Ocean-based Negative Emission Technologies

OCEAN NETs

Deliverable Title	Report on the expert workshop on current and future costs and learn curves
Lead	FMI
Related Work Package	WP 1
Related Task	Task 1.2
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Abstract: In this report the workshop on cost and scale of deployment scenarios for ocean liming is described. Participants discussed potential configurations of ocean liming deployment scenarios and the associated cost and scale levels. A simulation tool was used as a means to structure the discussions. Cost and scale scenarios for the period 2030-2050 were covered.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 869357.

Document History

Date	Version	Description	Name/Affiliation
01.12.2022	0.1	First version, sent to workshop participants for commenting	Van Kooten, Perrels, FMI
08.12.2022	1.0	Completed report, revised after feedback from workshop participants	Perrels, FMI
15.12.2022	1.1	Quality of Attachments has been improved	Van Kooten, FMI

1. Introduction

1.1 Context

OceanNETs is a European Union project funded by the 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.

1.2 Purpose and scope of the deliverable

This deliverable, D1.3, presents the workshop that constitutes Milestone 31 and is part of the activities under Task 1.2. The purpose of Task 1.2 is to provide an assessment of the unit-costs of different NETs, expressed in euros per ton CO_2 abated, both in the near future and several decades ahead when learning processes and scale economies might enable reduction of the unit-costs. The envisaged learning curve analysis could not be applied in the conventional way, owing to lack of sufficiently reliable data. The analysis of the structure and possible development of the unit-cost is nevertheless rooted in the spirit of learning curve analysis, i.e. understanding the influences of the constituting components on the unit-cost and casting this in a scenario tool in which the developments of the main features of the constituting components can be represented. Next to and in close association with prospects on *unit-cost* development, the assessment considers the development of the *scale of deployment* of different NETs.

The workshop presented in this report utilized the aforementioned scenario tool as a platform to engage with expert stakeholders from industry, NGO and research. The goal of this workshop was to gain a more profound understanding of the potential pathways for the cost and scale development of ocean liming linked to the selection of different deployment scenario configurations.

This workshop was specified to ocean liming as a means of ocean alkalinity enhancement. Ocean liming is the only ocean-based NET for which a scale and cost scenario study could be credibly performed since it depends mostly on existing industries contrary to most other NETs.

1.3 Relation to other deliverables

The workshop reported in this document is relevant for the investigations into the cost and scale development and thus competitiveness of different NETs performed in Task 1.2. Furthermore, task 1.2 was carried out in close cooperation with WP6 (Tasks 6.2 and 6.4). The indications for plausible scales of deployment are also relevant as background information for model exercises in WP4, aimed at checking the effects on atmospheric concentrations of CO_2 and on the levels of global warming until 2100. Lastly, the cost data of selected scenarios for ocean alkalinization have been used in the concurrent EU Horizon project NEGEM to check its competitiveness in comparison to other CO_2 abatement technologies.

1.4 Content of the report

The primary purpose of this report is to describe and summarize the workshop held on 23.11.2022. Given this purpose of properly representing the thoughts and issues that came forward during the workshop this report is not in retrospect discussing the validity of the arguments brought forward. Such judgements are only included if these were brought forward during the discussions in the sessions. The summary of the workshop is meant to enable the researchers to draw lessons in how to conduct and present the deployment scenario, which implies we had to somehow synthesize the comments made per discussion topic so as to arrive at sufficiently clear statements, hence participants will usually not directly find back their own statements. This in fact concords with the Chatham House rules.

2. Preparation and Programme

2.1 Preparation

The workshop was preceded by a joint workshop with WP6 on July 4th, 2022 exploring potential deployment scenarios of ocean liming. Moreover, informative consultations were held with a broad range of expert stakeholders. These earlier interactions have provided insights on the conditions of and possibilities for future ocean liming deployment scenarios. The workshop served to complement the earlier work by creating a connection between possible deployment scenario configurations and realistic scale and cost levels.

Prior to the workshop, FMI developed a scenario simulation tool for ocean liming. This tool allows users to make qualitative choices on the configuration of ocean liming. The tool computes cost and scale levels given a set of configuration choices. Based on earlier expert stakeholder engagements, six choice categories were formulated: International Regulation, Financial Sourcing, Organizational Form, Dispersion Technique, Land Operations and Operational Effectiveness. More details on the tool are included in Annexes 4.3, 4.4 and 4.7.

The overall goal of the workshop was to discuss current and future cost levels and learning curves for ocean liming. More specifically, the workshop aimed to determine the most likely ocean liming supply chain configurations for the 2030, 2040 and 2050 decades. The tool was meant to serve as a means to structure conversations and to assess the cost development of individual cost components in the workshop. The workshop would then provide feedback on the accuracy and usefulness of this tool at the same time.

Workshop participants were selected based on their expertise and background. It was attempted to gather a group of representatives from the lime and shipping industries, carbon capture projects, NGOs, research and policy makers. Several researchers from within the OceanNETs project were invited to participate as well. Moreover, two researchers from the NEGEM project attended the workshop. An effort was made to include participants from outside of the European Union to expand the scope of this workshop and contribute to more generalizable results. The workshop was conducted through Microsoft Teams.

Before the workshop, participants received a formal invitation (Annex 4.1). After participants confirmed their attendance, the official programme (Annex 4.2) was shared. At the same time, the tool was made available to participants through OneDrive (Annex 4.4) together with a description of ocean liming and of the tool itself (Annex 4.3). An online survey was opened for participants to share their initial ideas on the ocean liming scenario configurations which can be chosen in the tool (the set of survey questions can be found in Annex 4.5).

2.2 Programme

The workshop was structured as follows:

- **Introduction and general discussion:** In this part of the workshop a presentation on OceanNETs as a whole and the work in WP1 and Task 1.2 was given to provide participants with the workshop's context (see Annex 4.6). A second presentation focused on the earlier described tool (see Annex 4.7). After the presentations a short initial discussion followed. This part of the workshop was scheduled to last from 13.30 until 14.05 CET.

- **Breakout session 1:** Participants were split into three groups of approximately 5 participants. Each group was moderated by one of the organizers. In this breakout session, the tool was primarily used to identify the possible configuration for ocean liming in the 2030, 2040 and 2050 decades. Discussions focused on the most likely scenario selections and the linked scale outcomes. This part of the workshop was scheduled to last from 14.05 until 14.45 CET.

- **Break:** Participants were given a short break of approximately 15 minutes between breakout session 1 and 2. This part of the workshop was scheduled to last from 14.45 until 15.00 CET.

- **Breakout session 2:** The composition of the breakout groups remained identical to the group composition in the first breakout round. This session shifted the discussion from scale levels to cost levels of scenarios. The cost breakdown by supply chain element was a focus area. Additionally, some of the underlying parameters and assumptions of the tool were discussed. Participants were given the opportunity to reflect on the accuracy of these assumptions and provide feedback. Towards the end of the second breakout session, moderators formulated a brief summary of the key discussion points jointly with their breakout-group participants. This part of the workshop was scheduled to last from 15.00 until 15.35 CET. In one group a participant could not return to the second session after having dropped out due to a failing connection.

- **Concluding plenary:** All participants convened again in a joint session. First all three moderators presented the key discussion points from their respective breakout groups. Where necessary, participants complemented the moderators. A general discussion followed. The session was concluded with general remarks about the follow-up from this workshop.

3. Outcomes and Follow-up

3.1 Outcomes

This section presents the input from participants in the workshop and analysis by the authors of this report. All input discussed is grouped by theme.

3.1.1 Summary of input from participants

Simplifications of scenario features in the tool

Most participants did see value in using a tool as a way to systemically assess different scenario choices for ocean liming, though the tool might require some adjustments. However, during the discussions it became clear that a tool based on binary choices could be too simplistic, especially if it can be expected that in practice a combination of choice options would occur instead of either alternative. Some participants believed that a choice between public and collective financing would be the least likely binary choice, since the availability of private means would largely be driven by public incentives such as the offset compliance market. Participants interpreted the tool as having a strong path dependence despite all choices being available for all time periods. Moreover, concerns were expressed that the scenario information may be regarded as more authoritative than it merits and/or false validation would be extracted from this tool, even though it is not able to cover all relevant aspects of ocean liming.

Regulation and research

Given the current state of knowledge on the effects of ocean liming, some participants struggled to accept that by the 2040-decade, international regulation would already be facilitating. On the other hand, some other participants expressed that large scale possibilities would be necessary by 2040 to reach impactful scales. Participants communicated their belief that operational effectiveness and international regulation would be tightly connected. They would not expect even a restrictive regime under low operational certainty, while a facilitating regime was believed to be only possible under high operational confidence. At least medium confidence was expected by 2030. Moreover, participants indicated that they would expect the operational certainty to be directly linked with the discharge rate, while the rates used in the tool were perceived as low.

Role of the public sector

In earlier stages of ocean liming, a publicly resourced system seemed to be preferred by the participants. A public system would be able to deal with uncertainty regarding international regulations and lime discharge effectiveness. The scale of deployment possible by the public sector strongly depends on the availability of public finance, which was modelled as too low according to a group of participants. In later decades, participants would expect ocean liming to be carried out primarily commercially. It was noted that past 2050, the role of the public sector could increase if the goals of decarbonization set by Western economies are reached. Then, incentives for carrying out ocean liming by the private sector might be insufficient. Participants noted that the capacity under a publicly funded system was clearly below that of a privately funded system.

Dispersion design and land logistics

Some participants strongly preferred the use of dedicated ships as this would be cheaper due to specialization and be more effective in spreading lime to desired locations. Another participant expressed that partial capacity use could be expected in earlier phases as the required investment would be lower. One participant envisioned a transition from dedicated ships to partial capacity use over time, as ocean liming would be included in the basic design of most ships. The assumed construction and conversion capacity of ships were perceived as too high. Additionally, a participant wondered about alternative means of lime dispersion. Participants believed that the land logistics and ship design choice are tightly linked. If a large fleet of partial use would be created, a scattered supply seems the most likely option. One participant expressed concerns regarding the land-based emissions of such a logistical system, as the requirements for the lime production process as well as geological storage of released carbon dioxide can be expected to be highly centralized, thus preferring a centralized logistical design.

Development of cost levels

In general, participants noted a strong interdependence between the different years in terms of cost outcomes. They were however surprised by large shifts in cost levels due to changing regimes in especially transportation and land logistics choices. Some discussion around the cost levels of Carbon Capture and Storage (CCS) and lime production revealed that some participants were concerned about current high operating costs due to increased energy prices persisting in the future, whereas other participants were expecting more technological development leading to lower costs for both CCS and lime production.

Competitiveness of ocean liming

The projected cost raised a discussion amongst participants regarding the competitiveness of ocean liming as a means of carbon capture. Some participants commented that the projected costs would stay above the expected cost pathways of competing technologies such as DACCS, which would lead to a diversion of potential investments from ocean liming towards these other technologies. Another participant suggested that ocean liming could remain experimental until 2050 and would only become competitive after that when comparing it to the potential of BECCS and afforestation. Moreover, another group of participants expressed that the relative competitiveness of technologies is not of high importance as they believed that a mix of different technologies would be required anyhow.

Transparency and openness

Participants expressed that they would want to get more and better access to the tool. Uncertainty regarding the inclusion of several cost factors was expressed. Some participants had access to the tool prior to the workshop, but some technological difficulties prevented them from working with it. Moreover, participants mentioned that they would have wanted to have access to the underlying computations as well and they indicated that it was difficult to understand the relations between the different choice categories. Participants noted that clarification and more openness would strongly improve the transparency of the work.

3.1.2 Synthesis

General

Despite some shortcomings, the tool seems to provide relatively plausible estimates for both the cost and scale of ocean liming. With some suggested amendments, the tool could therefore be used to provide indications of the development of ocean liming cost and scale levels under alternative deployment conditions. Binary choices are more easily modeled and have therefore been implemented in the tool. The potential for hybrid options as indicated by the participants requires additional prudence in the interpretation of tool outcomes based on binary decisions. Furthermore, even though comments on various aspects are as such valid, participants may not fully grasp the consequences of suggested alternatives due to the fair degree of complexity. E.g., in case of parallel use of dedicated fleets and converted carriers there is good chance that persistent or semi-permanent unit-cost differences occur between the system segments.

In preparation of the workshop, it was decided that sharing all computations and parameters with participants would distract from the goals of this workshop's discussion. However, we strive to improve the descriptive materials and openness of the tool.

The scenario choices across breakout groups are clearly distinctive, differences are supported by arguments. This means that in later stages of this research, alternative scenarios with differing cost and scale ranges can be formulated, which will be fundamental in our complete cost and scale analysis.

Scale levels

In this workshop it has become clear that at least in the 2030-decade, a more restrictive and thus experimental scale of ocean liming seems plausible. Whether an increase in scale after 2040 or 2050 could happen, appears to depend strongly on the technological readiness of ocean liming and the interaction between technological readiness and the international marine regulations.

During the workshop, the link between the size of the ship construction industry and potential scale levels was explained. Yet, participants indicated that our estimates for the construction and conversion capacity were high. This would imply that the annual attainable capacity would be lower than assumed earlier. On the other hand, the identified higher potential for the discharge rate at higher operational effectiveness levels could lead to a significant increase in attainable annual volume of liming with the same fleet size.

The fact that the public sector could finance part of ocean liming has always been one of our considerations. In this workshop it became clear though, that at least the modeled disposable means for ocean liming could potentially be higher. Moreover, the role of public financing systems in a fully decarbonized economy to reach net negative goals is something that will require more investigation.

The competitiveness of ocean liming compared to other NETs remains an important topic for further investigation. Competing cost levels will require a significant scale, yet a significant scale will not be reached if those competing cost levels are within reach. Uncertainty on the technological and environmental levels currently prevent this. It seems that ocean liming might only become operational if these concerns are reduced within a limited time span. It appears that if ocean liming were to be postponed too long it might not be able to compete against other technologies anymore.

Cost levels

The development of cost levels over time turned out to be contentious, especially when different logistical systems were chosen. This means that the underlying assumptions for regime changes will need to be reassessed carefully. Moreover, discussions around the predicted CCS and lime production costs will require further unpacking. The relative importance of these two elements on the overall costs causes that the certainty of the overall cost prediction is strongly dependent on these cost element predictions. However, predictions for these factors are speculative and the result of an innovative process of which the outcome cannot be predicted accurately at this time.

3.2 Further research on ocean liming

This workshop will directly contribute to D1.4, and its analysis of the cost and scale potential of ocean liming. Together with our initial workshop, stakeholder engagements and literature analysis, it will feed into our final analysis of ocean liming deployment cost and scale outcomes.

Concretely, we will pursue follow-up meetings with some of the workshop participants to clarify some issues and gain a more profound understanding of the individual cost components. Moreover, some additional individual stakeholder engagements will take place to receive input from a broader audience.

The different scenario configurations created by participants will be analyzed to generate several conditioned ocean liming outcomes. This set of outcomes will contribute largely to our analysis of the most likely configurations and associated cost and scale indications.

The tool will be amended as suggested by participants. It will be made more accessible and user-friendly. In addition, more transparency will be provided regarding the underlying assumptions and computations. We strive to adjust the tool so that it could be available through open-access sources for interested parties, I.e. the scenario deployment tool is to become a part of the legacy of the project.

The complexity of the scenario design and the associated tool implies, that while analyzing the workshop output for the purpose of finalizing the tool and reporting on deployment challenges of ocean liming in the final report, we may realize that some arguments or propositions appear to be not valid or not very relevant owing to mechanisms overlooked or underrated during the workshop discussions. This notion will require careful interpretation when processing the results of the workshop in later stages of our research. Nevertheless, we are very grateful for the highly valuable contributions of all participants.

4. Annexes

4.1 Invitation to Workshop

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Invitation for Stakeholder Workshop (online)
Ocean Liming Cost and Scale Scenarios

Date: Wednesday 23 November 2022
13:30-16:15 (CET)

Dear Expert

One or several of the workshop hosts mentioned below have been in contact with you in the context of the EU research project OceanNETs (*Ocean-based Negative Emissions Technologies*), funded by the European Union's **Horizon 2020 programme, and aimed at** exploring methods to enhance the capacity of the oceans to absorb (more) atmospheric CO_2.

As part of the project, we are conducting a full assessment of ocean alkalinity enhancement (OEA), one of the methods currently being studied to remove CO_2 from the atmosphere.

We invite you to take part in an on-line workshop, to be held on Wednesday November 23rd.

The November 23rd workshop will focus on *ocean liming*, a particular version of OEA. More specifically, this workshop aims to explore cost and scale development scenarios of different deployment configurations. After a joint stakeholder meeting in July 2022 on possible ocean liming configurations, we have prepared a decision tool that guides the simulation of deployment scenarios in terms of plausible ranges of cost and scale of the ocean liming value chain components based on choices by component for the period 2030-2050.

In this new meeting we will deliberate the specific consequences of ocean liming deployment choices. The interaction between different configuration choices will be reviewed in connection with an in-depth discussion about the associated cost and scale levels. Moreover, we are keen on exploring the effect of associated cost levels on the preferences for specific ocean liming configurations.

Through a structured deliberation the workshop will attempt to cover the most crucial factors affecting the scale and costs of ocean liming. We intend to produce best-available figures for ocean liming scenarios from a wholistic view on the complete supply chain. The discussions will be instrumental in determining cost and scale levels different ocean liming scenarios and the associated likelihoods.

Participants will include experts from different segments of the production and distribution processes, together with experts on climate governance, maritime law, and environmental policymaking. The workshop is organised by researchers from the Finnish Meteorological Institute for the OceanNETs project.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 869357.

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We will send additional materials in preparation of the meeting at the end of October.

If you are unable to participate, you are welcome to propose a colleague with comparable expertise. Similarly, you may also suggest additional participants from other organisations.

We kindly ask you to confirm your participation to Sebastiaan van Kooten sebastiaan.van.kooten@fmi.fi stating your name, position, email address, and phone. Do not hesitate to contact us, if you have further questions on the procedure and contents of the workshop.

Looking forward to your engagement in the workshop.

<u>Hosts:</u>
Adriaan Perrels
Eeva Kuntsi-Reunanen
Sebastiaan van Kooten

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4.2 Agenda of the meeting

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Agenda

Time: November 23rd 2022, 13:30 CET (Brussels)

13:30 Welcome

13:35 Presentations from OceanNETs team

14:00 First working group discussion

14:30 Plenary feedback moment

14:55 Tea break

15:10 Second working group discussion

15:35 Plenary concluding discussion

Link to the Teams meeting

Meeting ID: 375 122 216 406
Passcode: 2TsDb5

Aims of the workshop

In this consultation we explore the associated costs and scale of different ocean liming deployment scenarios. To facilitate the discussion, we will provide very brief presentations on OceanNETs and ocean liming, the developed Ocean Liming Simulation Tool and preliminary outcomes of scenario configurations. At the end of the session, we expect to have a better picture of participants' perspectives on concrete supply chain configurations.

Our research on this topic does not presuppose any position, on our part, on the desirability or viability of ocean liming, or indeed any other industrial method of carbon dioxide removal. Our remit is to generate evidence that will help society make decisions about this and other forms of ocean-based carbon dioxide removal. In this case, we seek to develop deployment scenarios that consider the full range of technical, economic, legal and societal aspects necessary to make ocean liming a plausible proposition. We believe this will assist policy makers, and indeed the public as a whole, in making informed decisions about the desirability of this method of carbon dioxide removal.

We are very grateful for taking the time to join us for the first discussion on ocean liming.

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Rules for deliberative consultation

Below are some basic rules for our discussion.

Sponsorship: Our research is funded exclusively by the European Commission's Horizon 2020 Framework Programme, through the project OceanNETs (Ocean-based Negative Emissions Technologies). It has no commercial sponsors or expected outputs.

Outputs: Our research will be used to produce academic publications and policy briefs on the science and policy of ocean-based carbon dioxide removal. We will be happy to share drafts of any publications making use of material from the consultations.

Representation: You have been invited because of your individual expertise and experience. We will not interpret your statements as representing the position of your organisation, unless you refer explicitly to **your organisation's policies** or preferences.

Anonymity: During the session, the discussion will be conducted under **Chatham House Rule** (participants are free to use the information received, but neither the identity nor the affiliation of the speakers, nor that of any other participant, may be revealed). Academic outputs from the project will have no reference that might identify participants.

Participation: To facilitate the exchange of ideas participants should share their views in brief and respectful manner. The moderators will guide the discussion processes, but participants will be encouraged to actively speak and use the chat function during the session.

Teams: The meeting will take place on Teams. We encourage participants to keep their videos on throughout **the event, and during the break we'll ask participants to stay logged**-in to the Teams call.

Time: We will start promptly at 13:30 CET and we are committed to finish on time. We sincerely hope that participants remain fully engaged in the consecutive sessions over the entire course of the workshop.

Your hosts,

Adriaan Perrels

Eeva Kuntsi-Reunanen

Sebastiaan van Kooten

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4.3 Preparatory Material

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OceanNETs Research on Ocean Alkalinity Enhancement

Preparatory Materials for Workshop Participants

Introduction

As part of its research on ocean-based forms of carbon dioxide (CO_2) removal, OceanNETs is assessing the potential of ocean alkalinity enhancement (OAE). OAE refers to approaches that seek to increase ocean concentration of ions, such as calcium, to increase uptake of atmospheric CO_2 into the ocean, and in the process reverse acidification (this video, produced by ClimateWorks, provides a more detailed explanation of the concept).

Limestone has been proposed as one of the possible precursor agents for OAE, owing to its very high concentrations of calcium carbonate ($CaCO_3$). However, because surface ocean waters are supersaturated with respect to $CaCO_3$, limestone needs to be mined, crushed, milled, and then calcined before it can be used as an alkaline agent. The produced quicklime (CaO) or more likely the hydrated lime ($Ca(OH)_2$) would then be spread in the ocean to draw down atmospheric CO_2. This process is known as ocean liming [image 1].

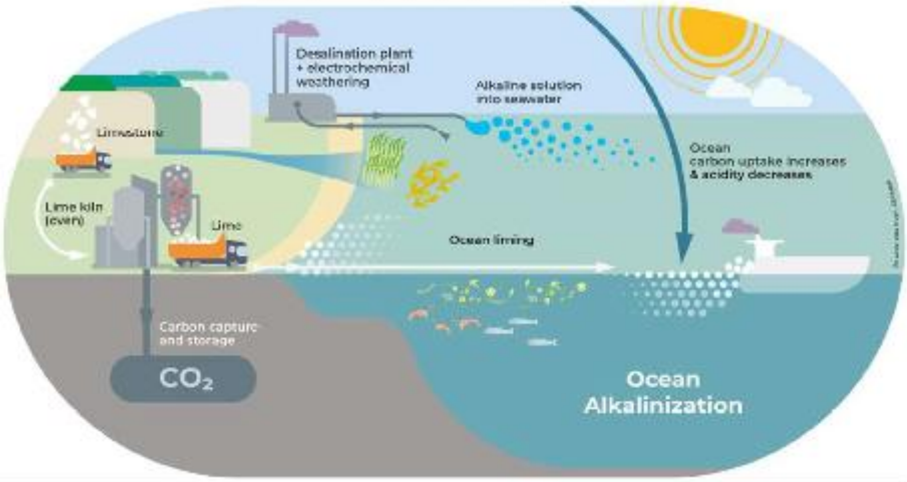

Image 1. Representation of possible paths for OAE

Source: www.oceannets.eu.

Most climate change mitigation pathways suggest that atmospheric CO_2 would need to be removed at a Gigaton (Gt) scale annually to keep the global temperature increase well below 2 °C. If ocean liming was ever to become a significant component of global CO_2 removal strategies, limestone extraction and processing would thus need to increase significantly to achieve such scales.

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Preparation for the workshop

The goal of this workshop is to discuss potential scenario outcomes for the cost and scale of ocean liming. Scenarios are based on supply chain configurations suggested in previous deliberations. All the scenarios have been combined in the scenario tool. As a preparation for the workshop, we invite you to experiment with this tool and share your findings with us.

We have shared the link to a oneDrive folder with you. In there, you can find an Excel file titled "*OceanNETs Ocean Liming Simulation Tool*". When opened, you will see that the sheet in this file is structured into three parts: a decision table, a cost breakdown table with belonging (empty) bar diagram and a table of key parameters. In each of the empty cells of the Decision Table a drop-down choice menu is available. For each period you can select your preferred scenario configurations. The result of the scenario selection is summarised in the bottom half of this table, broken down according to the cost categories in the Cost Breakdown Table and visualised in the bar diagram. The Key Parameters Table contains a set of parameters that play a crucial role in the cost and scale computations in this model.

You are free to try out the tool as much as you like. We would kindly request you to consider what you believe to be the most likely scenario configuration regardless of the output the tool produces. We would strongly appreciate it if you could share your most likely configuration with us through the following anonymous form before November 21st: https://link.webropolsurveys.com/S/8C76017EE72F07CE. Your reflections on the tool and model outputs given your scenario configurations are more than welcome.

We hope that you will enjoy working with this tool. If you have any questions or direct comments, feel free to reach out to Sebastiaan van Kooten: sebastiaan.van.kooten@fmi.fi

Interpretation of the tool and its outcomes

The OceanNETs Ocean Liming Simulation Tool portrays a simplified version of reality and therefore any model outputs may not be interpreted as exact predictions for the future costs or scale of ocean liming deployment. The tool provides an indication of the interaction of different crucial factors in the supply chain and serves as a benchmark for further discussions.

The time periods used in the tool should be interpreted as the starting point of a 10-year period, such that 2030 represents the 2030s or 2030-2039. The model output represents the result of this 10-year period under the selected configuration choices.

The remainder of this document contains more information regarding the tool and all the specific scenario configuration choices available.

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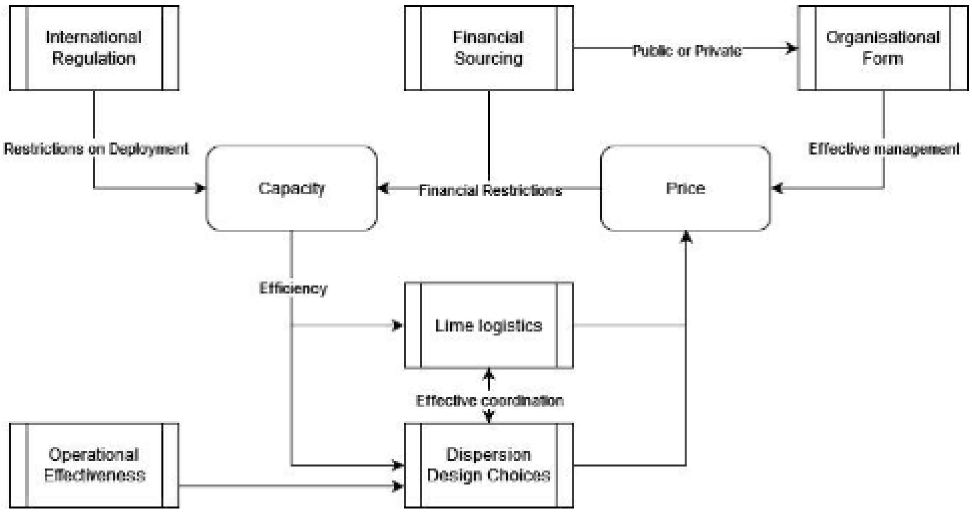
Detailed description of the tool

This choice simulation tool has been developed as a means of integrating expert opinions from different relevant stakeholders. Input gathered from such stakeholders has largely determined the parameters of this model and the interactions between the different parameters. Literature has been used to assess further parameter setting for this tool.

Based on the workshop of July 4 and follow-up meetings, 6 key scenario choice nodes have been identified. In each node, a few choices are available which would determine the configuration of the ocean liming supply chain for the years 2030, 2040 and 2050. These three years have been selected as natural points of reference to simulate the evolution of Ocean Liming deployment. Choices made for each time period influence the outcomes for the next period.



Flow scheme depicting how the decision nodes influence the cost and capacity outcomes of the Simulation Tool.

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Choice nodes and the corresponding options are the following:

1. **International Regulation:** The framework of international regulations and agreement that determine the legal framework surrounding Ocean Liming applications. Model choices determine the restrictiveness of international regulations with respect to Ocean Liming and thus determine the legal maximum capacity.
    a) **Prohibitive:** No Ocean Liming is allowed. Maximum legal capacity is always equal to zero.
    b) **Restrictive:** Ocean Liming is permitted in limited quantities corresponding more to piloting projects.
    c) **Facilitating:** Ocean Liming is freely allowed under International Regulation. Some maximum capacity restrictions exist but are relatively relaxed. Additional practical capacity restrictions could cause the deployment level to be below the Legal Maximum Capacity. This is summarized in the Practical Maximum Capacity output.

2. **Financial Sourcing:** The source of financial means that would pay for ocean liming in different scenarios.
    a) **Public:** Ocean Liming is fully dependent on public financial means. A sum of financial means is included that could restrict deployment quantities.
    b) **Private:** Ocean Liming is fully financed through private means. Private funds are generated through for instance the release of negative emission certificates.

3. **Organizational Form:** The organizational form determines under which conditions entities would execute Ocean Liming activities. In other words, this choice determines how "orders" for Ocean Liming are divided. Certain choices are modelled to be either more or less efficient over time, and thus influence the price. Options *a)* and *b)* are only possible if the *Financial Sourcing* is set to *Public*, whereas *c)* and *d)* are only possible if *Financial Sourcing* is set to *Private*.
    a) **Public tender:** Contracts for Ocean Liming operations are assigned to (semi-)private organizations through public tenders.
    b) **Public Enterprise:** A publicly owned enterprise executes all the desired Ocean Liming.
    c) **Auction of Negative Emission Rights:** Rights to be allowed to operate in the Ocean Liming sphere are auctioned off to the most competitive offer in a tender, operations will generate negative emission rights.
    d) **Tradeable Negative Emission Rights:** Operations within the Ocean Liming sphere are freely organized, and Ocean Liming generates freely tradeable negative emission rights.

4. **Dispersion Technique:** This choice determines the mode of preference for Ocean Liming operations. Choices here influence the price in combination with the land operations.
    a) **Dedicated Ships:** Dedicated large ships will be constructed for just ocean liming.
    b) **Partial Capacity Use:** newly built merchant ships are adjusted to dedicate a share of their capacity to ocean liming operations.

5. **Land Operations:** This choice records the preference for the spatial distribution of land operations. The choices here and under dispersion technique jointly determine the price of ocean liming.
    a) **Concentrated operations:** A few large-scale production and logistics hubs are created specifically for ocean liming operations.

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b) **Scattered supply:** Many facilities are available scattered across multiple locations from where ships could load materials for discharge at sea.

6. **Operational effectiveness:** This choice captures the uncertainty around the effectiveness of the discharge technologies for calcium hydroxide. At the moment, it is unclear at what rate and under what circumstances materials could be added to the ocean optimally.
   a) **High:** Large (scientific) consensus on the effectiveness of used discharging technology, such that design capacities for dispersion can be fully utilized.
   b) **Medium:** There is agreement that ocean liming could be effective, but the exact conditions remain to be clarified, implying that design capacities for dispersion cannot be fully utilized, e.g. due to dispersion restriction guidelines differentiating by sea areas, weather conditions, etc..
   c) **Low:** Uncertainty still exists on the effectiveness of ocean liming, requiring prudence in the application of calcium hydroxide to the ocean and implying that design capacities for dispersion are hardly ever fully utilized, resulting on average in still significantly lower utilization rates than in option b)

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4.4 Tool as shared with participants

Note: This tool is only meant to be used in preparation for the OceanNETs Ocean Liming workshop on November 23, 2022. Any participant is kindly yet urgently requested not to share these materials with anyone not joining the workshop. An adjusted version will be made public in a later stage of the research project.

Decision Table

Decision tree element	Choice 2030	Choice 2040	Choice 2050	
International Regulation				
Financial Sourcing				
Organisational Form				
Dispersion design choices				
Lime Logistics				
Operational effectiveness				
	Situation 2030	**Situation 2040**	**Situation 2050**	
Legal Maximum Capacity	#N/A	#N/A	#N/A	megaton
Practical Maximum capacity	#N/A	#N/A	#N/A	megaton
price per tonne CO2	#N/A	#N/A	#N/A	

Cost Breakdown

	2030	2040	2050
Lime production	#N/A	#N/A	#N/A
CCS	#N/A	#N/A	#N/A
Port handling	#N/A	#N/A	#N/A
Shipping	#N/A	#N/A	#N/A
Overhead	#N/A	#N/A	#N/A

Key Parameters				
	2030	2040	2050	
Lime discharge rate	50	50	50	kg/s
Ship Building capacity	50	65	85	ships
Ship Conversion capacity	200	250	325	
Unit price ship	#N/A	#N/A	#N/A	
Liming equipment price	#N/A	#N/A	#N/A	per ship
Share of visited ports with lime facilities	#N/A	#N/A	#N/A	

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4.5 Questionnaire list

Webropol questionnaire question list

Introduction

Thank you for taking the time to experiment with the OceanNETs Ocean Liming Simulation Tool. In this questionnaire we would please ask you to record what you believe to be the most likely scenario configurations. We are very keen to hear your reflections on the tool and the scenario outcomes.

All your input will be treated anonymously and will only be handled by the Finnish Meteorological Institute for the purposes of the OceanNETs project.

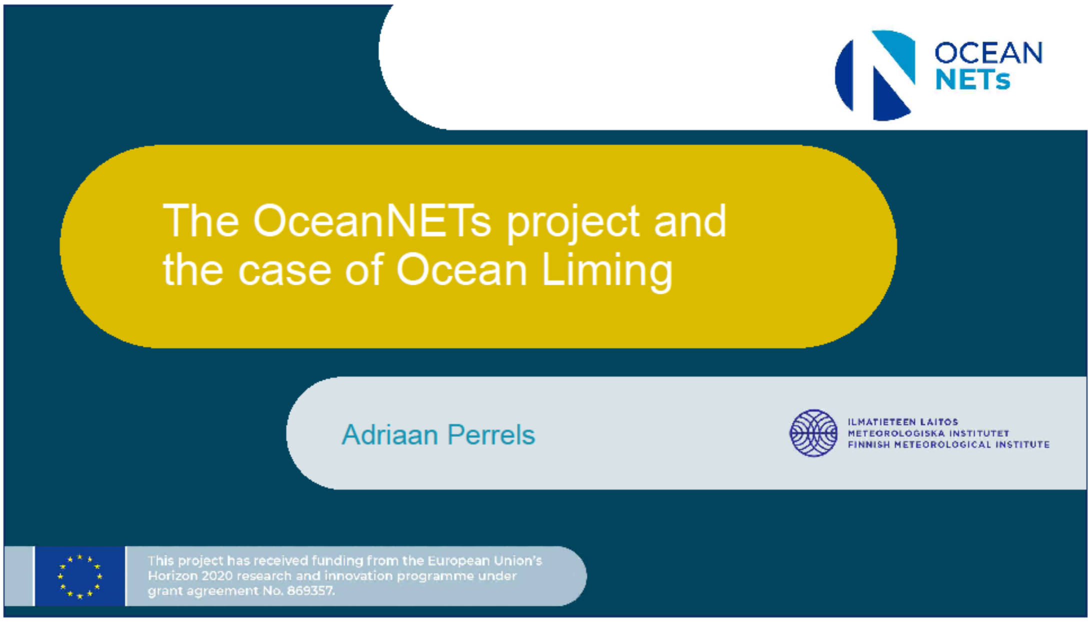
Questions

1. (Multiple choice) Which configuration have you selected for International Regulation in 2030?
    a. Facilitating
    b. Restrictive
    c. Prohibitive
2. (Multiple choice) Which configuration have you selected for Financial Sourcing in 2030?
    a. Collective
    b. Private
3. (Multiple choice) Which configuration have you selected for Organisational Form in 2030?
    a. Public Tender
    b. Public Enterprise
    c. Auction of Negative Emission Rights
    d. Tradeable Negative Emission Rights
4. (Multiple choice) Which configuration have you selected for Dispersion Design Choices in 2030?
    a. Dedicated Ships
    b. Partial Capacity Usage
5. (Multiple choice) Which configuration have you selected for Lime Logistics in 2030?
    a. Centralised Hubs
    b. Scattered Supply
6. (Multiple choice) Which configuration have you selected for Operational Effectiveness in 2030?
    a. High
    b. Medium
    c. Low
7. (Multiple choice) Which configuration have you selected for International Regulation in 2040?
    a. Facilitating
    b. Restrictive
    c. Prohibitive
8. (Multiple choice) Which configuration have you selected for Financial Sourcing in 2040?
    a. Collective
    b. Private
9. (Multiple choice) Which configuration have you selected for Organisational Form in 2040?
    a. Public Tender
    b. Public Enterprise
    c. Auction of Negative Emission Rights
    d. Tradeable Negative Emission Rights
10. (Multiple choice) Which configuration have you selected for Dispersion Design Choices in 2040?
    a. Dedicated Ships
    b. Partial Capacity Usage
11. (Multiple choice) Which configuration have you selected for Lime Logistics in 2040?

    a. Centralised Hubs
    b. Scattered Supply

12. (Multiple choice) Which configuration have you selected for Operational Effectiveness in 2040?
    a. High
    b. Medium
    c. Low
13. (Multiple choice) Which configuration have you selected for International Regulation in 2050?
    a. Facilitating
    b. Restrictive
    c. Prohibitive
14. (Multiple choice) Which configuration have you selected for Financial Sourcing in 2050?
    a. Collective
    b. Private
15. (Multiple choice) Which configuration have you selected for Organisational Form in 2050?
    a. Public Tender
    b. Public Enterprise
    c. Auction of Negative Emission Rights
    d. Tradeable Negative Emission Rights
16. (Multiple choice) Which configuration have you selected for Dispersion Design Choices in 2050?
    a. Dedicated Ships
    b. Partial Capacity Usage
17. (Multiple choice) Which configuration have you selected for Lime Logistics in 2050?
    a. Centralised Hubs
    b. Scattered Supply
18. (Multiple choice) Which configuration have you selected for Operational Effectiveness in 2050?
    a. High
    b. Medium
    c. Low
19. (Open question) What is your opinion on the simulated outcomes of this tool with respect to cost and scale? You may comment both on outcomes of segments as well as the final results.
20. (Open question) What is your opinion about this tool in terms of possible purposes, usefulness, transparency, development needs, possible user groups, or any other item you wish to raise [in general]?
21. (Open question) How do you expect the global economy and global trade, climate policy ambitions, as well as global knowledge sharing to develop in the next 10 to 30 years?
22. (Multiple choice) Which of the following describes most accurately the type of organization you are representing?
    a. Government entity
    b. Lime industry
    c. Shipping industry
    d. Non-profit/climate action
    e. Other, namely… (leave space for input)

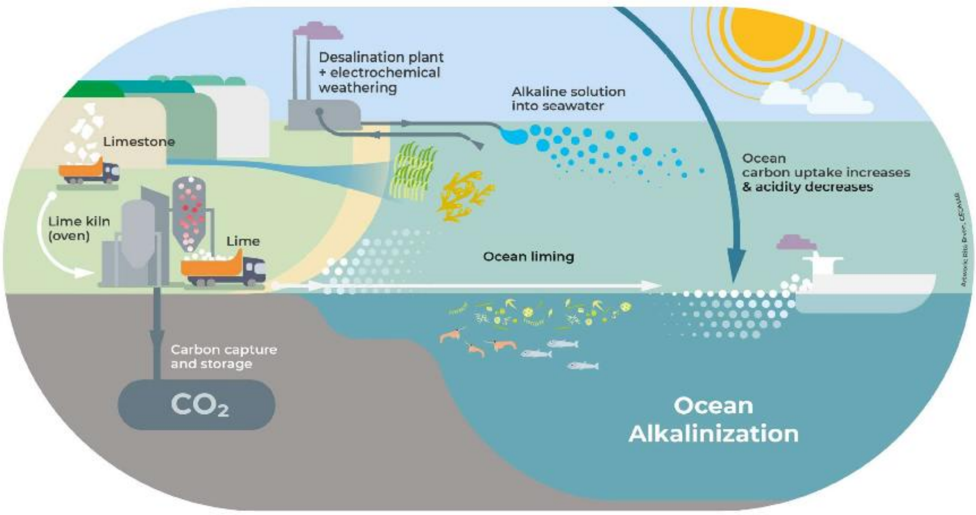
4.6 Introductory presentation



OceanNETs: general objectives

- To determine to what extent, and under what conditions, large-scale deployment of ocean-based negative emission technologies could contribute to realistic and effective pathways for Europe and the world to achieve climate neutrality and the goals established in the Paris Agreement
  - more in particular, it refers to reducing risks of so-called 'overshoot scenarios'
- To identify and prioritize plausible options with the most potential with regard to CO_2 mitigation, environmental impact, risks, co-benefits, technical feasibility, cost effectiveness, and political and societal acceptance
- Alkalinity enhancement seems to be one of the more promising options, at least in theory, hence this is one of the NET options studied more closely;
  - within the option cluster *ocean liming* was identified as having potential for significant NET contribution
  - Task 1.2 also studies *blue carbon* more closely, but that is outside today's scope

Modalities of ocean alkalinity enhancement



Our goals with respect to ocean liming

- Describe the probable supply chain configurations with the associated business cases
- Translate probable supply chain configurations into cost and scale scenarios with reasonable likelihood
- Side remark:
  - Other deployment approaches for lime have been suggested in the literature, but considering the amounts of lime involved, these do not seem capable of being the principal way of delivery

Today's meeting

- Rules: Chatham House rule; participation in a personal capacity;
- Outputs:
  - participants can receive a draft workshop report and comment; fairly tight schedule
  - participants can get a notification when the related Deliverable (report) is public

Programme (*times in CET*)

13.30 Opening & practical information

------- Introduction to the project and topic
------- Introducing the scenario tool
------- Q&A

14.05 Group session I – 3 groups of 5~6 participants + moderator

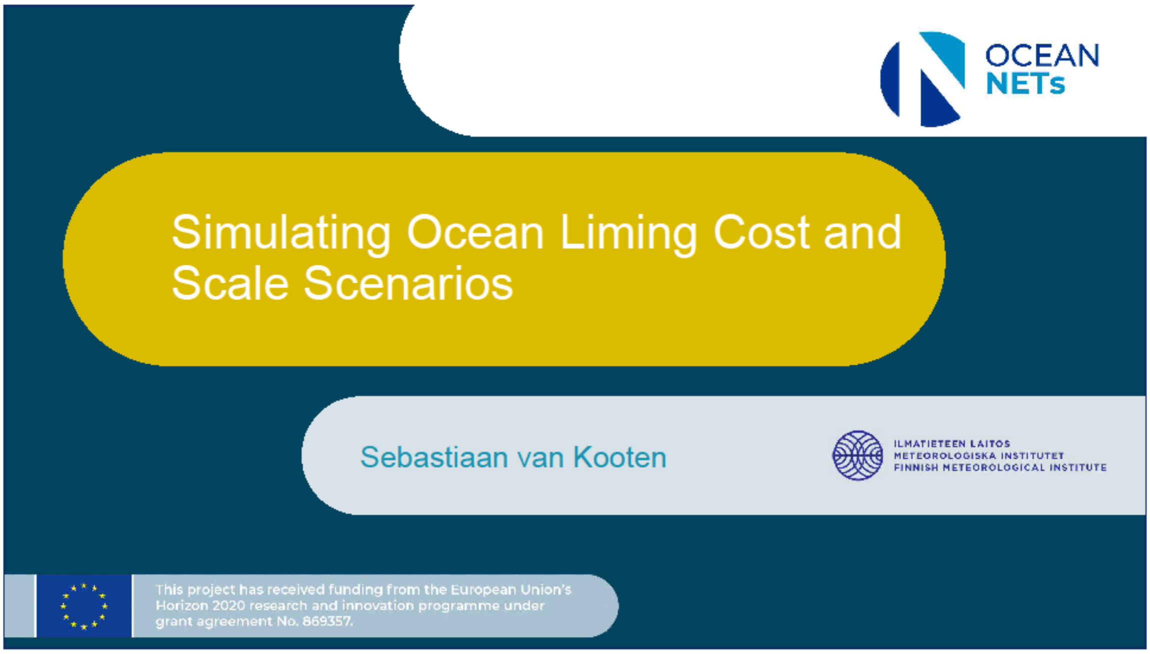
14.45 Break

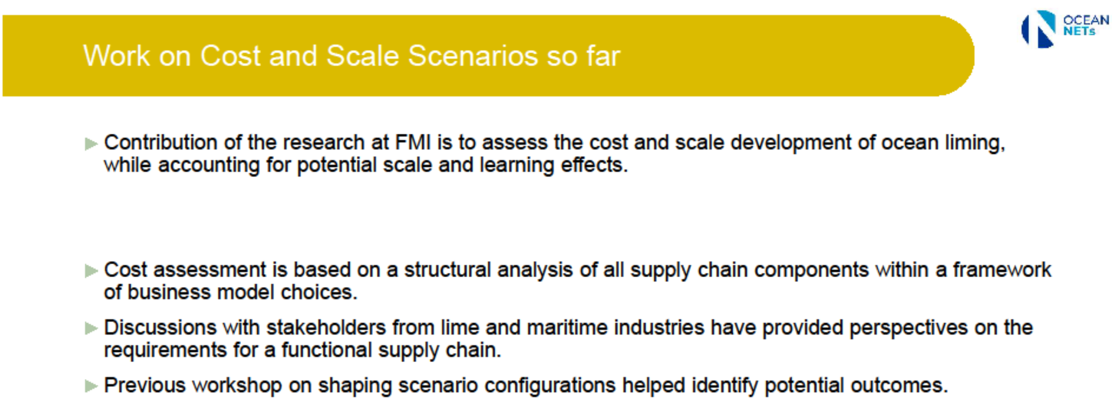
15.00 Group session II – same 3 groups of 5~6 participants + moderator

15.35 Concluding plenary – feedback from groups / discussion

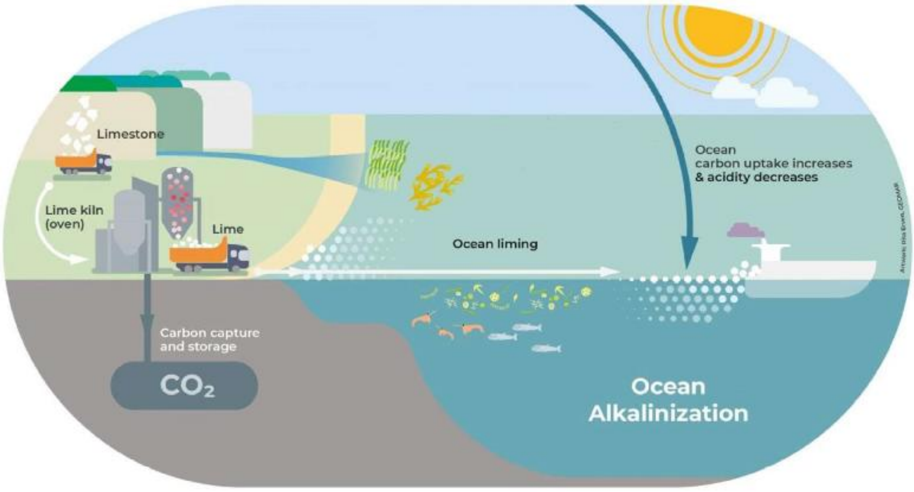
16.00 Closure

4.7 Tool presentation





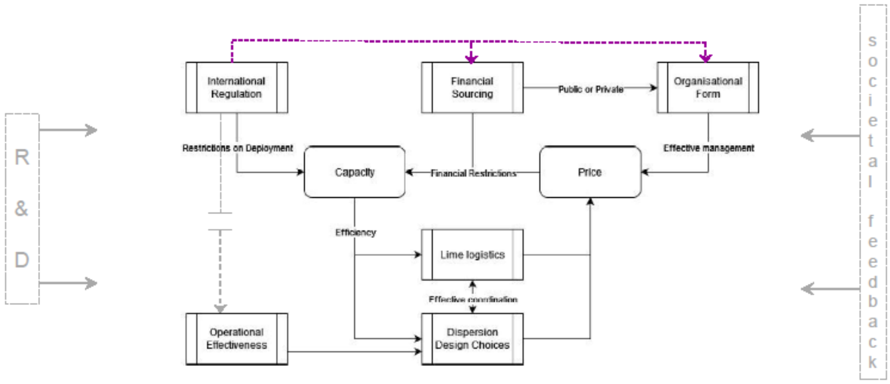
Ocean Liming Supply Chain



Looking at Ocean Liming as a whole

- Even though single elements of the supply chain currently exist, Ocean Liming operations cannot start right away.
- Important factors that influence both the scale and cost potential are not captured in the individual supply chain elements.
  - Law of the Sea
  - Environmental concerns and operational certainty
  - No existing reward system for Ocean Liming operations
- Complex interactions between all factors prevent the accurate analysis of individual factors

Complex interaction between multiple factors



- Possible influence of R&D and societal discourse is not explicitly modelled, but to some extent accounted for in the several scenario variable boxes; some project partners may provide new insights over the course of the project.

Simulation tool

- We have developed a tool to model the different interactions. The tool will help to provide structure and contextualise the findings so far to guide discussions and provide input to future model simulations.

- The tool allows for selecting specific scenario configurations for 2030, 2040 and 2050. Given the configuration, the tool computes the capacity and cost per ton of CO_2.
- Scenario choices in 6 categories: Regulation, Financing, Organisational Form, Dispersion choices, Lime Logistics and Operational Effectiveness.
- Underlying computations are based on input from previous activities and literature. Elements such as economies of scale and learning benefits are accounted for within the different supply chain partitions.

- Note: Scenario outcomes must not be accepted as factuals or point estimates. Rather, outcomes serve as an indication.

Scenario Tool: Example of Input and Output

Decision Table				
Decision tree element	**Choice 2030**	**Choice 2040**	**Choice 2050**	
International Regulation	Restrictive			
Financial Sourcing	Collective			
Organisational Form	Public enterprise			
Dispersion design choices	Dedicated ships			
Lime Logistics	Centralised hubs			
Operational effectiveness	Low			
	Situation 2030	**Situation 2040**	**Situation 2050**	
Legal Maximum Capacity	5.00	#N/A	#N/A	megaton
Practical Maximum capacity	1.70	#N/A	#N/A	megaton
price per tonne CO2	238.54 €	#N/A	#N/A	

Today's workshop

- Discussions in break-out groups.
- Use the tool to understand what your views are on the different Ocean Liming scenarios. The tool serves as a starting point for the discussion on the overall system. What configurations do you predict for 2030, 2040 or 2050?
- Discuss the output of the tool and share reflections on the output values.
- Key parameters: how much do the crucial investment parameters affect the overall system cost (per ton CO_2 abated)?