEW avoids the need for such energy and associated carbon emissions and environmental impacts because it does not require any further chemical processing or CO_2 management once ground to an appropriate size for application to coastlines. CEW using 100 μm particles has a total energy requirement of 710-4,850 GWh for just the mining, grinding, and transportation (Foteinis et al., 2022; 2023).

EBS

Using the electrolysis method, EBS generates roughly 1 tonne of chlorine gas per tonne of CO_2 removed. With the current market for chlorine at around 60-70 Mt per year, a scaled up EBS industry must find new ways to manage this by-product (NASEM, 2022). For example, chlorine can be combined with hydrogen to produce hydrochloric acid (HCl), which can further react with silicates to form salts (NASEM, 2022), thereby expanding the scope of possible waste management pathways for EBS.

Wastewater condensates are generated by brine purification and treatment processes, as well as bleach from chlorine gas absorption systems (NASEM, 2022). According to NASEM (2022), industrial-scale EBS facilities are expected to generate wastewater, however, the generation and treatment of EBS wastewater is not covered in the available literature.

Summary: The energy required to covert limestone into hydrated lime for OL is more than 3 times higher than the energy used in the limestone mining process. Climate-relevant EBS will need to find new ways to manage the megatonnes of chlorine gas that will be produced as a by-product, in addition to safe management of wastewater streams.

Impacts of OAE application to the ocean

Impacts relevant to all OAE technologies

OAE materials would be applied at specific locations, as it is impractical to spread them evenly over entire oceans (Bach et al., 2019; Caserini et al., 2021). Consequently, alkalinity will be delivered at point sources or localised areas at high concentrations, likely resulting in greater environmental impacts nearer to the application source, which then dissipate further away (Köhler et al., 2013; Bach et al., 2019; Caserini et al., 2021). Bach et al. (2019) identified three areas where alkalinity would be concentrated: in the wakes of ships dispersing OAE materials into the ocean, in the region of on- or offshore platforms that release OAE materials, or beaches / shallow shelf seas where OAE materials may be placed to exploit wave energy and natural water mixing that facilitates equilibration between seawater and air (e.g. CEW).

Modelling indicates that localised pH increase in the wake of a ship dispersing hydrated lime fluid into the surface ocean would be less than 1.5 units. At high discharge rates, pH changes exceeding 1 unit would persist for only a few minutes, while at low discharge rates the pH variations would be less than 0.2 units at distances of 1.4-1.6 km from the point of discharge (after 230-330 seconds) (Caserini et al., 2021). The authors noted that it is common for seawater pH to naturally fluctuate by 0.2 units in a diurnal cycle (Caserini et al., 2021; Schulz & Riebesell, 2013), implying that this may have little effect on ocean biogeochemistry and the ecosystem. However, a lack of empirical evidence on these effects and their potential environmental impacts under real-world conditions makes this an uncertain conclusion.

Alkalinity increase

As discussed in the introductory sections, the conversion of CO_2 into carbonate and bicarbonate ions via OAE leads to a deficit in dissolved CO_2 in the water column, which is replenished by equilibration with air. Realistically, there will be a lag in achieving equilibration, depending on various factors such as the amount of turbulence and mixing in the water column, the concentration of the alkalinity agent added, the area over which the alkalinity is spread (e.g., whether from a point source) and the rate at which CO_2 reacts with the alkalinity source.

As CO_2 is used in photosynthesis, a decrease in dissolved CO_2 in seawater could inhibit primary production in the water column (Riebesell et al., 1993; Bach et al., 2019), potentially reducing the availability of food for photosynthetic plankton and slowing their growth rates (Bach et al., 2019). However, if complete equilibration of seawater receiving OAE materials with air and mixing with fresh seawater is attained, the CO_2 limitation may be considered insignificant in the overall productivity of marine ecosystems across large ocean regions (Bach et al., 2019). Nevertheless, localised short-lived reductions in CO_2 saturation and high pH levels at specific locations of OAE delivery may affect local ecosystem species composition, possibly causing knock-on effects on wider marine ecosystems and potentially leading to altered biogeochemical processes (Bach et al., 2019). For example, plankton blooms in areas of high OAE perturbations might be dominated by smaller species better suited to low CO_2 concentrations, potentially reducing the transfer of organic carbon to the deep oceans (Bach et al., 2019).

Increased alkalinity is expected to have a disproportionate effect on calcifying marine organisms by significantly enhancing ocean conditions for calcification. This is because the resulting lower CO_2 concentrations and lower acidity increases the concentration at which calcium carbonate is saturated in the water column (Bach et al., 2019). Calcifying plankton species may gain an energetic advantage over other species, such as silicifying marine organisms (e.g., diatoms), that could result in larger calcifying populations, and shifts in species composition among primary producers. Such changes can potentially affect biogeochemical carbon fluxes between the deep oceans and atmosphere.

Biological calcification transforms dissolved calcium carbonate into a precipitated solid form, effectively reducing the available alkalinity in the ocean that can react with CO_2. Therefore, a potential increase in biological calcification induced by OAE may diminish the carbon removal efficiency of OAE over time (Bach et al., 2019). Each unit of $CaCO_3$ produced causes alkalinity to be reduced by two units in the ocean, acting as an "alkalinity sink" and making it more difficult to achieve OAE (Bach et al., 2019). Low rates of dissolution for $CaCO_3$ would result in the solid form sinking to the deep ocean rather than dissolving at the surface, where it could remove atmospheric CO_2 (Bach et al., 2019). However, this effect could also facilitate the transport of organic carbon created through photosynthesis, sequestering atmospheric carbon in the deep ocean (Bach et al., 2019). It is unclear how these varied impacts might affect the overall efficiency of OAE.

Summary: OAE feedstock will most likely be applied to the oceans in concentrated form at specific locations, potentially resulting in spatial hotspots of higher environmental impacts. By increasing alkalinity, OAE risks diminishing dissolved CO_2 levels in seawater, which can reduce photosynthesis and compromise the basis of marine food chains. Additionally, because different plankton species respond differently to changes in alkalinity, OAE may cause changes in ocean plankton composition, which has implications for the carbon cycle as well as the long-term effectiveness of OAE.

Silicates

Trace elements

Silicate minerals are commonly impure, containing various trace elements such as copper, nickel, iron, chromium and cadmium (Bach et al., 2019). Such impurities can have potentially toxic effects on marine organisms and induce various biogeochemical perturbations to the oceans (Bach et al., 2019). There are many uncertainties around the effects these could have at the scale being discussed for OAE, but various hypotheses have been outlined which are discussed below.

Silicate rocks typically contain iron, which, when used for OAE, would be released into the ocean water (Taylor et al., 2016; Bach et al., 2019). Dissolved iron concentrations in ocean surface water are generally a limiting factor on photosynthesis (Moore et al., 2013; Bach et al., 2019) and additions of a few tonnes of iron in certain regions may trigger plankton blooms that are so large they would be observable from space (Boyd et al., 2007; Bach et al., 2019). There is evidence suggesting that the increase in productivity resulting from iron released from silicate addition would increase OAE efficiency, though this aspect is poorly understood (Bach et al., 2019). There are also concerns around iron addition in areas that are not iron-limited, which, counterintuitively, could decrease the overall amount of dissolved iron, resulting in lower productivity (Bach et al., 2019). Nitrogen is often limited along with iron in the oceans. Therefore, iron addition could increase the number of photosynthesising microorganisms that are a capable of nitrogen fixing, thereby potentially affecting the composition of plankton communities (Bach et al., 2019).

Nickel, a trace metal abundant in silicates (Bach et al., 2019), could significantly increase in concentration at OAE silicate addition points, potentially causing toxicity to marine organisms (Bach et al., 2019). Foteinis et al. (2023) noted that spreading of crushed silicate rock on coastlines was associated with nickel releases in the water column, with coastal spreading contributing 29.5% of the overall lifecycle environmental footprint. Marine ecotoxicity due to nickel release was ~70% of this impact. Over time, dilution in the ocean water would lead to a reduction in nickel concentrations, and could result in a fertilising effect on certain nitrogen-fixing bacteria in places where nickel is limited. It is hypothesised that modest increases in dissolved nickel could enhance marine productivity in certain locations (Bach et al., 2019). Nonetheless, marine ecotoxicity associated with nickel release has also potential impacts on human health, with the Foteinis et al. (2023) reporting that nickel released in the ocean was linked with a carcinogenic effect on humans.

Other trace metals, such as chromium (Cr), copper (Cu) and cadmium (Cd), can also be released following the use of silicates for OAE, leading to them bio-accumulating and causing toxicity in food chains, eventually affecting humans (Bach et al., 2019). The LCA conducted by Foteinis et al. (2023) also highlighted carcinogenicity to humans associated with the bioaccumulation of heavy metals following coastal spreading of silicates. Thus, it is important to ensure OAE materials contain safe concentrations of these metals (Bach et al., 2019), which constrains the geologic resources available for silicate-based OAE. Alternatively, safe levels could be achieved through extra processing of contaminated silicates, but this will increase costs and energy use, potentially counteracting the carbon benefits. The importance of safeguarding the ocean environment from contaminants underscores it as a decisive factor in the selection of OAE technology and material type (Bach et al., 2019).

Summary: Silicate-based OAE is likely to release various trace metals into the ocean including iron, nickel, chromium, copper and cadmium. At appropriate concentrations, iron and nickel may have a fertilising effect that could increase ocean productivity and enhance OAE effectiveness, while other trace metals can bio-accumulate and cause toxicity to food chains, so release of these may need to be controlled.

Effects on ocean ecosystems

The use of silicate rocks for OAE can increase the concentration of dissolved silicate, an essential nutrient for certain globally distributed plankton species that is deficient in modern ocean waters (Sarmiento et al., 2004; Bach et al., 2019). Using silicates for OAE could alleviate this deficiency, and it is unclear what effects this could have on their proliferation and growth. Some hypotheses include faster growth rates of silicate-dependent plankton species, leading to species composition shifts and greater abundances (Bach et al., 2019). It is unclear how this would interact with the increase in alkalinity that favours calcifying plankton, but Bach et al. (2019) hypothesise that it would lead to silicifying plankton outcompeting carbonate-based species, leading to a greater efficiency of OAE, as more alkalinity remains unused by marine organisms in the surface oceans and is thus chemically available, in contrast to the “alkalinity sink” described above with calcifiers (Bach et al., 2019). The lack of empirical evidence observing such effects, and the complexity and uncertainties associated with ocean, atmosphere and ecological feedbacks at the global scale makes it difficult to estimate the magnitudes of these potential effects, or the timescales involved.

The study by Fakhraee et al. (2023) also modelled the effects of different feedstocks on the organic content of marine particles and the rates of feeding and faecal pellet production by marine zooplankton. Zooplankton and their faecal pellet production are important for the distribution of organic carbon in the ocean, affecting nutrient abundance and food availability at the base of the marine food chain. They found that the average organic content of marine particles reduced by over an order of magnitude when applying olivine or basalt, even at relatively low rates of application. This was due to a lower relative organic matter content of marine aggregates due to the higher abundance of slowly dissolving mineral particles. This in turn led to a significant decrease in zooplankton feeding and faecal pellet production. Silicate-based OAE may therefore have a negative effect on nutrient availability to primary producers, thereby limiting nutrients throughout marine food chains from the base upwards.

An LCA by Foteinis et al. (2023) for CEW identified environmental impacts of coastal spreading associated with particle sizes that are important to consider. Namely, there is potential for small particle sizes to cause silt pollution in coastal ecosystems with potential knock-on effects e.g. on light penetration and turbidity in the water column. Additionally, there is an associated concern around potential damage to human health, especially of local communities located close to sites of application. Conversely, one benefit of using larger particles for CEW was that they may have the benefit of being able to be integrated into coastal beach nourishment schemes, where large amounts of sand are needed to combat erosion.

Summary: Using silicate-based feedstocks for OAE could alleviate nutrient deficiency among silicate-dependent plankton species in the oceans, causing them to out-compete other species. Conversely, silicate-based OAE may have a large negative effect on organic carbon availability, hence nutrient abundance and food availability in the ocean, with potentially severe negative consequences for marine food chains. Also, small particle sizes used for coastal spreading of silicates may cause silt pollution in coastal systems and could damage human health.

Carbonates and ocean liming

Secondary carbonate precipitation

An environmental concern with carbonate-based OAE is the potential for dissolving $CaCO_3$ in seawater to the point of saturation. This then causes $CaCO_3$ to precipitate, through an abiotic processes known as secondary precipitation (Moras et al., 2022). This poses a risk of increasing ocean pH (as discussed in the section on biological calcification) and increased CO_2 saturation, opposite to the goals of OAE. Moras et al. (2022) investigated this effect in seawater using CaO and $Ca(OH)_2$, finding an increase in total alkalinity (500 μM/kg) resulted in the precipitation of calcium carbonate minerals (aragonite). During this process, the added alkalinity was completely removed, along with significant amounts of the alkalinity initially present in seawater (termed ‘runaway precipitation’). This led to a reduction in CO_2 uptake potential from 0.8 mol/mol of alkalinity added to only 0.1 mol/mol (88% lower). They also observed that runaway precipitation could continue even after seawater alkalinity had depleted to levels where no precipitation was observed in other experiments. Runaway precipitation not only exacerbates ocean acidification but also reduces the CO_2 uptake efficiency. Therefore, the conditions that induce runaway precipitation through OAE must be avoided. Moras et al. (2022) found that 250 μM/kg of alkalinity addition did not induce $CaCO_3$ precipitation, suggesting this is likely a safe threshold limit. It should be noted, however, that this experiment was conducted at 21°C, and regional specific data would be needed to set thresholds.

Moras et al., (2022) also noted that a high sediment load (e.g., as present in coastal settings) increases the likelihood of precipitation. This is attributed to suspended particles providing platforms for $CaCO_3$ to precipitate onto. Factors that reduced the chances of precipitation occurring included:

- mixing and dilution of alkalinity-enriched seawater with the surrounding seawater by coastal tides or in the wake of ships;
- ensuring seawater CO_2 is constantly equilibrated with air prior to and during the addition and dissolution of OAE materials. This ensures that the CO_2 consumed by

the alkalising agent is immediately replenished, preventing an increase in pH that risks precipitation, and;

- targeting low temperature waters for OAE due to higher CO_2 solubility.

Even with alkalinity application rates well below a safe threshold, to avoid precipitation of calcium carbonates when applied to coastal zones, Moras et al. (2022) estimated that 550 Gt of CO_2 could still be removed from the atmosphere between 2020 and 2100. This amounts to a drop of ~260 ppm in atmospheric CO_2. Given that the experiment by Moras et al. (2022) was conducted at 21°C, safe limits for alkalinity addition is likely to be higher in UK waters for most months of the year. For comparison, a simulation of various alkalinity addition levels based on the findings in the Moras et al. (2022) estimated that ~3 times as much alkalinity can be added at 5°C compared to 30°C, indicating the potential effect size of temperature on the safe threshold for alkalinity. This suggests that, despite the risks of carbonate precipitation, OAE still has the potential to achieve significant, climate-relevant removals of atmospheric CO_2 in a UK-specific context.

Hartmann et al. (2023) investigated solid carbonate precipitation comparing alkaline solution additions with reactive alkaline solids. The solutions were equilibrated with CO_2 prior to addition to seawater, as recommended by Moras et al. (2022), to buffer a large pH increase. They found that solutions with the lowest risk of carbonate precipitation had alkalinity additions of less than 2400 μM/kg, and similar to Moras et al. (2022), they found that the addition of alkaline solids at >600 μM/kg caused a net loss in alkalinity. This suggests that using CO_2-equilibrated alkaline solution instead of alkaline solids for OAE affords a much higher threshold to avoid carbonate precipitation. Hartmann et al. (2023) also noted that even when precipitation does occur, the carbonates that form might not be permanent. This is because unstable precursors of carbonate minerals form from OAE, which then partially dissolve (Hartmann et al., 2023). However the use of solutions has additional environmental considerations, as additional water will be required to create the alkaline solutions.

Effects on marine biota

The use of calcium carbonates for OAE purposes would result in higher calcium (Ca) ion concentrations in seawater (see Equation 1). All marine organisms need to maintain Ca ion concentrations within their cells at levels approximately 10-20 thousand times lower than those found in seawater (Carafoli, 1987; Bach et al., 2019). Achieving this has a metabolic cost, so any increase in calcium ion concentrations may increase this cost, with implications for food webs (Bach et al., 2019). Magnesium ions, which would be released by OL with Brucite and MgO, are maintained at concentrations in cells 2.5 times lower than generally found in seawater (Bach et al., 2019).

Bach et al., (2019) put forward several potential impacts that require further research regarding the ability of marine organisms to calcify and take up nutrients due to increased calcium or magnesium loads in the ocean, including:

- Increased biological calcification from higher calcium loads.

- Higher magnesium concentrations inhibit inorganic calcite precipitation.
- Changes to the Mg/Ca ratio in the ocean induces a shift in plankton community composition.
- Nutrient uptake is inhibited for phytoplankton under higher Mg and Ca concentrations.

Another potential impact on phytoplankton is the reduction of the organic content of marine particles and the rates of zooplankton feeding and faecal pellet production when using MgO as an OAE material (Fakhraee et al., 2023). A simulation by Fakhraee et al. (2023) found that there was a relatively minor effect on these measures, which increased with larger particle sizes. In the case of CaO addition, there was a negligible effect on these measures due to its rapid dissolution in the surface ocean. This implies that fast-dissolving alkaline materials are favourable to avoid negative effects on ocean food chains.

As discussed previously for silicates, minerals commonly contain various trace elements, some of which may have a fertilising effect depending on their concentration (Bach et al., 2019). Similarly, industrially produced lime is not 100% pure and may contain impurities such as iron oxides. However, the addition of iron from lime would be substantially lower than for silicates (Bach et al., 2019), and unlikely to have the same potential magnitude of effect on ocean productivity.

EBS

Summary: Excessively large increases in seawater alkalinity via carbonate-based OAE can cause a reversal in chemical reaction underpinning OAE, leading to an increase in ocean acidity and releasing CO_2 back to the ocean-atmosphere system. With proper management of this risk, OAE can still be effective.

On another note, carbonate-based OAE increases metal cation concentrations in seawater, which could have a range of bioenergetic and ecological impacts on marine life, and it is unclear how this could impact the long-term effectiveness of OAE.

Some membrane systems have associated with elevated mercury concentrations in effluent waters and surrounding sediments, as well as other potentially toxic metals. Some systems have also been reported to emit asbestos particles to water and air. However, many of these older types of system are now being replaced by modern versions that do not have such impacts (NASEM, 2022).

Summary of environmental impacts

Table 1 summarises the known environmental impacts discussed above with respect to each OAE method, indicating whether the effect is positive / beneficial to the goals of OAE and a healthy environment (+), negative/harmful (-), inconclusive (e.g. where feedbacks / higher order interactions make the overall effect difficult to discern and / or the effect is non-linear and dose-dependent) (+/-), where the effect is not applicable (N/A), or where no evidence was found as part of the review (?).

It is evident from Table 1 that there are significant evidence gaps regarding the impacts of each OAE technology. For instance, it is uncertain whether two forms of OAE are carbon and environmental net negative over their life cycle. Importantly, there are also major uncertainties around feedbacks and ecological / environmental interactions that may buffer or amplify a given impact.

Table 1 A summary of expected environmental impacts of each OAE technology.

Environmental impact	Coastal Enhanced Weathering	Crushed limestone application	Ocean liming	Electro-chemical brine splitting
Carbon negative over life cycle	+	?	+	?
Overall environmental impact over life cycle	+	?	+	?
Feedstock mining	-	-	-	N/A
Organic carbonate precipitation	+/-	+/-	+/-	+/-
Inorganic (secondary) carbonate precipitation	N/A	N/A	+/-	N/A
Si concentration increase	+/-	N/A	N/A	N/A
Mg/Ca concentration changes	N/A	+/–	+/–	N/A
Trace element contamination	+/–	+/–	+/–	+/–
Organic matter	–	?	+/–	?

As no comprehensive LCA has been conducted for EBS (NASEM, 2022) or crushed limestone application, these are denoted as "?" in Table 1. In the case of OL, the benefit that cancelled out the costs to environment and carbon from the limestone feedstock supply chain mostly came from reduction in global warming due to OAE (Foteinis et al., 2022). Since limestone is supersaturated in the surface ocean (Eisaman et al., 2023), additional energy would likely need to be expended to target bottom water for raw limestone application to achieve the global warming reduction, unless application was spatially constrained to specific upwelling regions. However, the lack of need for the industrial processing steps in OL (calcination, hydration, and CCS) (Foteinis et al., 2022) would make a substantial reduction to the overall footprint of raw limestone application. Without a comprehensive LCA it is unclear whether these factors on balance would result in a net environmental and carbon benefit.

In the case of CEW, while the LCA indicated it is beneficial to the environment overall, it is important to note that there is a temporal lag of multiple years for the negative impacts to be compensated for (in the case of large (1000μm) particle application) (Foteinis et al., 2023). This is a significant consideration because a continuous application of CEW feedstock over extended periods would impose a continuous environmental penalty until many years after the final application ceases. It is also noteworthy that with much smaller particle sizes, while this effect would shorten to the order of months, it will still be present along with other potential impacts such as particulate pollution.

Organic carbonate precipitation by calcifying marine organisms is denoted with a +/- for all OAE technologies (Table 1) because any increase in ocean alkalinity is expected to favour this (Bach et al., 2019). Organic carbonate precipitation is expected to cause a reduction in OAE efficacy (Bach et al., 2019) however it is not clear if greater abundance of calcifying plankton in the ocean would increase the ecological functioning of marine ecological systems and food webs, and hence have beneficial higher-order impacts to the environment. Additionally, under a CEW scheme, it is unclear how this effect would interact with the potential fertilising effect of Si additions on silicifying plankton species (Bach et al., 2019) e.g. whether Si fertilisation would outweigh the alkalinity-induced benefit to calcifiers, thereby causing silicifiers to dominate the oceans.

Further, the effects of increases in Mg and Ca concentrations in the ocean under carbonate-based OAE, and for trace metals for both carbonate-based and CEW OAE methods, is also denoted by +/-. As discussed, it is unclear if the potential fertilising effects of Mg, Ca and Fe will on balance be beneficial to ocean ecology and biogeochemical cycling or if potential cytotoxic, ecotoxic and other metabolic effects of these (and other trace metals identified in CEW feedstocks) will lead to environmental harm (Bach et al., 2019). In the case of EBS, trace element contamination is denoted with +/- because this depends on whether older technologies (that can release mercury to the water column) or modern facilities are used (NASEM, 2022).

For organic matter, CEW may induce a lower relative organic matter content of marine aggregates and inhibit feeding and faecal pellet production by marine zooplankton (Fakhraee et al., 2023), hence is denoted by "-" in Table 1. In the case of ocean liming with MgO, the magnitude of this effect depended on the particle sizes used, while in the case of

CaO use it is negligible, hence ocean liming is denoted with +/- in Table 1. At this stage, research into effects on organic carbon cycling from other OAE technologies is not available, so potential direct or indirect effects are unclear.

Social implications

This section explores the potential social implications of OAE identified within the existing evidence. It also identifies areas where research currently falls short of exploring these implications adequately. Given that OAE is a technology that has not yet been widely implemented, research into the long-term social implications for different types of OAE technology is not feasible. Therefore, this section discusses more immediate social implications of OAE. In instances where evidence of specific social implications of OAE are lacking, wider research on marine-based carbon reduction technologies is explored where applicable and available, to provide the broadest scope possible.

As social aspects are often intertwined, with industry, community and governance each interdependent on and influencing one another, the identified social implications of OAE are likely to apply to a broad range of stakeholders, as well as being intrinsically linked to the environmental impacts identified within other sections of this report. However, for the purposes of this review, and to identify where evidence gaps exist, the following topics identified within the available evidence around OAE are explored:

- **Social acceptance and acceptability** – explores public opinion and the factors that can influence this both positively and negatively.
- **Implications for local communities** – explores the implications on those who work or reside within the immediate vicinity, and how OAE could impact their livelihood and cultures.
- **Industry acceptance** – explores the potential impact of on business, both local and in the wider community.
- **Other impacts** – brief exploration into the wider social implications, including the potential impacts of policy and governance.

Social acceptance and acceptability

Oceans and ocean culture have high social significance, including in the UK. Exploration into social acceptance embodies a large proportion of the existing evidence into the social implications of marine-based technologies, such as OAE. Small changes in the ocean environment can have global consequences, and so studies have mostly considered country-wide populations, in areas both close to potential deployment zones and further afield. Research on public perception and acceptance of OAE technologies specifically is limited. A holistic approach is usually applied (Satterfield et al., 2023), with the research that exists tends to be in line with evidence for other carbon reduction marine-technologies (such as off-shore energy sources), and is generally perceived as negative overall, especially when compared to terrestrial equivalents (Bertram and Merk, 2020; Spence et al., 2021). Most studies on the public perception of OAE and other carbon removal methods have taken place on a country-wide scale in Western Europe. Smith et al., (2023) found low awareness of GHG removal technologies amongst the general public, perceptions in this nascent field are still forming, with ocean fertilisation being perceived as the riskiest option.

Within the evidence exploring social acceptability of CCS technologies and OAE specifically, there is a consensus identifying similar key factors that can affect the public's acceptance of the technology, as outlined below.

- **Experience of the technology** – prior experience of the technology can be both a positive and negative factor on social acceptance. Lack of experience can create uncertainty and increase perceived risk, whereas previous experience with the technology can mitigate some of these risks. However, the nature of that experience is critical and can also influence this factor negatively (L'Orange Seigo et al., 2014; Boettcher et al., 2023).
- **Technical understanding of the technology** – a lack of understanding of OAE can lead to the public holding general misconceptions that negatively impact social acceptance (Spence et al., 2021). Education on the technology, and management of perceived risks, would be required to gain social acceptance (L'Orange Seigo et al., 2014). For more novel GHG removal technologies, such as OAE, where wider knowledge gaps exist, public perceptions may be more influenced by how the method is framed by researchers and policymakers (Smith et al., 2023).
- **Fairness** – distribution of wealth and equality in resource and land use can influence social acceptance (Boettcher et al., 2023). Heavy reliance on mining for source materials is likely to be negatively perceived (Spence et al., 2021). However, the deployment of this carbon removal technology could assist in the just transition to a green economy, by employing those in declining coal industries.
- **Perceived benefits** – a strong indicator of social acceptance amongst local communities is the presence of local benefits, such as job creation. In addition, those with stronger perception that climate change is a problem are likely to perceive the benefits of OAE more favourably (Boettcher et al., 2023), as are those who understand how the benefits will be distributed over time (Shrum et al., 2020).
- **Perceived risk** – another strong indicator of acceptance is the perception of risk, with concerns over whether the process is reversible and the long-term impact on marine life as key factors in determining the perceived risk of OAE (Cooley et al., 2023). Evidence has generally found that there is a perceived fragility of the ocean that can be a major factor in risk tolerance for marine-based technologies, such as OAE (Nawaz et al., 2023). Where risk perception in relation to OAE has been studied, those who viewed the ocean as controllable and resilient tended to perceive the risk to be lower, than those who perceived the ocean as being sensitive to impacts of change and less resilient than other eco-systems (Nawaz et al., 2023; Boettcher et al., 2023). As the long-term effects of OAE on marine ecosystems has yet to be fully established evidentially, perceived risk may continue to be an overriding opinion in guiding public perception and social acceptance of OAE (Cox et al., 2020; Shrum et al., 2020).
- **Naturalness** – often defined as an interference with nature, perceptions of "naturalness" are identified within the evidence as important factors in social acceptance of terrestrial carbon removal technology, and are likely to also affect the acceptability of OAE (NASEM, 2022). Carbon removal approaches that are

perceived as more ‘natural’ are generally perceived more favourably than engineered approaches, with OAE generally perceived by the public as being engineered (Bertram and Merk, 2020; Smith et al., 2023).

Summary: The social acceptance of OAE may vary according to factors including technical understanding and experience of the technology, perceived benefits and risks, and perceived “naturalness”. As it is a nascent technology public perception is still forming, though marine carbon reduction approaches are generally viewed with suspicion.

Implications for local communities

OAE’s impact on communities could be significant and varied, depending heavily on the local community and how they use and perceive the ocean. The ocean is viewed by some as; a sacred or socially important space, an area of cultural significance, a free use area of recreation and reflection (NASEM, 2022). As such, the impacts of OAE are difficult to predict (Cooley et al., 2023). OAE could represent a restriction on an existing way of life, particularly if use or access of the coastline or ocean is restricted (or perceived to be restricted) by OAE deployment, or if it is perceived to result in job losses.

The requirement for increased limestone mining to source feedstock materials for OAE could also have potentially significant impacts on local communities. The extent and nature of these impacts will be heavily influenced by the local geographic and social context of the area where mining occurs, but the expansion of mining is generally associated with demographic change (e.g., from non-resident workforces), social inequality, pressure on services, appropriation of land and health impacts in mining workforces (NASEM, 2022). Moreover, the mining of limestone is more likely to occur in less developed countries and regions, leading to concerns regarding the equitable distribution of upstream (i.e., from mining) and downstream (i.e., from OAE implementation) impacts (Nawaz et al., 2023).

Coastal application of mineral particles could result in indirect impacts to human health, for example impact on the mental wellbeing of the community from perceived or actual changes or restrictions to previously open-access areas of the ocean or coastline (NASEM, 2022).

Conversely, OAE could also represent opportunities from job creation and, therefore, be viewed positively by local communities (Boettcher et al., 2023). Moreover, communities vulnerable to the effects of climate change, such as extreme weather or flooding, may see the potential global benefits of OAE of climate change as more of an influencing factor than communities who may not experience such effects. Perception of benefit is also heavily influenced by trust in the organisation that deploys the technology, and to what extent the benefits would apply locally (Boettcher et al., 2023). Local knowledge would play a key role in determining the strength of these factors in influencing public opinion and social acceptance. Thorough and inclusive local stakeholder engagement would, therefore, be critical at each intended location of OAE deployment, to capture this local knowledge and tailor an approach that satisfies the nuanced perception of each individual community (Boettcher et al., 2023).

As with judging the impact of OAE on social acceptance, there is no one-size-fits-all approach to determine the impact on local communities. To fully understand the context and how deployment of OAE could impact on their community, evidence suggests that a holistic place-based approach is required, where key stakeholders and local experts are consulted. This would include consideration, and mitigation, of potential impacts such as awareness of power balances, both current and historic (Cooley et al., 2023), how best to engage with affected communities, and cultural and historical values the community may hold with the ocean (Boettcher et al., 2023). Identifying this context can lead to informed decisions about the specific impacts OAE may have on a community.

Impacts on specific social groups should also be considered in OAE deployment, including the identification of groups and individuals that would be directly impacted by OAE; this could include both human and non-human groups (Boettcher et al., 2023), and habitat loss.

Summary: The impacts of OAE on local communities appears to be dependent on the relationship the community has with the ocean, and whether the technology brings any economic development to the community. OAE also potentially has health implications on local communities, both from the technology deployment and from feedstock mining.

Industry acceptance

There is a lack of specific evidence currently existing for the potential impact of OAE on industry, owing to the infancy of the technology and lack of real-world applications. However, as with other marine-based technologies, there is some evidence on general impacts to existing industries caused by changes to marine landscapes and usage, which may influence industry acceptance. Large-scale limestone mining for OAE could re-employ some of the equipment and workforce used in the coal mining coal sector, which extracts roughly 7 Gt per year globally (Caserini et al., 2022). The current scale of the global mining industry is roughly equivalent to the scale of limestone extraction required to sequester 1 Gt of carbon from the atmosphere annually in the UK.

The presence of existing marine industry infrastructure and assets could be a factor in industry acceptance, as could the infrastructure's adaptability to potential changes required for OAE deployment, such as the specification and benefits of co-location alongside OAE infrastructure or additional land take (Eisaman et al., 2023) or mitigation measures to manage the changing ocean alkalinity on existing infrastructure. Industries that collect data from the ocean could also be impacted by the deployment of OAE technologies (Boettcher et al., 2023). These factors could apply to industry both locally and nationally should OAE be deployed at scale, however whether this impact, and the industry's acceptance, would be positive or negative depends largely on the industry itself.

Summary: There is a lack of evidence relating to industry acceptance of OAE technologies, as there are currently no large-scale deployments. Evidence suggests that existing marine infrastructure could be reused in OAE implementation.

Government policy

There is no single comprehensive legal framework or international legal regime that specifically addresses OAE (Boettcher et al., 2023). The oceans are governed by a fragmented regulatory landscape, with grey areas surrounding the ownership of international waters and who has rights to them. Around 60% of ocean waters do not fall under the authority of any single country, necessitating cooperation between countries when conducting research or implementing projects, especially when environmental impacts could transport across international boundaries. Consequently, individual countries adapt international laws to formulate policies, or multiple government policies may be applicable for OAE research (Steenkamp & Webb, 2023). Historically, this has tended to result in OAE research being carried out in areas with less stringent legal frameworks (Boettcher et al., 2023). The introduction of a stringent and specific governance system for OAE could impact on the scope of research in this field and its deployment. Governance and research could therefore become co-dependent as the technology grows.

The implementation of OAE is governed to an extent by various existing environmental laws, treaties and regulations (Webb et al., 2021). The most applicable is the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the "London Convention") and accompanying Protocol, which regulate the dumping of materials into ocean waters. Other examples include:

- The Convention on Biological Diversity;
- The Biodiversity of Areas Beyond National Jurisdiction Treaty;
- The United Nation Convention on the Law of the Sea;
- The International Convention for the Prevention of Pollution from Ships;
- The Basel Convention;
- The European Union Marine Strategy Framework Directive.

The applicability of these will be determined by how and where OAE occurs. Moreover, various principles of customary international law, such as the "no harm" rule, could also apply.

Studies examining the factors affecting social acceptance of OAE and similar technologies indicate that effective governance and policy can be a positive factor (Satterfield et al., 2023). Policies seeking to mitigate the perceived risks of OAE, such as responsibility for maintenance or introducing a 'polluter pays' approach are likely to increase social acceptance. The level of trust in regulatory bodies also affects the social acceptance of new technologies (Cooley et al., 2023). Furthermore, there are also broader policy questions surrounding the financing of OAE and its integration into carbon markets, as well as implementing robust monitoring, reporting and verification (MRV). These factors which will affect the extent to which OAE is positively regarded in markets and amongst the public (Ho et al., 2023).

Summary: As OAE is a nascent technology, most governments lack specific policy, though some aspects of its implementation is covered by existing marine legislation. Effective governance and policy are perceived to be critical in increasing the social acceptability of the technology.

Socio-economic impacts

The evidence of socio-economic impacts of OAE is limited to direct impacts on ocean and coastal-based businesses, such as limiting the activities of industries like fisheries, tourism and transportation (Eisaman et al., 2023). In addition, within the current legislative landscape, research of OAE could be skewed towards areas with less stringent laws, such as less-developed countries (Boettcher et al., 2023). It is unlikely that the current evidence provides a fully representative picture of all socio-economical situations and communities, and so the impacts of OAE requires further study in a wider variety of contexts.

Summary: Evidence is lacking on the socio-economic implications of OAE, other than that they are likely to be highest impact on marine-based industries.

Conclusions

Summary of environmental and social implications

The environmental impacts of OAE are varied and significant. Scaling OAE to climate-relevant levels would require the development of a new global mining industry, putting substantial demand on energy and material production systems. This scaling would take multiple decades, which is problematic given the urgent need for carbon removal to mitigate the effects of climate change. Conflict with other land uses, such as biodiversity conservation, food production, or housing, may also arise in places where industrial operations are needed for OAE.

Mineral-based OAE, particularly using limestone, poses a considerable resources demand. The energy requirements for the industrial operations involved are prohibitive, potentially representing a significant portion of the UK's electricity demand. The OL method particularly is highly energy intensive, being an order of magnitude higher than the energy requirement for CEW, mainly due to the energy required to process limestone into lime. Without a transition to a decarbonised electricity grid and replacing the use of diesel in the heavy machinery integral to mineral-based OAE, there is potential to cause significant environmental impacts from fossil fuel use.

The use of silicates for OAE raises a concern over its impurities that are potentially toxic to ecological and human health, which could influence the selection of OAE technology for large-scale deployment (Foteinis et al., 2023; Bach et al., 2019). Silicates can also disrupt carbon cycling processes (Fakhraee et al., 2023) and coastal environments under CEW (Foteinis et al., 2023). Further empirical research is needed to assess the costs and benefits of silicates in comparison to other minerals for OAE.

The EBS approach is favourable for OAE due to several key advantages. Unlike mineral-based OAE, EBS does not need complex supply chains or port infrastructure. It has a relatively low energy demand, with the total energy consumption estimated at <5% of the energy required to process crushed limestone into lime for OL. It also avoids the addition of toxic elements to the ocean and since EBS removes acidity from the ocean (rather than neutralising it by the addition of alkalinity), it may have less potential to disrupt biogeochemical cycles. However, managing the by-products of the EBS process poses a significant challenge, especially considering the scale required for OAE. For example, if the electrolysis method of EBS is used to deliver 25 Mt CO_2 sequestration through OAE, it would generate roughly 25 million tonnes of chlorine gas per year.

The environmental impacts of OAE technologies remain poorly understood, lacking real-world data to evidence the theoretical understanding of their potential benefits and trade-offs. Moreover, the impact of increased ocean alkalinity on various ecological processes, which may trigger feedbacks disrupting oceanic biological, ecological and biogeochemical processes are even less well understood. While recent laboratory experiments have helped determine alkalinity application thresholds that prevent runaway $CaCO_3$

precipitation caused by OAE (Moras et al., 2022; Hartmann et al., 2023), large-scale experiments on functioning ecosystems are required to study the higher-order ecosystem effects of OAE, which poses a substantial risk to ocean ecology.

Regarding the social implications, the research suggests that public perceptions and social acceptance of technologies that alter natural processes are generally low, particularly amongst impacted local communities. However, perceptions vary depending on factors such as whether communities are experiencing negative impacts from climate change or stand to benefit from local jobs in new coastal-based industries. Moreover, the ocean holds varied and diverse meanings and significance to many cultures and, as such, diverse social values are applied to the oceans. Any interference or intervention strategy could have impacts on the societies that rely on oceans, both for individuals and industries. The implementation of robust government policy appears to assist in alleviating these perceived risks.

Evidence gaps and research priorities

While OAE holds potential as a carbon dioxide removal method, there are numerous unanswered questions regarding its the long-term ecological impacts and the feasibility for implementation on a climate-relevant scale. Further research and development efforts are needed to step-up the readiness level of different OAE approaches, and to determine which, if any, approaches are most appropriate for scaling up. Notably, mineral-based OAE methods face significant logistical challenges in terms of loading and storage of megatonnes of feedstocks at port facilities, which may necessitate large new infrastructural projects. The environmental and resource implications of this are likely to be substantial, and have not yet been comprehensively investigated to our knowledge.

More research is also needed to determine the risk level of the various environmental impacts associated with OAE applications, and to attempt to balance the impacts outlined in Table 1 and ascertain which of OAE technologies are the most sustainable. Eisaman et al. (2023) suggested the establishment of a comprehensive research programme, involving pilot-scale facilities, to accelerate OAE technology development. Research areas of interest include:

- Environmental impact of mineral application, such as:
    - Potential carbonate chemistry perturbations from increased alkalinity, which may alter ecological succession patterns and biogeochemical processes (Bach et al., 2019);
    - Changing responses of calcifying plankton to OAE (Bach et al., 2019);
    - Potential shift in diatom communities to more heavily silicified or calcified species (Bach et al., 2019);
    - Implications of disturbing faecal pellet production and zooplankton grazing on the wider food chain (Fakhraee et al., 2023);
- Potential formation of secondary minerals, which can reduce net carbon dioxide sequestration;
- Management strategies, including promoting transparency and public engagement;

- Regionally specific constraints of OAE approaches.

Only one *in situ* experiment published in the academic literature was identified, which was carried out in a coral reef environment (Hartmann et al., 2023), though there have been industry pilot trials. A broader understanding of how potential dissolution products affect different species and ecosystems is needed before OAE can be deployed with confidence. For example, elevated levels of Ca and/or Mg could have adverse effects on plankton, yet research is currently limited in this area. Proposed experiments include studying the Black Sea, which has a naturally high alkalinity, and sites of intense natural weathering of basaltic rocks, which could provide insights into the effect of alkaline solutions on a regional level. Furthermore, studies in palaeoceanography may be able to give us a better understanding of how periods of high alkalinity have affected our oceans in the past (Bach et al., 2019).

Questions also arise around the long-term effects of the accumulation of certain trace metals used in OAE on those at the end of the food chain, such as humans. It is therefore also important to identify which minerals come with risks for end members of the food chain (Bach et al., 2019).

Further research into alternative alkaline solutions, such as Na_2CO_3 and $NaHCO_3$, is also needed. These solutions dissolve quickly due to their high solubility, and so could enhance the use of OAE on a larger scale. However, they have previously been discarded from research due to limited availability (Hartmann et al., 2023). Therefore, a better understanding of how these could be produced in a more time and energy efficient manner would improve OAE options.

Gaps in evidence also exist in determining the desirability, effectiveness, and capacity of OAE. Further research into these areas should ensure that scaling challenges are addressed and best practices can be determined. Ethical considerations around the experimentation of species and ecosystems should be discussed in an open public discourse relating to risk assessments (Bach et al., 2019).

There is significantly less evidence available relating to the potential social implications of OAE, and only a small amount of that is specific to the UK. The evidence on the social implications of OAE is limited, with most evidence focused on public perception and social acceptance. Smith et al., (2023) identified that research into GHG removal technologies from natural science and engineering perspectives heavily dominates over research from the social sciences and humanities perspectives. More research is required into the potential long-term impacts on the communities and industries that could be affected by OAE to build a complete picture and better inform of the impacts of OAE beyond the environment. Moreover, the research needs to be holistic and involve meaningful stakeholder engagement throughout the lifecycle of OAE (including the upstream impacts from limestone mining and downstream impacts). However, such research is currently hindered by the relative infancy of the technology and lack of specific policy direction globally, as well as the currently generally low social acceptance of the technology.

Appendices

Methodology

Parameters for including suitable sources in the review were devised according to academic best practice based on the timeliness, accuracy, authority and objectivity of the research, thereby excluding sources of insufficient quality to contribute to the required quality of results. All sources used as part of this research were assessed against this source reliability protocol (included in Table 2 overleaf).

Relevant literature was identified, including ‘grey’ literature (e.g., conference papers, government publications, social surveys, industry standards, market reports, and policy statements) and scientific papers, using a range of search strings on both public and academic platforms.

A framework of research questions was used to form the basis for collating information. Following the assessment of all relevant literature, a gap analysis was undertaken to identify research gaps in the available evidence. A final search relating to these specific gaps was conducted to ensure that no relevant literature was missed.

Table 2 The source reliability protocol used to assess the and suitability reliability of sources used in the research.

Criteria	Red	Amber	Green	Grey
1. Currentness				
How up to date is the information?	20-30 years' old	10-20 years' old	0-10 years' old	Date not identifiable
2. Accuracy				
Does the item have a clearly stated aim or brief? Is it detailed and factual? Does the work contradict itself? Does the work appear to be carefully prepared (e.g. well-written or designed, mostly free of errors, easy to navigate)? Does it have a stated methodology?	No clear aims or methodology, contains several errors, contradicts itself	Aims and methodology explored in less detail, some errors	Detailed aims and clear methodology, very few errors	N/A

Criteria	Red	Amber	Green	Grey
3. Authority				
Is the author associated with a reputable organisation? Do they have relevant professional qualifications or experience? Are they cited by others? If published by an organisation, is the organisation reputable? Is the organisation an authority in the field? Does the item have a detailed, credible reference list? Has it been peer reviewed? Has it been edited by a reputable authority?	No clear expertise and / or not reputable organisation, no reference list, no reference to review/editing process,	Some relevant expertise, review/editing process unclear	Reputable organisation, considerable expertise, reviewed and / or edited by technical experts and well-supported by credible sources,	N/A
4. Objectivity				
Is the author presenting their opinion or factual evidence? Is the goal of the work to inform or persuade? Does the work seem to be balanced and consistent? Independent expert or vested interest? Who funded/sponsored the work?	Clear vested interest, strong opinions presented, written to persuade rather than inform	Possible vested interest, opinion-driven	Independent expert, balanced views / factual evidence presented, clearly identified funding source with lack of vested interest	No evidence of funding source

References

BACH, L. T., 2024. The additionality problem of ocean alkalinity enhancement. Biogeosciences, 21(1), 261-277.

BACH, L. T., GILL, S. J., RICKABY, R. E., 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).

BENDOUMA, S., SERRADJ, T., & VAPUR, H. (2020). A case study of the life cycle impact of limestone quarrying on the environment. International Journal of Global Warming, 22(4), 432-447.

BERTRAM, C. & MERK, C., 2020. Public Perceptions of Ocean-Based Carbon Dioxide Removal: The Nature-Engineering Divide?, Frontiers in Climate, 2, 594194.

BGS, 2014. Minerals Planning Factsheet, Cement. London: Department for Communities and Local Government.

BOETTCHER, M., CONATHAN, M., KELLER, D., LEZAUN, J., SCOBIE, M., CHAI, F., COOLEY, S., KLINSKY, S., RENFORTH, P., AND WEBB, R., 2023. A Code of Conduct for Marine Carbon Dioxide Removal Research. Aspen Institute. Available from: https://www.aspeninstitute.org/publications/a-code-of-conduct-for-marine-carbon-dioxide-removal-research/ [Accessed January 2024]

BOYD, P. W., JICKELLS, T., LAW, C. S., BLAIN, S., BOYLE, E. A., BUESSELER, K. O., COALE, K. H., CULLEN, H. J. W., FOLLOWS, M., HARVEY, M., LANCELOT, C., LEVASSEUR, M., OWENS, N. P. J., POLLARD, R., RIVKIN, R. B., SARMIENTO, J., SCHOEMANN, V., SMETACEK, V., TAKEDA, S, TSUDA, A., TURNER, S. & WATSON, A. J., 2007. Mesoscale iron enrichment experiments 1993-2005: Synthesis and future directions. Science 315, 612–617.

CAMPBELL, J., FOTEINIS, S., MADANKAN, M. & RENFORTH, P., 2023. Report on the detailed life cycle analysis results of the two case studies: ocean alkalinity enhancement potential of Spain. Ocean-based Negative Emission Technologies, 4815899.

CARAFOLI, E., 1987. Intracellular calcium homeostasis. Annual Review of Biochemistry, 56, 395–433.

CASERINI, S., PAGANO, D., CAMPO, F., ABBÀ, A., DE MARCO, S., RIGHI, D., RENFORTH, P. & GROSSO, M., 2021. Potential of maritime transport for ocean liming and atmospheric CO_2 removal. Frontiers in Climate, 3(22).

CASERINI, S., STORNI, N., & GROSSO, M., 2022. The availability of limestone and other raw materials for ocean alkalinity enhancement. Global Biogeochemical Cycles, 36(5).

COOLEY, S. R., KLINSKY, S., MORROW, D. R., & SATTERFIELD, T., 2023. Sociotechnical Considerations About Ocean Carbon Dioxide Removal, Annual Review of Marine Science, 15, 41–66.

COX, E., SPENCE, E., & PIDGEON, N., 2020. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nature Climate Change, 10, 1–6.

EISAMAN, M. D., GEILERT, S., RENFORTH, P., BASTIANINI, L., CAMPBELL, J., DALE, A. W., FOTEINIS, S., GRASSE, P., HAROT, O., LÖSCHER, C. R., RAU, G. H. & RØNNING, J., 2023. Assessing the technical aspects of ocean-alkalinity-enhancement approaches. State Planet: SP, 2(3), 1-29.

EKE, J., YUSUF, A., GIWA, A. & SODIQ, A., 2020. The global status of desalination: An assessment of current desalination technologies, plants and capacity. Desalination, 495, 114633.

FAKHRAEE, M., LI, Z., PLANAVSKY, N.J. & REINHARD, C. T., 2023. A biogeochemical model of mineral-based ocean alkalinity enhancement: impacts on the biological pump and ocean carbon uptake. Environmental Research Letters, 18(4).

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.

FOTEINIS, S., CAMPBELL, J. S., & RENFORTH, P., 2023. Life Cycle Assessment of Coastal Enhanced Weathering for Carbon Dioxide Removal from Air. Environmental Science & Technology, 57(15), 6169-6178.

GUO, J. A., STRZEPEK, R. F., SWADLING, K. M., TOWNSEND, A. T. & BACH, L. T., 2023. Influence of Ocean Alkalinity Enhancement with Olivine or Steel Slag on a Coastal Plankton Community in Tasmania. EGUsphere, 2023-2120.

HANGX, S. J. T. & SPIERS, C. J., 2009. Coastal spreading of olivine to control atmospheric CO_2 concentrations: A critical analysis of viability. International Journal of Greenhouse Gas Control, 3, 757–767.

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, 185–194.

HARTMANN, J., SUITNER, N., LIM, C., SCHNEIDER, J., MARÍN-SAMPER, L., ARÍSTEGUI, J., RENFORTH, P., TAUCHER, J. & RIEBESELL, U., 2023. Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches–consequences for durability of CO_2 storage. Biogeosciences Discussions, 1-29.

HARVEY, L. D. D., 2008. Mitigating atmospheric CO_2 increase and ocean acidification by adding limestone powder to upwelling regions. Journal of Geophysical Research, 113, C04028.

HO, D. T., BOPP, L., PALTER, J. B., LONG, M. C., BOYD, P. W., NEUKERMANS, G., and BACH, L. T., 2023. Monitoring, reporting, and verification for ocean alkalinity enhancement. In: Guide to Best Practices in Ocean Alkalinity Enhancement Research, Copernicus Publications, State Planet, 2-oae2023, 12.

HONJO, S., T.I. EGLINTON, C.D. TAYLOR, K.M. ULMER, S.M. SIEVERT, A. BRACHER, C.R. GERMAN, V. EDGCOMB, R. FRANCOIS, M.D. IGLESIAS-RODRIGUEZ, B. VAN MOOY, and D.J. REPETA. 2014. Understanding the role of the biological pump in the global carbon cycle: An imperative for ocean science. Oceanography 27(3):10–16, http://dx.doi.org/10.5670/oceanog.2014.78.

JONES, E., QADIR, M., VAN VLIET, M. T. H., SMAKHTIN, V. & KANG, S.-M., 2019. The state of desalination and brine production: A global outlook. Science of the Total Environment, 657, 1343-1356.

KIRCHNER, J. S., BERRY, A., OHNEMÜLLER, F., SCHNETGER, B., ERICH, E., BRUMSACK, H.-J., AND LETTMANN, K. A., 2020. Reducing CO_2 Emissions of a Coal-Fired Power Plant via Accelerated Weathering of Limestone: Carbon Capture Efficiency and Environmental Safety, Environmental Science and Technology, 54, 4528–4535.

KOGEL, J. E., TRIVEDI, N. C., BARKER, J. M. & KRUKOWSKI, S. T., 2006. Industrial Minerals and Rocks: Commodities, Markets, and Uses. 7th ed. Society for Mining, Metallurgy, and Exploration.

KÖHLER, P., ABRAMS, J. F., VÖLKER, C., HAUCK, J. & WOLF-GLADROW, D. A., 2013. Geoengineering impact of open ocean dissolution of olivine on atmospheric CO_2, surface ocean pH and marine biology. Environmental Research Letters, 8, 014009.

LAMARE, R. E., & SINGH, O. P., 2016. Limestone mining and its environmental implications in Meghalaya, India. ENVIS Bulletin Himalayan Ecology, 24, 87-100.

LI, H., TANG, Z., LI, N., CUI, L. & MAO. X-Z., 2020. Mechanism and process study on steel slag enhancement for CO_2 capture by seawater. Applied Energy, 276, 115515.

L′ORANGE SEIGO, S., DOHLE, S., & SIEGRIST, M., 2014. Public perception of carbon capture and storage (CCS): A review. Renewable and Sustainable Energy Reviews, 38, 848-863.

MA, D., GREGOR, L., & GRUBER, N., 2023. Four decades of trends and drivers of global surface ocean acidification. Global Biogeochemical Cycles, 37(7), e2023GB007765

MADANKAN, M. & RENFORTH, P., 2023. An inventory of UK mineral resources suitable for enhanced rock weathering. International Journal of Greenhouse Gas Control, 130, 104010.

MOORE, C. M., MILLS, M. M., ARRIGO, K. R., BERMAN-FRANK, I., BOPP, L., BOYD, P. W., GALBRAITH, E., GEIDER, R. J., GUIEU, C, JACCARD, S. L., JICKELLS, T. D., LAROCHE, J., LENTON, T. M., MAHOWALD, N., MARANON, E., MARINOV, I., MOORE, J. K., NAKATSUKA, T., OSCHLIES, A., SAITO, M. A., THINGSTAD, T. F., TSUDA, A. & ULLOA, A., 2013. Processes and patterns of oceanic nutrient limitation. Nature Geoscience, 6, 701–710.

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.

MPA, 2023. Profile of the UK Mineral Products Industry. Available from: https://mineralproducts.org/MPA/media/root/Publications/2023/Profile_of_the_UK_Mineral_Products_Industry_2023.pdf [Accessed 22 March 2024]

MPA Cement, 2024. About Us [online]. London. Available from: https://cement.mineralproducts.org/About-Us.aspx [Accessed 22 March 2024]

NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE (NASEM), 2022. A research strategy for ocean-based carbon dioxide removal and sequestration. Washington, DC: The National Academies Press.

NAWAZ, S., PETERSON ST-LAURENT, G., & SATTERFIELD, T., 2023. Public evaluations of four approaches to ocean-based carbon dioxide removal. Climate Policy, 23(3), 379-394.

OPPON, E., RICHTER, J. S., KOH, L. S. C. & NABAYIGA, H., 2023. Macro-level economic and environmental sustainability of negative emission technologies; Case study of crushed silicate production for enhanced weathering. Ecological Economics, 204, 107636.

ORR, J. C., FABRY, V. J., AUMONT, O., BOPP, L., DONEY, S. C., FEELY, R. A., GNANADESIKAN, A. GRUBER, N., ISHIDA, A., JOOS, F., KEY, R. M., LINDSAY, K., MAIER-REIMER, E., MATEAR, R., MONFRAY, P., MOUCHET, A., NAJJAR, R. G., PLATTNER, G., RODGERS, K. B., SABINE, C. L., SARMIENTO, J. L., SCHLITZER, R., SLATER, R. D., TOTTERDELL, I. J., WEIRIG, M., YAMANAKA, Y. & YOOL, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437(7059), 681-686.

PAQUAY, F. S. & ZEEBE, R. E., 2013. Assessing possible consequences of ocean liming on ocean pH, atmospheric CO_2 concentration and associated costs. International Journal of Greenhouse Gas Control, 17, 183-188.

PARKER, R. L., 1967. Composition of the Earth's Crust. Data of Geochemistry, 440(D).

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, 2674–2679.

RENFORTH, P. & CAMPBELL, J. S., 2021. The role of soils in the regulation of ocean acidification. Philosophical Transactions of the Royal Society of London B, 376(1834).

RENFORTH, P. & HENDERSON, G., 2017. Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics, 55, 636-674.

RENFORTH, P., JENKINS, B. G. & KRUGER, T., 2013. Engineering challenges of ocean liming. Energy, 60, 442-452.

RIEBESELL, U., BASSO, D., GEILERT, S., DALE, A. W., KREUZBURG, M. & Meysman, F., 2023. Mesocosm experiments in ocean alkalinity enhancement research. State Planet: SP, 2(6), 1-14.

RIEBESELL, U., WOLF-GLADROW, D. A. & SMETACEK, V., 1993. Carbon dioxide limitation of marine phytoplankton growth rates. Nature, 361, 249-251.

SALAS, E. B., 2023. UK: Average daily water usage per person 2022. Statista. Available from: https://www.statista.com/statistics/1211708/liters-per-day-per-person-water-usage-united-kingdom-uk/ [accessed 22/02/2024].

SARMIENTO, J. L., GRUBER, N., BRZEZINSKI, M. A. & DUNNE, J. P. (2004). High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature, 427, 56–60.

SATTERFIELD, T., NAWAZ, S., & BOETTCHER, M., 2023. Social considerations and best practices to apply to engaging publics on ocean alkalinity enhancement, in Guide to Best Practices in Ocean Alkalinity Enhancement Research. State of the Planet, 11.

SCHULZ, K. G. & RIEBESELL, U., 2013. Diurnal changes in seawater carbonate chemistry speciation at increasing atmospheric carbon dioxide. Marine Biology, 160, 1889-1899.

SHARIFIAN, R., WAGTERVELD, R. M., DIGDAYA, I. A., XIANG, C. & VERMAAS, D. A., 2021. Electrochemical carbon dioxide capture to close the carbon cycle. Energy and Environmental Science, 14, 781-814.

SHRUM, T.R., MARKOWITZ, E., BUCK, H., GREGORY, R., VAN DER LINDEN, S., ATTARI, S. Z. & VAN BOVEN, L., 2020. Behavioural frameworks to understand public perceptions of and risk response to carbon dioxide removal. Interface Focus,10

SMITH, S. M., GEDEN, O., NEMET, G., GIDDEN, M., LAMB, W. F., POWIS, C., BELLAMY, R., CALLAGHAN, M., COWIE, A., COX, E., FUSS, S., GASSER, T., GRASSI, G., GREENE, J., LÜCK, S., MOHAN, A., MÜLLER-HANSEN, F., PETERS, G., PRATAMA, Y., REPKE, T., RIAHI, K., SCHENUIT, F., STEINHAUSER, J., STREFLER, J., VALENZUELA, J. M., & MINX, J. C., 2023. The state of carbon dioxide removal. 2nd ed.

SPENCE, E., COX, E., AND PIDGEON, N., 2021. Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy. Climatic Change, 165(23).

STEENKAMP, R.C. & WEBB, R., 2023. Legal considerations relevant to research on ocean alkalinity enhancement, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research. State of the Planet, 11.

STREFLER, J., AMANN, T., BAUER, N., KRIEGLER, E. & HARTMANN, J., 2018. Potential and costs of carbon dioxide removal by enhanced weathering of rocks, Environmental Research Letters, 13, 034010.

STRONG, A. L., CULLEN, J. J. & CHISHOLM, S. W., 2009. Ocean Fertilization: Science, Policy, and Commerce. Oceanography Society, 22(3), 236-261.

TAYLOR, L. L., QUIRK, J., THORLEY, R. M. S., KHARECHA, P. A., HANSEN, J., RIDGWELL, A., LOMAS, M. R., BANWART, S. A. & BEERLING, D. J., 2016. Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nature Climate Change, 6, 402–406.

VESTA, 2023. Vesta Annual Monitoring Report: Coastal Carbon Capture at North Sea Beach. Available from:

https://drive.google.com/file/d/1f0Nepfxxdqhx_jqgm6KFBL7EbyMBCTgf/view [Accessed 20 February 2024]

VOOSEN, P., 2022. Ocean geoengineering scheme aces its first field test. Science, 378(6626), 1266-1267.

WEBB, R. M., SILVERMAN-ROATI, K. & GERRARD, M. B., 2021. Removing carbon dioxide through ocean alkalinity enhancement: legal challenges and opportunities. Sabin Center for Climate Change Law. Available from:

https://climate.law.columbia.edu/sites/default/files/content/Webb%20et%20al.%20-%20Removing%20CO2%20Through%20Ocean%20Alkalinity%20Enhancement%20%20-%20August%202021.pdf [Accessed 21 February 2024]

List of abbreviations

Abbreviation	Definition
AWL	Accelerated weathering of limestone
CCS	Carbon capture and storage
CEW	Coastal enhanced weathering
CO_2	Carbon dioxide
GHG	Greenhouse gas
Gt	Gigatonne
H_2O	Chemical formula for water
OAE	Ocean alkalinity enhancement
OL	Ocean liming

Glossary

Term	Definition
Carbon sequestration	The process of capturing and storing atmospheric carbon dioxide.
Geoengineering	Large-scale manipulation of an environmental process that affects the climate, generally to counteract the effects of global warming.
Greenhouse gas	Gases in the atmosphere that raise earth's surface temperature; consisting of CO_2, CH_4, N_2O, HFCs and PFCs.
Greenhouse gas removal	Also known as negative emissions technologies, greenhouse gas removal technologies encompass a range of techniques for reducing the concentration of GHGs in earth's atmosphere.
Ocean alkalinity enhancement	A geoengineering method that involves the application of various chemical mineral) to seawater in order to increase the pH of the ocean, thereby increasing carbon sequestration.

Would you like to find out more about us or your environment?

Then call us on

03708 506 506 (Monday to Friday, 8am to 6pm)

Email: enquiries@environment-agency.gov.uk

Or visit our website

www.gov.uk/environment-agency

Incident hotline

0800 807060 **(24 hours)**

Floodline

0345 988 1188 **(24 hours)**

Find out about call charges (https://www.gov.uk/call-charges)

Environment first

Are you viewing this onscreen? Please consider the environment and only print if absolutely necessary. If you are reading a paper copy, please don't forget to reuse and recycle.