POLICY BRIEF

Realistic Deployment Scenarios for Ocean Alkalinity Enhancement

Brine Splitting

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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])

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[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).

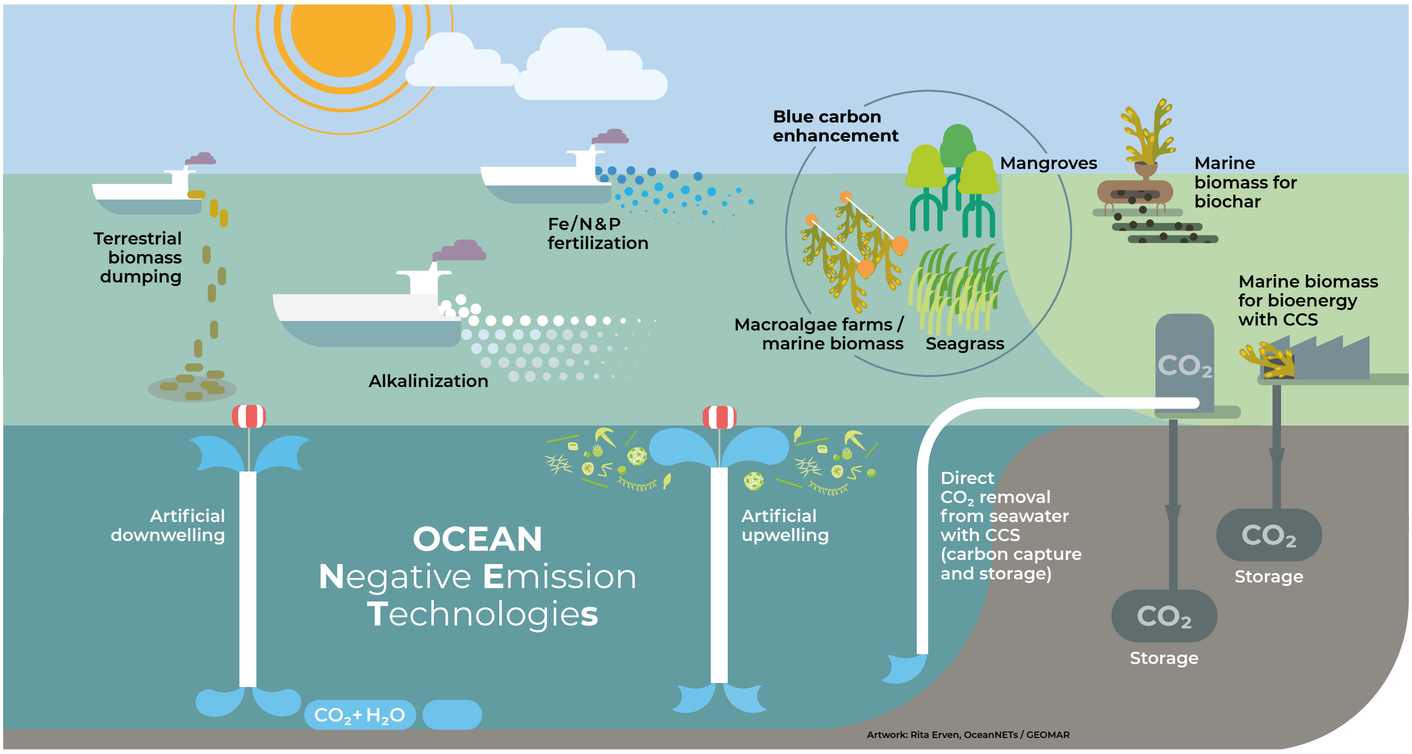

Fig 1 - Proposed methods for CDR in the marine environment

Source: Rita Erven, OceanNETs/GEOMAR

In more detail, 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.

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[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.

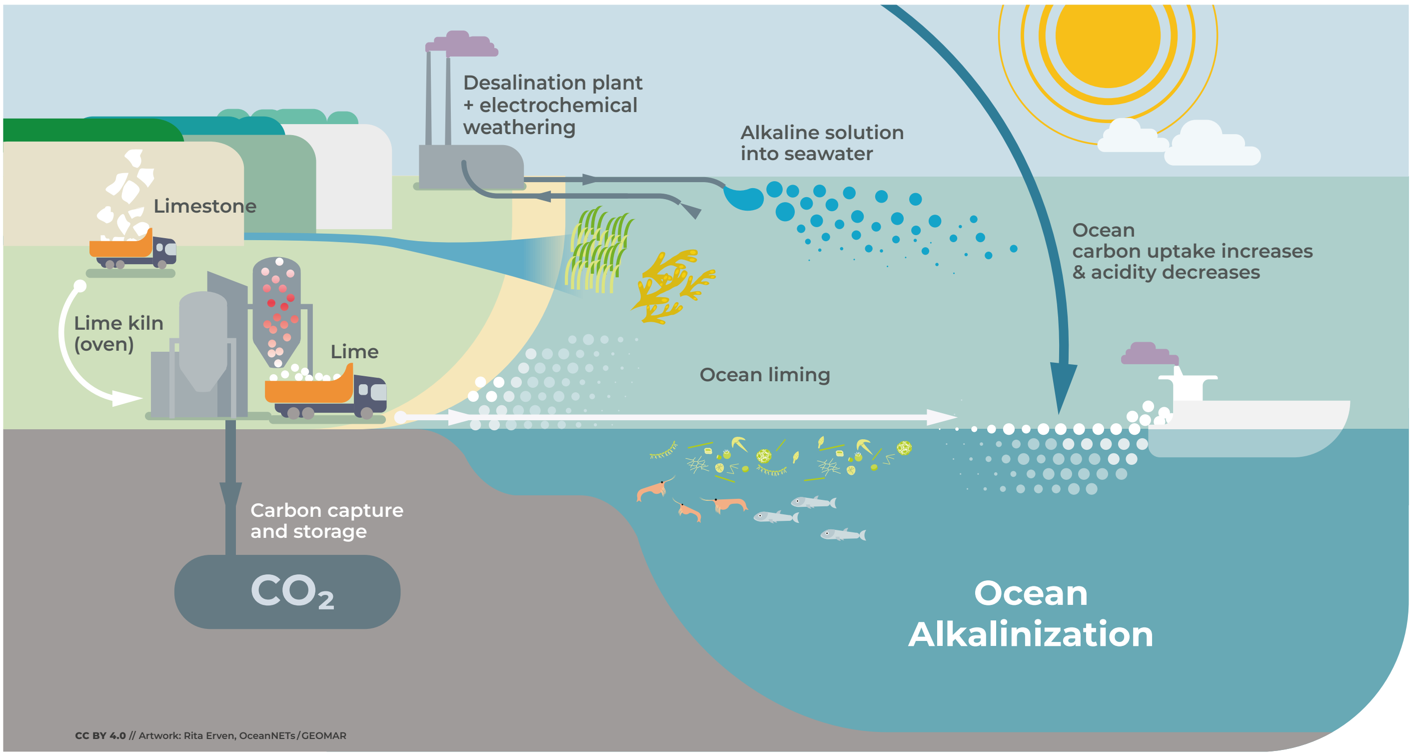

Fig 2 - Ocean alkalization coupled with existing industrial processes (lime production & desalination)

Source: Rita Erven, OceanNETs/GEOMAR

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[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 still 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]

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[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 electrochemical brine splitting for OAE

Brines such as seawater can offer an abundant source of alkalinity in the form of sodium hydroxide (NaOH), which can be extracted through electrochemical treatments. There are two main electrochemical methods for generating alkalinity from brines: electrolysis and electrodialysis. Electrolysis decomposes water and produces a higher concentration of aqueous sodium hydroxide, along with gaseous hydrogen and chlorine. Electrodialysis focuses on ion transport across membranes and produces sodium hydroxide in lower concentrations, together with hydrochloric acid. Electrodialysis is about 60 % more energy efficient, but is less mature as a technology (approximately 99.5 % of sodium hydroxide production worldwide is generated through electrolysis, primarily by the chloralkali process).

Waste or reject brines from desalination plants have a higher concentration of aqueous sodium chloride (NaCl) which facilitates its extraction. The infrastructure used to dispose and disperse reject brines from desalination plants could be used to release this alkalinity into the ocean.

There is thus an opportunity to integrate alkalinity production for ocean alkalinization with the desalination sector in a cost-effective and carbon-negative manner. This integration is contingent on a series of factors, detailed below.

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[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.*

Existing potential

Growing water scarcity and insecurity are driving a significant expansion in seawater desalination capacity worldwide. Desalination is estimated to generate globally more than 141 million m^3 of brine every day. Those brines are typically discharged into the oceans, negatively affecting coastal ecosystems. Desalination capacity is expected to more than double by 2030.

This represents a massive untapped alkaline resource, with the potential to generate large-scale removals of atmospheric CO_2. In a detailed study of the potential of current desalination infrastructure in Spain to generate alkalinity for CDR, and on the basis of the LCA detailed below, we estimated a potential to capture 2 $MtCO_2$ per year in that country alone.[12]

Components of the life-cycle assessment

The LCA indicates that electricity consumption is, the main environmental hotspot of electrochemical brine splitting (EBS) and, as such, the critical factor in its carbon footprint. Although electrodialysis offers high potential for better energy efficiency, given the current level of readiness of the technology (TRKL), and its limited penetration in the desalination sector, we consider electrolysis as the separation technology available for production at scale over the next decade.

A carbon-negative deployment of EBS will require a faster transition of desalination plants to renewable energy sources. This transition is proceeding at different pace (if at all) in different regions and countries.

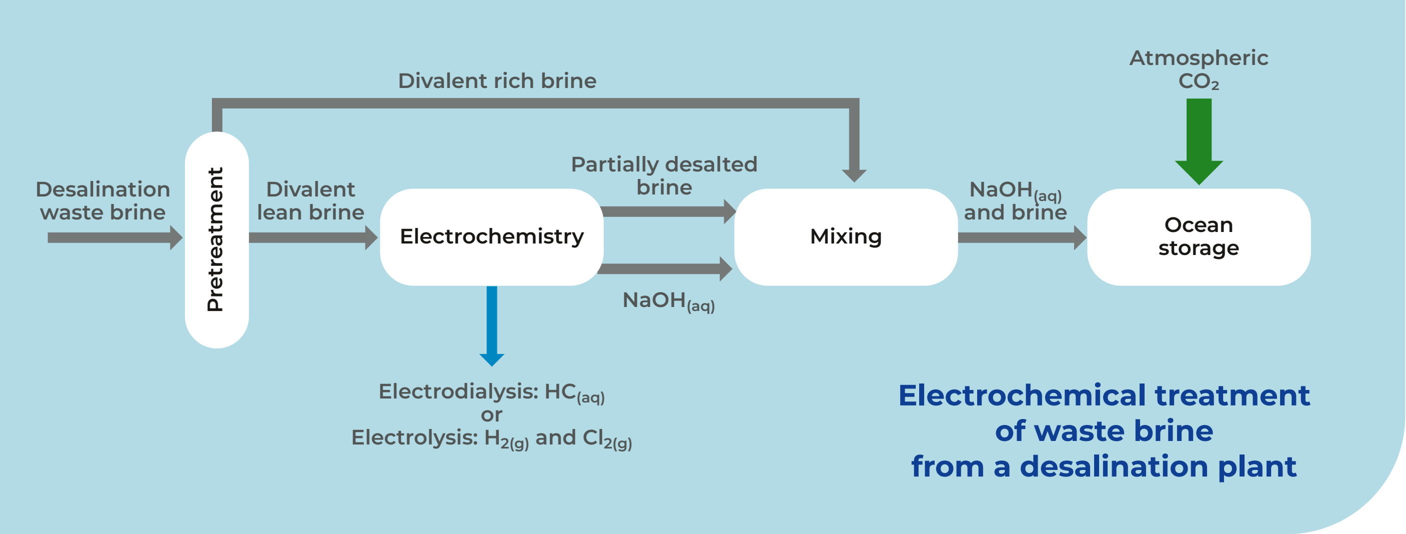

Fig 3 - Simplified process flow diagram for electrochemical treatment of waste brine from a desalination plant

Source: Rita Erven after Campbell, J., Foteinis, S., Madankan, M. and Renforth, P., 2023. Report on the detailed life cycle analysis results of the two case studies: ocean alkalinity enhancement potential of Spain.

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[12] *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.*

Environmental hotspots

If electrolysis is used to generate the alkalinity, any large-scale electrochemical splitting of brines will generate large amounts of chlorine gas, beyond what the current market for this byproduct can absorb. Chlorine gas is a potential environmental hazard. However, it can be combined to form hydrochloric acid (HCl), which can be stored in a more diluted form or neutralised through reaction with alkaline materials. Electrodialysis also generates hydrochloric acid as a by-product.

Significant increases in sodium hydroxide production for ocean alkalinization will thus require new infrastructures for the safe handling and storage of the byproducts of brine splitting through electrolysis.

Constraints and bottlenecks for further development

Stakeholders engaged to discuss the LCA identify a series of bottlenecks constraining the development of EBS to a higher level of readiness.

- Absence of national and international frameworks to account for removals via ocean alkalinisation as a condition for proper governance and economic compensation. As with any other type of OAE, without adequate monitoring, reporting, and verification (MRV) there are no incentives for investment or conditions for an adequate governance of this climate intervention.
- Carbon-negative ocean alkalinisation with electrochemically splitted desalination reject brines is contingent on a full transition of the relevant desalination plants to renewable energy. Although this transition is underway, it is far from complete, and in many of the areas where desalination capacity is concentrated it has barely started.
- Presently, regulations for brine management and disposal may not permit the release of brines with much higher concentrations of sodium hydroxide. Environmental impact assessments for this scenario are not ready.
- Handling, storing, and neutralising some of the hazardous byproducts of electrochemical splitting is a challenge in many jurisdictions. Industry actors and regulators are not ready to neutralise a massive increase in chlorine gas or hydrochloric acid production levels.

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

For technology development purposes, brine-splitting processes for alkalinity production can be built on top of existing desalination plants. This allows a better characterisation of the full process's carbon footprint, from seawater extraction to the return of extracted alkalinity. However, more efficient use of brines for alkalinity production will likely require stand-alone plants optimised as a separately engineered system.

1. **Develop models for the localised governance/permitting of desalination coupled with electrochemical production of alkalinity for OAE.** Existing regulatory frameworks for desalination do not contemplate the possibility of disposing of highly concentrated sodium hydroxide. Explore what the governance of such a coupled system might look like in regions where large-scale desalination capacity and brine disposal infrastructure already exist.

2. **Plan for the integration with existing water and electricity infrastructure:** Existing infrastructure includes desalination plants, but also ancillary infrastructure like water discharge pipelines and electricity grids. The increased electricity demand from brine splitting will need to come from zero-emissions sources in systems with higher reliance on variable energy.
3. **Track the evolution of electrolysis and electrodialysis industries:** The advancement of these critical technologies, and particularly of electrodialysis, is contingent on trends in electricity decarbonisation and the evolution of other industries, like hydrogen production or lithium extraction. Although the LCA considers ways of integrating these technologies into existing desalination plants, experts suggest brine-splitting processes would ideally be optimised as a separately engineered system.
4. **Invest in brine mining technologies more generally.** Brine-splitting for alkalinity will benefit from a broader programme to research and incentive different approaches of extracting valuable minerals from desalination waste brines.
5. **Support better management and utilisation options for brine-splitting by-products:** The LCA and stakeholder discussions highlighted the challenge of managing large volumes of hydrochloric acid. Explore potential large-scale industrial uses of this product.
6. **Assess the public acceptability of expanding desalination capacity and its potential contributions to climate action:** The availability of large desalination infrastructures and relevant environmental regulations are promising starting points for public debate. Such debate should focus on the conditions for co-optimising different processes (reducing water waste, enhancing desalination potential, developing capacity for low-emissions electricity generation).

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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