OCEAN NETs

POLICY BRIEF

Realistic Deployment Scenarios for Ocean Alkalinity Enhancement

Ocean liming (OL)

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About

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Removing carbon dioxide from the atmosphere to reach net zero

There is a consensus in scientific climate research that humanity will only curb global warming and the resulting climate impacts if it reduces its carbon dioxide (CO_2) emissions to net zero. But even with ambitious climate policies, experts believe that we will still be emitting residual amounts of CO_2 (5 to 15 percent of current CO_2 emissions) by the middle of the 21st century, thus further driving global warming. These residual emissions will be generated, for example, in cement and steel production, in air and heavy-duty transport, but also in agriculture and waste incineration.

One solution to compensate these residual emissions is through targeted carbon dioxide removal (CDR) and storage (carbon capture and storage = CCS) processes. The release of some emissions can be prevented if CO_2 is captured at the emission source and subsequently stored geologically. This is important for those industrial sectors that cannot currently avoid emissions of fossil origin. Moreover, there are several approaches to removing CO_2 from the atmosphere. **Many carbon dioxide removal processes investigated to date are land-based. However, ocean-based approaches and processes are being increasingly explored.** The ocean covers over 70 % of the Earth's surface and will be the predominant, largest long-term sink for man-made CO_2. These factors alone suggest that ocean-based CDR approaches should have at least as much – and potentially much more – CDR potential than land-based removal processes.

The Earth's climate system uses physical, chemical, and biological processes to remove carbon dioxide from the atmosphere and store it on land, in the ocean, or in the geological subsurface. The world ocean utilizes these processes to such an extensive degree that it has buffered very large changes in atmospheric CO_2 concentrations throughout Earth's history. **Because of its natural CO_2 uptake capacity, the ocean is the major player in the global carbon cycle.** However, CO_2 uptake processes in the ocean and ocean floor occur on long time scales. Various CDR approaches could accelerate such processes and thereby increase the ocean's CO_2 uptake rate.

It is important to understand which methods are applicable at all, under which local and global conditions they work, and which approaches have to be discarded. In this context, science has the task of providing public and transparent information for informed and inclusive decision-making. **Which solutions for countering climate change will be used in the future must be negotiated politically and in society in an open debate.**[1]

Carbon Dioxide Removal in climate stabilisation scenarios

Meeting national and international climate stabilisation targets will require new capabilities to remove CO_2 from the atmosphere at industrial scales. Scenarios that limit warning to 1.5 °C or 2 °C assume that CDR will become a key climate change mitigation strategy in the second half of the century (1.5 °C scenarios estimate a range of 450–1200 gigatons of atmospheric carbon dioxide removed by 2100; whereas 2 °C scenarios estimate a range of 460–1100.[2])

1 *David Keller, Sandra Ketelhake, Judith Meyer, Barbara Neumann, Andreas Oschlies, Alexander Proelß and Wilfried Rickels (2022): Achieving Climate Neutrality and Paris Agreement Goals: Opportunities for Ocean-Based Methods of Carbon Dioxide Removal, Science Policy Brief, DOI: 10.3289/cdrmare.oceannets_1*

2 *Lamb, W.F., Gasser, T., Roman-Cuesta, R.M., Grassi, G., Gidden, M.J., Powis, C.M., Geden, O., Nemet, G., Pratama, Y., Riahi, K. and Smith, S.M., 2024. The carbon dioxide removal gap. Nature Climate Change, pp.1-8*

Ocean basins buffer some of the worst effects of elevated levels of atmospheric greenhouse gases. They absorb about 30 percent of all anthropogenic CO_2 emissions, and much of the excess heat trapped in the biosphere by greenhouse gas emissions (GHG). This means that the ocean is also severely impacted by climate change. From 1901 through 2020, average global sea surface temperature has increased by about 0 0.08 °C per decade, leading to disruptions in ocean circulation patterns, rising sea levels, acidification, and other effects detrimental to marine life and human activities.

Marine CDR and ocean alkalinisation

As by far the largest sink for atmospheric CO_2, the ocean presents multiple opportunities for enhancing its capacity to remove and sequester atmospheric CO_2. Some of the methods to do so are geochemical, relying on the dissolution of alkaline minerals for OEA to durably store atmospheric CO_2 and dissolve ocean bicarbonate (HCO_3).

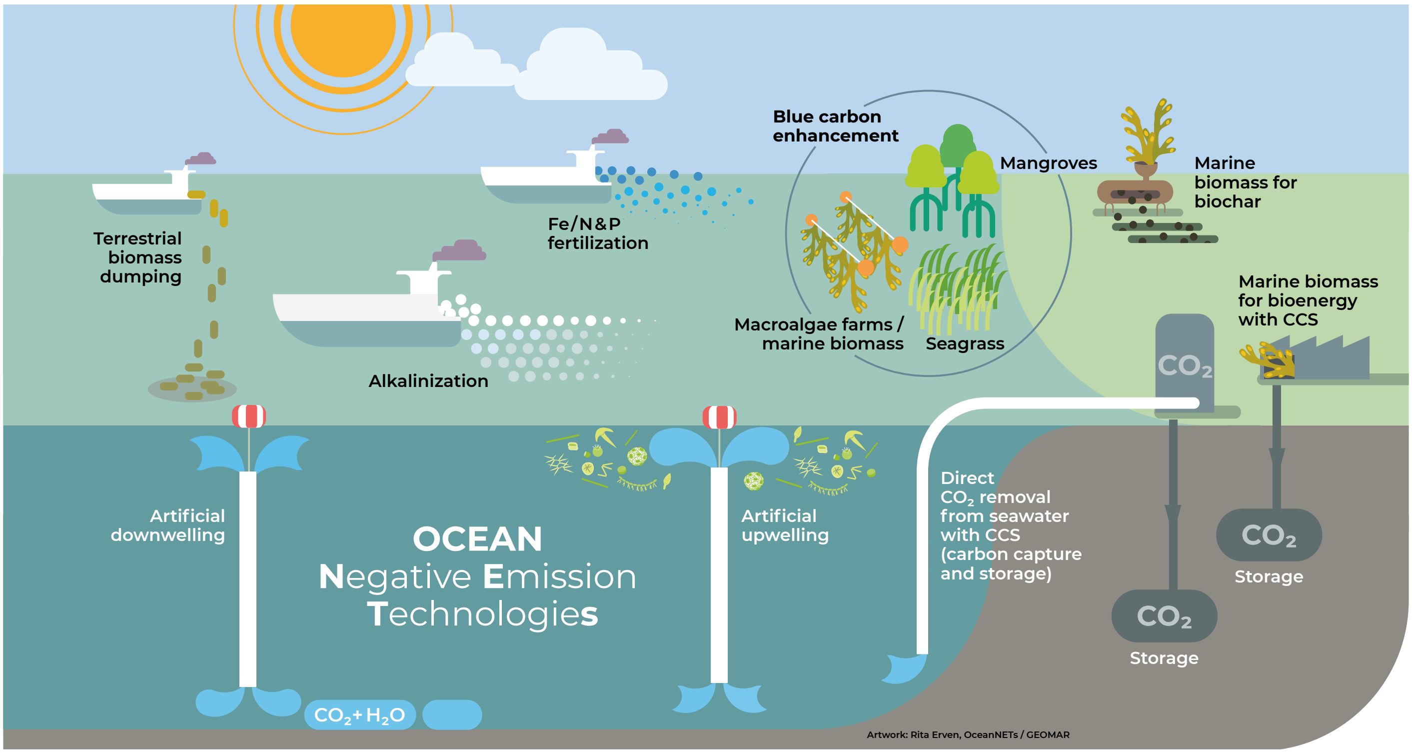

Fig 1 - Proposed methods for CDR in the marine environment

Source: Rita Erven, OceanNETs/GEOMAR

More specifically, OAE refers to interventions that increase the alkalinity of the upper ocean (<100 m) to increase uptake of atmospheric CO_2. There are many potential pathways: employing different alkaline agents (silicates and carbonate minerals) and devising different mechanisms to deliver and disperse additional alkalinity in the oceans. There are currently multiple ongoing studies seeking to assess the CDR potential, and possible environmental risks, of different forms of OAE.

In addition to its climate benefit, in terms of CDR, alkalinisation might provide localised reductions in acidification.[3] Mineral additions can also favour certain plankton populations. Research to assess these potential co-benefits in different marine environments is also underway.

3 *Bach, L.T., Gill, S.J., Rickaby, R.E., Gore, S. and Renforth, P., 2019. CO2 removal with enhanced weathering and ocean alkalinity enhancement: potential risks and co-benefits for marine pelagic ecosystems. Frontiers in Climate, 1, p.7.*

Realistic deployment scenarios: Capitalising on existing industrial processes, capabilities, and supply chains

We currently lack realistic scenarios for the deployment of OAE at climate-relevant scales. Our understanding of ocean alkalinisation is based on models that elucidate the interaction between ocean basins and the rest of the Earth system, but do not incorporate the factors that will determine whether OAE is deployed in a socially, economically, or environmentally viable way.

For example, achieving gigaton (Gt) scale removals of CO_2 via OAE would require sourcing gigatons of alkaline materials. The most economically efficient and environmentally sustainable way of doing so is by repurposing existing spare production capacity in relevant sectors, and by using wastes and byproducts from existing industrial processes as a source of alkalinity. In other words, creating entirely new global industries and supply chains for the primary purpose of ocean alkalinisation will not be an environmentally viable proposition at least in the short term, nor would it be cost-effective in relation to alternative pathways to decarbonisation or CDR. Thus, existing supply chains can be used for the initial deployment, even if these are not sufficient to reach large-scale removals.

An example of spare capacity is in the global cement sector, where existing underutilised kilns could be used to produce lime for use in ocean alkalinisation applications.[4] As for wastes and byproducts, it is estimated that 7 Gt of alkaline minerals are generated annually in the course of industrial processes, landscaping or quarrying.[5] This implies a combined potential to capture and store 2.9–8.5 Gt of atmospheric CO_2 by 2100.[6] An example of a waste or byproduct that could be utilised to produce alkalinity is the reject brines generated in the course of seawater desalination.

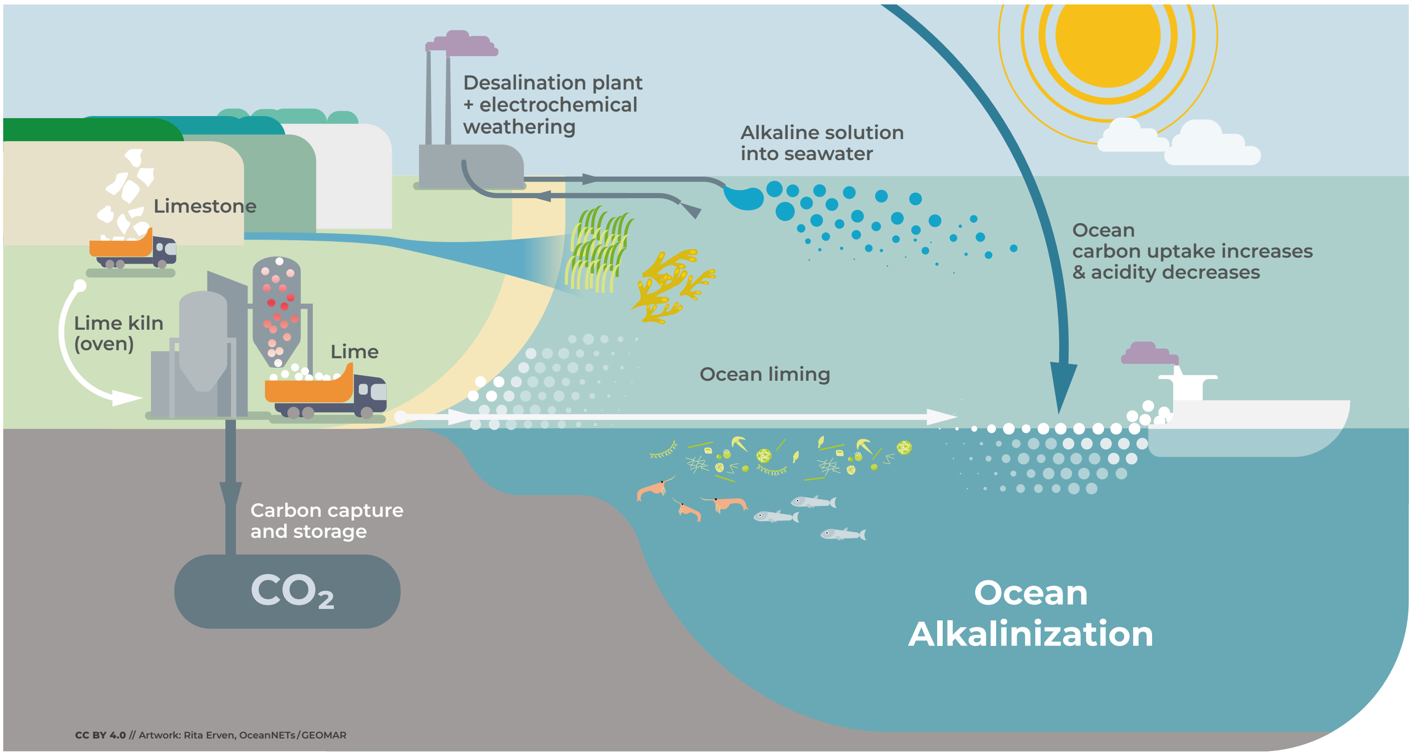

Fig 2 - Ocean alkalization coupled with existing industrial processes (lime production & desalination)

Source: Rita Erven, OceanNETs/GEOMAR

4 *Renforth, P., Jenkins, B.G. and Kruger, T., 2013. Engineering challenges of ocean liming. Energy, 60, pp.442-452.*

5 *Dijkstra, J.J., Comans, R.N., Schokker, J. and van der Meulen, M.J., 2019. The geological significance of novel anthropogenic materials: Deposits of industrial waste and by-products. Anthropocene, 28, p.100229.*

6 *Renforth, P., 2019. The negative emission potential of alkaline materials. Nature communications, 10(1), p.1401.*

Environmental impacts of ocean alkalinisation

There are too many uncertainties about how ocean alkalinisation might affect marine biological communities and other aspects of the marine environment. Research on these dynamics has only started relatively recently, and much more field evidence needs to be gathered before responsible decisions about deployment can be made.

What is apparent is that environmental risks are contingent on the method used to increase alkalinity (e.g. type of alkaline material, whether it is added directly or in a solution, etc.) and the geography of deployment (e.g. oligotrophic or eutrophic waters). Work is underway to assess the potential impacts of different OAE methods on pelagic communities and the biogeochemical fluxes they control.

In a series of contained experimental studies, OceanNETs has assessed the impact of CO_2-equilibrated and non-CO_2-equilibrated additions of alkalinity on natural planktonic communities under natural conditions in oligotrophic and eutrophic marine environments. These studies have detected no obvious threat to pelagic microbial communities, but the data suggests a non-linear response of these communities to the total alkalinity gradient. In some experimental configurations, high levels of additional alkalinity have triggered abiotic precipitation of carbonate materials. This consumes alkalinity and increases dissolved CO_2 in seawater, therefore compromising the efficiency of OAE for CO_2 removal.[7]

Public opinion

Research conducted by the OceanNETs project suggests that familiarity with ocean alkalinity enhancement methods is currently very low among the general public. Support for this form of CDR is also a priori low relative to other forms of ocean-based negative emissions technologies.[8] In quantitative surveys and focus group research, respondents found this form of intervention "risky", "costly" and "more artificial" than other ways of enhancing the carbon removal and sequestration potential of marine environments.

Given the low levels of pre-existing knowledge about this form of climate action and the very few studies available, it is difficult to anticipate how public perceptions of OAE will evolve in the coming years and decades. Research on terrestrial enhanced weathering indicates concerns over upstream (mining) and downstream (runoff pollution of coastal environments) variables that are relevant to many varieties of ocean alkalinisation enhancement under consideration.[9]

7 *Suitner, N., Faucher, G., Lim, C., Schneider, J., Moras, C.A., Riebesell, U. and Hartmann, J., 2023. Ocean alkalinity enhancement approaches and the predictability of runaway precipitation processes–Results of an experimental study to determine critical alkalinity ranges for safe and sustainable application scenarios. EGUsphere, 2023, pp.1-35.*

8 *Veland, Siri and Merk, Christine (2021) Lay person perceptions of marine carbon dioxide removal (CDR) – Working paper*

9 *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(1), p.23.*

Relevant regulatory frameworks

There are, at the moment, no international or national laws dealing specifically with ocean alkalinisation, but the relevant activities will fall under existing regulatory frameworks and instruments. Depending on where they might occur, ocean alkalinisation activities might be regulated under the London Convention/London Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. Other international legal frameworks (e.g., the Convention on Biological Diversity, the UN Convention on the Law of the Sea, the International Convention for the Prevention of Pollution from Ships, the Basel Convention, or the European Union Marine Strategy Framework Directive) might be relevant if the activities take place or affect extra-territorial waters. The specific implications of these or any other legal instruments will be contingent on the type of alkalinisation process.[10] A relevant new international framework is the Biodiversity Beyond National Jurisdiction (BBNJ) treaty, which establishes new tools and obligations to protect marine biodiversity. While its specific application to OAE research and deployment is still highly speculative, it is possible that signatories to this new treaty will introduce new threshold to assess the potential positive and negative impacts of climate interventions that involve introducing "pollution" in marine environments.[11]

Both national regulatory frameworks and international law allow, under certain conditions, scientific research activities that involve the release of materials in open marine environments. Recent and current studies of ocean alkalinisation in contained and open systems have been authorised by the relevant regulatory authorities in several countries (e.g. UK, Spain, Norway, Germany, United States, Canada).

Key characteristics of ocean liming

Ocean liming (OL) involves spreading particulate calcium oxide (CaO) or calcium hydroxide in ocean waters to increase their alkalinity. The approach relies on the ability of these materials to dissolve rapidly in the ocean surface. That dissolution triggers a series of reactions in the oceans' carbonate system which result in a drawdown of atmospheric CO_2.

This approach was first proposed in the 1990s, and is currently being assessed through modelled simulations and field studies.[12] There is significant experience in some countries of small-scale liming to reverse acidification of lakes and river systems. OL extrapolates this idea to the oceans, with the primary purpose of enhancing their role as atmospheric carbon sinks.

The purpose of this scenario is not to recommend this (or any other) form of OAE, but to characterise the potential of this kind of climate action and to identify the factors that will need to be addressed before OL can become a viable option for large-scale CDR.

Our analysis draws on a full life-cycle assessment (LCA) of OL, and a series of discussions with relevant industry actors and other stakeholders to determine potential scenarios for the further development and eventual deployment of this technology. In those discussions we have tried to imagine conditions for a potential deployment by 2040-2050 in line with current climate change mitigation targets.

10 *Webb, R.M., Silverman-Roati, K. and Gerrard, M.B., 2021. Removing Carbon Dioxide Through Ocean Alkalinity Enhancement: Legal Challenges and Opportunities.*

11 *Will Burns and Romany Webb, "The Biodiversity Beyond National Jurisdiction treaty and its implications for marine-based carbon dioxide removal." Illuminem. 23 August 2023.*

12 *Kheshgi, H.S., 1995. Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. Energy, 20(9), pp.915-922.*

Existing potential

The global CDR potential through ocean liming has been modelled in the order of 1 $GtCO_2$ by 2055, assuming early and ambitious deployment.[13] It is equally plausible that initial adoption of this approach will be regional and small-scale. In a detailed case study for Spain, the potential CO_2 removal of OL, when using existing limestone resources and cement production facilities, has been estimated at 23 $MtCO_2$ per year.[14]

Life cycle assessment

Achieving a carbon-negative use of lime is a challenging proposition. Lime production is emissions-intensive, particularly in the comminution and calcination of limestone (the cement industry accounts for about 7 % of total anthropogenic emissions). If OL is to contribute a net reduction of atmospheric CO_2, it is necessary to consider its full life-cycle, and account for all the emissions associated with its production, transportation and dispersion in surface ocean waters.

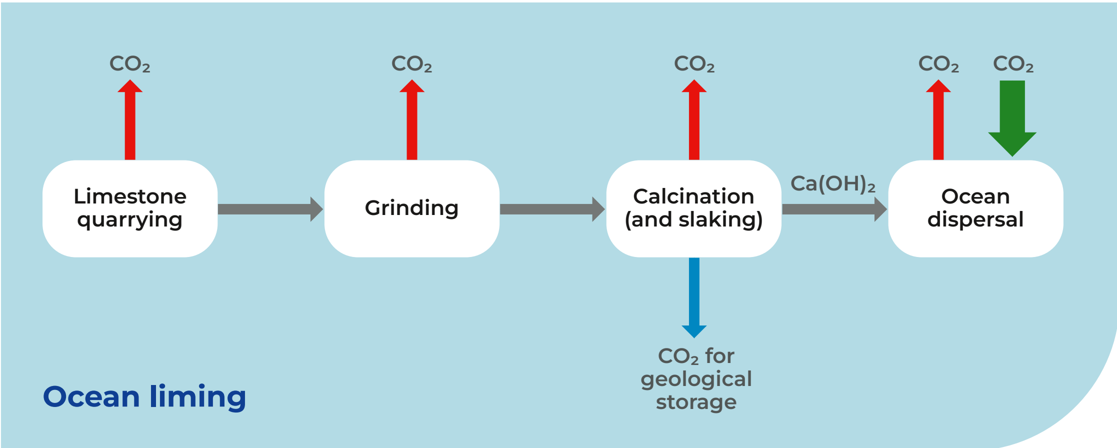

Fig 3 - Simplified process flow diagram for ocean liming, identifying sources of CO_2 emissions and removals

Source: Rita Erven after Spyros Foteinis and James Campbell

Considering the current situation of the European cement sector as the base scenario, the optimal scenario to ensure that OL (calcium hydroxide) can achieve a net removal of atmospheric CO_2 includes the following assumptions:

- An energy efficient kiln type: 10 % reduction compared to the base scenario.
- Calcination heat provided by a thermal plasma torch (hydropower driven): 30 % reduction compared to the base scenario.
- Limestone mining takes place next to the coastline, i.e., road transportation is not required: 4 % reduction compared to the base scenario.
- Renewable electricity (hydropower) is used throughout the process: 42 % reduction compared to the base scenario.
- Low-grade heat is recovered and used for district heating: 9 % reduction compared to the base scenario.

Additionally, it will be necessary to equip the lime production facility with the capability to capture and storage the carbon emissions (CCS) generated in the calcination process. Under these

13 *Ocean alkalinity technologies are deployed as early as 2025, considering a 0.1 % initial allocation of carbonate and silicate minerals from the construction aggregates industry and a 12 % annual growth rate (OceanNETs First periodic report, p.57).*

14 *Foteinis, S., Campbell, J. Bullock, L. Madankan, M., Valenzuela, J.M., Lezaun, J. and Renforth, P. (Unpublished). Spain's realistic carbon dioxide removal potential through ocean alkalinity enhancement.*

conditions, the carbon footprint of OL will be as follows (Red: life cycle carbon emissions; green: removed carbon), as seen in Figure 1.

Assuming these conditions are met, when 1.321 tonnes of calcium hydroxide are spread in the ocean, the uptake is 1 tonne CO_2 from the atmosphere, while the greenhouse gas emissions of the process, up to the spreading of the lime, will amount to 449 kg CO_2eq (base scenario). In this sense, with existing technology and for the European setting, OL's net carbon benefit is 551 kg CO_2 for every 1761 kg of limestone that is mined, processed, and spread into the ocean as calcium hydroxide.[15]

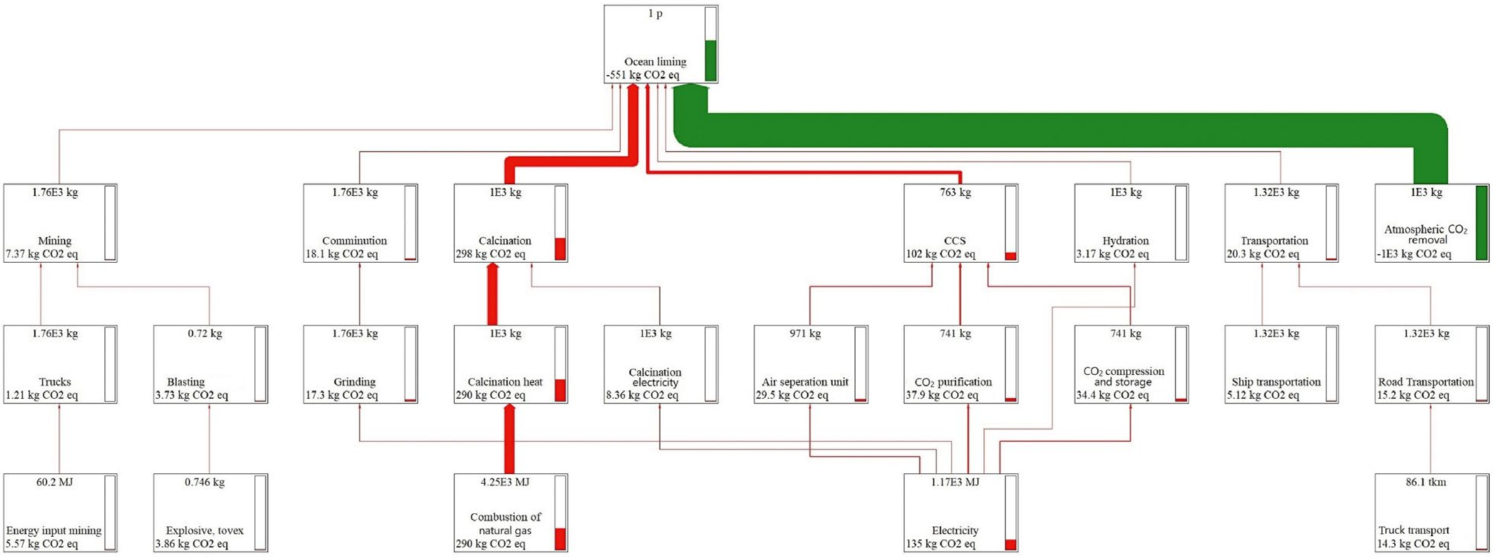

Fig. 4 - Dendrogram showing the main life cycle for the base scenario (Note: Carbon emissions in red and removals in green).

Source: Foteinis, S., Andresen, J., Campo, F., Caserini, S. and Renforth, P., 2022. Life cycle assessment of ocean liming for carbon dioxide removal from the atmosphere. Journal of Cleaner Production, 370

Environmental hotspots

CO_2 emissions are not the only environmental impact associated with lime production and spreading. The expansion of limestone mining and the management of CO_2 storage creates additional environmental hotspots.

The expansion of limestone mining activities is specific to this approach, which we were able to discuss with stakeholders (see below). The production of low-emissions lime should respond to the concerns raised in these discussions.

Concerns over the proper storage of CO_2 for long-term geological storage has been addressed in regulation, as this activity is seen as central to the decarbonisation of key industrial sectors.[16]

Constraints and bottlenecks for further development

Stakeholders identify a series of key constraints or bottlenecks that will need to be addressed, if OL is to become a viable option for large-scale CDR:

- Absence of national and international frameworks to account for removals via ocean alkalinisation as a condition for proper governance and economic compensation. Without such a framework, there are no economic incentives to invest in OL (or any other form of OAE).

15 *Foteinis, S., Andresen, J., Campo, F., Caserini, S. and Renforth, P., 2022. Life cycle assessment of ocean liming for carbon dioxide removal from the atmosphere. Journal of Cleaner Production, 370, p.133309.*

16 *See the European CCS Directive which addresses safe geological storage of CO_2 (https://climate.ec.europa.eu/eu-action/carbon-capture-use-and-storage/legal-framework-safe-geological-storage-carbon-dioxide_en).*

- Recent investments in high-efficiency kilns driven by current emissions regulations, which might slow down the transition to new zero-emissions calcination infrastructure.
- Competition for low- or zero-emissions lime. There are currently much more technologically and economically mature markets for 'carbon neutral' lime. It is not apparent how OL would become an attractive utilisation option in the absence of clear accounting and compensation mechanisms (see above).
- Uncertainties regarding the regulation and public acceptability of CCS facilities. This is true in the European Union, perhaps less so in other jurisdictions.
- Constraints on the expansion of limestone extraction. In several jurisdictions (including EU and UK) any expansion of mining or quarrying activities is likely to confront severe regulatory scrutiny and public opposition.
- Lack of clear economic incentives/compensation for repurposing existing shipping fleets for the transportation and dispersion of calcium hydroxide at scale.

Steps towards meaningful demonstration projects (for potential deployment in the 2040s)

Here we identify some of the steps that will need to be taken over the coming decade, if OL is to become a viable option in the 2040s.:

1. **Produce a clearer picture of potential environmental risks** associated with the introduction of calcium hydroxide in marine environments. Fund additional laboratory, mesocosms, and possibly field experiments to better characterise the interaction of different concentrations of calcium hydroxide with marine biological communities.
2. **Address the role of decarbonisation across relevant sectors:** For OL to be a compelling proposition, a prerequisite is the decarbonisation of lime production and maritime shipping. Stakeholders have high confidence in a fuller decarbonisation of calcination and shipping by 2040, but there is clear potential to accelerate these trends.
3. **Resolve the economic and engineering uncertainties regarding dissemination logistics:** Stakeholders struggled to imagine what a large-scale marine dissemination infrastructure for lime or slaked lime might look like. Research is needed to explore whether commercial fleets might incorporate liming in their business plans, whether purpose-built ships will be necessary, and the conditions for appropriate monitoring, reporting, and verification.
4. **Discuss potential scale of deployment with regulatory authorities and national publics:** In the short term, focus attention on the regulation of OAE R&D activities under the London Convention and the London Protocol. Encourage public debate over the role of ocean liming within an extensive set of ocean-based climate interventions in international governance, addressing its relation to biodiversity conservation and ocean protections.
5. **Debate the availability of limestone:** The availability of limestone is an obvious constraint for the development of OL as a climate-relevant option. Foster public and political debate on the desirability (or not) of expanding limestone production as an example of increased mineral extraction associated with energy and climate transitions.

OceanNETs is a European Union project funded by the European Commission's Horizon 2020 program under the topic of Negative emissions and land-use based mitigation assessment (LC-CLA-02-2019), coordinated by GEOMAR Helmholtz Center for Ocean Research Kiel (GEOMAR), Germany.

OceanNETs responds to the societal need to rapidly provide a scientifically rigorous and comprehensive assessment of negative emission technologies (NETs). The project focuses on analyzing and quantifying the environmental, social, and political feasibility and impacts of ocean-based NETs. OceanNETs will close fundamental knowledge gaps on specific ocean-based NETs and provide more in-depth investigations of NETs that have already been suggested to have a high CDR potential, levels of sustainability, or potential co-benefits. It will identify to what extent, and how, ocean-based NETs can play a role in keeping climate change within the limits set by the Paris Agreement.

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