Ocean-based Negative Emission Technologies

OCEAN NETs

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Abstract: This Deliverable provides an assessment of the unit-costs of different NETs, expressed in euros per ton CO2 abated. On the basis of literature study, expert interviews and two expert workshops the main drivers of ocean based NETs' deployment were identified and operationalized in scenario deployment exploration tool, with special reference to ocean liming. The realized scenario exploration tool has a theoretical underpinning in evolutionary economics and learning curves. Scenario exploration results are presented, whereas also the prospects of Blue Carbon and Electrochemical carbon dioxide removal are discussed.

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List of abbreviations, acronyms and definitions

Term	Description
BECCS	Bioenergy with carbon capture and storage (BECCS) is the process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere. BECCS can be a "negative emissions technology" (NET), provided the use of the biomass does not significantly impacts the sink function of the biomass.
Blue carbon	Blue carbon is a term used in the climate change mitigation context that refers to "biologically driven carbon fluxes and storage in marine systems that are amenable to manag;ement."[2]:2220 Most commonly, it refers to the role that tidal marshes, mangroves and seagrasses can play in carbon sequestration
CCS	Carbon capture and storage refers to a collection of technologies that can capture carbon dioxide gas (CO2) from the emissions of industrial processes (and transport) and store it in a – usually undergound – location from which it should not re-emit into the atmosphere. A subclass of CCS is called CCU (carbon capture and utilization), implying that instead of storing all or a part of the CO2 emissions are used in industrial processes to create new materials or in greenhouses to enhance plant growth
CDR	Carbon dioxide removal refers to processes in which carbon dioxide gas (CO2) is removed from the atmosphere by deliberate human activities and durably stored in geological, terrestrial, or ocean reservoirs, or in products. CDR methods include afforestation, reforestation, agricultural practices that sequester carbon in soils (carbon farming), wetland restoration and blue carbon approaches, bioenergy with carbon capture and storage (BECCS), ocean fertilization, ocean alkalinity enhancement,[7] and direct air capture when combined with storage. Hence CCS is a sub-class of CDR.
DAC; DACCS	Direct air capture refers to technologies utilizing chemical or physical processes to extract carbon dioxide directly from the ambient air. DAC is usually part of DACCS - direct air carbon capture and sequestration
Learning curve	A learning curve is a mathematical concept that graphically depicts how a process is improved over time in terms of efficiency (resource use for given output) or quality (e.g. fraction of rejects in the output) due to learning and increased proficiency. It can be applied to separate production steps or tasks as well as to entire product chains.
NEGEM	Other Horizon Europe project running parallel with OceanNETs which aims to assess the realistic potential of Negative Emission Technologies and Practices (NETPs) and their contribution to climate neutrality, as a supplementary strategy to emissions mitigation.
NET	Negative emission technology refers to intentional human efforts to remove CO2 emissions from the atmosphere. The main categories of NETs are: (1) technical removal of CO2 emissions from the atmosphere, often in close connection with localized CO2 emissions from biomass-based energy conversion (BECCS), (2) enhancement of natural sinks, i.e. by enhancing biomass growth, notably of forests and marine biomass (blue carbon) , and (3) (chemo-)technical engineering of carbon absorption capacity of the seas and soils, such as ocean liming.
TIMES model	The TIMES model generator combines two different, but complementary, systematic approaches to modelling energy: a technical engineering approach and an economic approach. TIMES is a technology rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy

	system, optimized according to a number of user constraints, over medium to long-term time horizons.

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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 by various experts to have a high CDR[1] potential, levels of sustainability, or potential co-benefits (see chapter 2). 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 D1.4 presents the approach and findings of the work carried out in Task 1.2. The purpose of Task 1.2 was 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 sufficient reliable data. The presented 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 constituent 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 results provide an impression of the prospects based on current knowledge. However, as the level of knowledge is still evolving significantly these prospects may change accordingly. The *scenario tool* developed in Task 1.2 enables to monitor the prospects as new insights for key tool parameters emerge, and thereby it is part of the *legacy* of the project.

1.3. Relation to other deliverables

The findings reported in this report are relevant for the investigations into aspects of a possible NETs based permit market in WP1 (Task 1.1 and Task 1.3). Furthermore, task 1.2 was carried out in close cooperation with WP6 (Task 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. Last but not least, the cost data of selected scenarios for ocean alkalinization have been provided to the concurrent EU Horizon project NEGEM to check the competitiveness in comparison to other CO_2 abatement technologies by means of explorations with TIMES model.

[1] CDR – carbon dioxide removal; see the glossary of terms and abbreviations at page 5, also for the remaining abbreviations and terms in the report.

2. Overview of considered NETs and selection of NETs for cost analysis

2.1. Brief overview of NETs

Delineation

The approaches to be included should entail interaction with marine (bio)physical and (bio)chemical processes aimed at carbon dioxide reduction in the atmosphere. Based on this guideline, albedo enhancement and the use of renewable energy potential at sea (offshore wind, tidal, wave) are not considered. Neither are options considered which are practically banned by the London Protocol (IMO web site), such as seabed storage of carbon dioxide (GESAMPT 2019).

Hitherto feasibility studies of various NETs, notably ocean-oriented NETs, tend to pay limited attention to costs and dynamics in costs, while often using also point estimates from previous studies (Fuss et al 2018; Nemets 2018). To our knowledge this is the first study which attempts to consider several types of drivers of unit-costs of ocean-oriented NETs and their interactions.

Short descriptions

NETs meant for application at sea can be categorized into four groups as shown in table 1[2]. The collection shown is not exhaustive regarding all options that can be found in the literature but nevertheless represents the most often mentioned options. The distinction between 'local' and 'global' applications refers to the logic of the option's deployment strategy. A part of the options has localized drivers. Hence, the realization and efficiency does hardly or not at all depend on realization of the same option elsewhere. Other options are typically meant to be designed and applied at an (almost) global scale. Some options could be understood as having a multi-local potential and thereby still a notable global potential, even if not driven by a global strategy. Seaweed cultivation and olivine-rich rock material can be applied as local approach in numerous locations. In addition, there are propositions to apply these options through large endeavors as global solutions. Yet, in that case the nature of these options is different in several respects.

Table 1. *Considered ocean-based NETs by main category and by extent of application*

	Local	**Global**
Enhancement of vegetation (blue carbon)	- coastal wetland rehabilitation - seaweed cultivation - combined with biochar	- seaweed cultivation
Ocean alkalinization	- electrochemical weathering - enhanced weathering of olivine-rich rock material in coastal areas - ocean liming	- ocean liming - enhanced weathering of olivine rich rock material at sea
Ocean fertilization	- iron fertilization	- iron fertilization
Artificial upwelling and downwelling	- upwelling in semi-enclosed sea areas (bays, fjords, etc.)	- upwelling in the open ocean
Marine biomass for biochar or bioenergy with CCS	- algae breeding ….. if in tanks is it sea based? ….. combined with iron fertilized	-

Blue carbon refers to the several options by which marine vegetation and other biomass is enhanced. The enhanced growth implies an increased amount of sequestered carbon contained in the biomass and possibly in the soil of the considered basin. However, the effectiveness and permanence of the sequestration depends on the lifecycle of the involved vegetation. In case of

[2] Chapter 2 is based on an extensive literature review. Key sources are mentioned in under table 2 on page 13. For selected NETs more details are discussed in sections 4.1., 4.2 and chapter 5.

coastal wetland rehabilitation the effect is comparable to reforestation, leading to continued increased carbon sequestration. In case of seaweed cultivation it depends on the use of harvested seaweed or conversely on the way seaweed at the end of its lifetime decomposes and whether it leads to more carbon storage at greater depths, hence for longer time or permanent.

Ocean alkalinization can be implemented by means of various methods. In all these methods the agent added to the sea raises the alkalinity, which in turn enables the sea to bind more CO_2 from the atmosphere. Alkalinization decreases the acidification effect of the additional carbon sequestration, which constitutes an important environmental benefit.

Electrochemical weathering aims at the release of the alkaline agent from seawater without adding externally sourced minerals. There are two main technology options, either implying the extraction of CO_2 from water or the enhancement of ocean alkalinity (see section 4.1). All options face major obstacles related to (1) the large amounts of climate neutral electricity needed per unit of abated CO_2 and (2) the creation of substantial amounts of hazardous rest products. As a consequence, electrochemical weathering seems only feasible as add-on to existing processes, such as desalination plants, but major challenges remain and overall potential would be limited. This option is discussed in more detail in section 4.1. Also, Deliverable 6.4 discusses this option.

Ocean liming entails the application of calcium oxide or calcium hydroxide, contained in lime obtained from chalk through calcination, to the surface layer of the sea. The production and distribution of lime is described in detail in chapter 4. This option is assessed in more detail in a life cycle assessment in WP6, discussed in Foteinis et al. (2022). Important challenges are the realization of climate neutral lime production chains at a global scale, the assurance of *effective* lime application at sea, and the alignment of climate mitigation aware business models of the lime industry and the sector(s) taking care of the maritime dispersion of lime.

Olivine-rich rock material (crushed) can be spread into the sea and along shores with tidal variation. Production of such rock material is clearly cheaper than the production of lime. In terms of logistic costs application on shores, e.g. mixed with beach sand, has moderate and scalable cost. On the other hand, per volume unit the sequestration is lower and much slower than of lime, which after all can drive up effective cost per sequestered ton of carbon. Also, the slow build-up of the effect may be a disadvantage. There are several trials going on with applications on shores (e.g. Vesta).

Ocean fertilization encompasses the addition of a nutrient to sea water, provided the selected nutrient is the limiting factor in biotic growth (GESAMP 2019). Under those limiting circumstances adding the critical nutrient can increase the sequestration of carbon. The most likely candidate agent from a collection of options is fertilization by spreading iron at sea. A significant number of field tests has provided sufficient evidence of – *in principle* – a significant sequestration effect. This option is applicable on a global scale, even though not necessarily in every sea area. The achievable effectiveness varies by location. This option is expected to have quite some environmental effects both at surface level and deep sea. Some experts are more critical on these effects than others, as the uncertainty about the manageability of these risks is high. Iron fertilization may have positive effects for fisheries, but this is not yet evidenced in practice. Cost levels seem manageable compared to many other NETs. The unit-cost may be reasonable, if sufficient upscaling can be achieved and environmental risk management would not tremendously raise the costs. Nevertheless, upfront investment costs are high, as is the case with other global – engineering oriented – options. Apart from experimentation ocean fertilization is forbidden in the London Protocol (IMO 2013).

Artificial upwelling aims to get large amounts of cold, dense and nutrient rich water from the deep sea (beyond 200 meters depth) to the upper 20 meters, which should enhance carbon (CO_2) sequestration through organic processes. However, the sequestration effect should be large enough to compensate for the inorganic carbon brought up with the upwelling. So far there is not any empirical evidence that a net sequestration effect can be achieved. Furthermore, the energy inputs for the pumping, which drives the upwelling, are very large. In principle, the energy could be derived from the temperature difference between deep sea water and surface water. The large structures needed for upwelling are prone to damage, especially when located in the open ocean. The few working facilities all operate in bays or fjords. All in all, this application has very high uncertainties in terms of (1) eventual sequestration effect, (2) applicable areas and hence potential, and (3) cost efficiency compared to other NETs. Even larger uncertainties surround judgement of artificial downwelling. There are also suggestions for combined use of up- and downwelling, which may reduce the risk of too much inorganic carbon releasing in the surface water.

For the time being upwelling seems to have less chances than various other options, and if anything, may only get applied in secluded sea areas. It might be attractive when also other objectives are pursued, such as stimulating biomass growth in secluded sea areas, e.g. for the purpose of food production. Such dispersed localized applications would mean altogether quite limited carbon sequestration potentials.

2.2. Selection criteria for picking more promising NETs

The options introduced in the previous section were reviewed for a set of criteria with the purpose of selecting options that seem altogether most promising. Direct CO_2 capture from seawater and biomass dumping options were not considered. The former option is as yet poorly studied and scarce cost estimates indicate very high cost, whereas the latter option will probably not be granted any exception in the London convention (which forbids dumping).

The following criteria are included:

- Tentative abatement capacity, while accounting for probable legally imposed restrictions to applications
- Current knowledge level and data availability regarding effectiveness, applicability, costs and side-effects
- Environmental and social spillover effects (+ or -)
- Synergy with other climate actions (joint production), which may improve acceptability and lower unit-cost
- prospects for unit-cost (cost per abated ton of CO_2)

Other relevant considerations are the *permanence* of the reductions and *governance challenges*, including the feasibility and cost of monitoring. Permanence refers to the duration of the net abatement effect of an option, which can degrade over time. Meaningful contributions of NETs to limit global warming would imply that most abated CO_2 remains out of the atmosphere for – say - at least 50 years. After which continued CDR efforts should take care that the extra sequestered amounts of CO_2 stabilize and/or progress in climate neutrality of the economy would compensate for it. If degradation is significant, it would necessitate correspondingly extra efforts to compensate for those losses.

If the implementation, supervision, resourcing, and monitoring of an option is complex, which is usually at least the case for the globally applicable solutions, it may take considerable time before such an option gets juridical and political approval, whereas the eventually acceptable version may be much more costly. In turn this may slow down the willingness to dedicate large amounts of development resources to such options. Therefore, if the governance of a NET is expected to be complex and the resolution of several issues remains quite uncertain, it is often difficult to find sufficient resources for the further development of the option.

Since information on the considered effects is mostly tentative and at best semi-quantitative there is no point in applying a formalized weighing procedure based on criterion scores. So, the selection is based on comparing the outcomes and present an argumentation of what seems the most plausible options for further assessment.

Table 2. *Summary of literature based ratings of the properties of selected ocean NETs*

	tentative abatement capacity	**knowledge level w.r.t. applicability**	**spillover effects (+ / -)**	**climate action (dis)synergy**	**(unit)cost prospects**
Artificial upwelling	modest; notable degradation over time; quick reversion if stopped	medium	at large scale: risks for reduced precipitation;	requires climate neutral electricity	costly (e.g. energy and engineering cost)
Blue carbon: - **coastal wetland rehabilitation**	modest	(fairly) good	supporting biodiversity	adaptation benefits (local)	low to high (depending on purposes)
- **seaweed cultivation**	modest (when accounting for likely limitations)	limited for application at larger scales	may reduce land use stress; marine biodiversity risks with increasing scale		moderate?
Marine biomass for biochar or bioenergy with CCS	See seaweed cultivation				
Alkalinization: - **Ocean liming**	medium to large	varying over components	probably more + than – if deployment well managed	requires CCS and climate neutral electricity	moderate to high; high upfront costs
- **Electro-chemical weathering**	modest (focused)	limited	depends on material and location	climate neutral electricity	unsure, roll-off options
- **Other enhanced weathering**	large, but builds up very slowly	limited	both + and/or – depending on material, method, site; toxicity effects may imply scale limits		low to moderate
Ocean fertilization	modest (explicitly forbidden in the London Protocol)	moderate	notable risks for marine ecosystems		rising as spillovers are to be managed

sources: Fuss et al 2018; Gattuso et al 2018, 2021; GESAMPT 2019; NAS 2019; Cobo et al 2022
capacity indications: modest < 1 GT; moderate: 1 ~ 3 GT; large: > 3 GT
cost indications: low < 100$/ton CO_2; moderate: 100$ ~ 170$/ton CO_2; high: > 170$/ton CO2
*) e.g. ameliorating ocean acidification

The logic of the selection is that large potentials take precedence, unless the technology entails significant negative spillover effects on ecosystems and/or livelihoods. Low knowledge levels mean that it will be harder to explore meaningful deployment scenarios with such options. Low or moderate unit-cost boost the attractiveness, but this is only relevant if spillover effects seem manageable. With these guidelines we chose ocean liming and blue carbon as best prospect choices, though for different reasons. Ocean liming seems to have a significant abatement potential and seems not plagued by significant detrimental side-effects. Blue carbon on the other hand, despite its limited abatement potential is attractive thanks to its synergy with adaptation, and its – partly – moderate unit-cost level. We also considered electrochemical weathering to some extent, due to its integrability into industrial processes, which is indeed further studied in WP6 (Foteinis et al 2022). Yet, it appeared to be not meaningful at this stage to explore deployment scenarios for electrochemical weathering.

3. Towards an approach for unit-cost assessment

3.1. Theoretical underpinning of drivers for technology uptake

Optimal incentives or innovation process

The question of which NETs are emerging as part of a greenhouse gas emission reduction portfolio and how the uptake may unfold can be cast as a *policy design topic*. This can be summarized as assessing effective incitation of appropriate investment and behaviour to attain certain goals. It can be cast just as well as an *innovation process analysis*. To our opinion both angles are relevant. However, with many NETs still being in quite immature states of development, the innovation process approach seems more relevant for the moment. It allows for more detailed considerations about the strengths and weaknesses of alternative technologies and their deployment alternatives, and it is not gravitating to picking a winner, but rather to indicate what are critical success factors for different options. Subsequently, critical success factors can be addressed by means of an appropriate policy mix, including emphasis on certain innovations and innovation phases.

There are different innovation theories, inter alia giving more or less weight to cost competitiveness of alternatives. For example, innovation diffusion theory (Valente & Rogers, 1995), evolutionary economy approaches (Geels & Schot, 2007), Since NETs are not a so-called basic innovation, which permeate many or all sectors and operations in society, but rather a specific innovation, cost considerations will be important. This seems a fortiori valid due to the large scale at which it has to be applied. Notwithstanding the importance of cost efficiency, various other features are important as well, such as a quite high degree of certainty about actual performance, minimal or easily correctible negative side-effects, and tractability and transparency of the performance. For example, various green carbon applications can be relatively cheap in terms of unit-cost per ton of CO_2 abated, but the verification and attribution of the amount of abated CO_2 is difficult and hence is either expensive and/or not so reliable. In other words, the straightforward drive for cost-efficient solutions is in practice significantly influenced by demands for manageability of associated risks of the proposed solution. These demands are usually mediated through legislative and resourcing frameworks on which the realization of a NET will depend.

There is a quickly expanding body of literature about the possibilities of (ocean-based) NETs, including a growing number of scenario explorations on prospects for upscaling of one or several alternatives, e.g. (Fuss et al., 2018; Gattuso et al., 2021a; GESAMP, n.d.; Minx et al., 2018; National Academies of Sciences, 2022). Nonetheless, the amount of literature which digs deeper into particularities of innovation processes which seem relevant for ocean-based NETs is much smaller. (Nemet et al. 2018) provide an overview, based on a typology of six stages during an innovation process, being (1) research and development (R&D), (2) demonstration, (3) upscaling, (4) niche markets, (5) demand pull, and (6) public acceptance. The first three stages are mainly driven by supply side developments, while stages 4-6 depend largely on demand side developments. There is feedback between the stages. Nemet et al (op. cit.) find that of the 1184 articles deemed relevant a clear majority (~83%) covers the supply side phases, with an emphasis on the first phase, R&D (61%). Furthermore, marine oriented NETs constitute a quite small fraction of all the development efforts as reflected in the number of articles (11%).

Primarily early development phases

Based on the study by Nemet et al and the literature review for Task 1.2 it can be stated that ocean-based NETs are in early development stages, with the exception of ocean fertilization and some forms of blue carbon. This means that cost efficiency is often *not a prime concern* in that stage, but rather proof of steady, predictable and reliable performance is.

In general, it applies that innovations tend to be less risky when they are meant for existing users and uses, or conversely if an innovation denotes to a large extent the adaptation of an existing product for new applications and/or user groups (the so-called Ansoff matrix). For example, coastal rehabilitation oriented blue carbon projects denote the broadening of the scope of purposes of an existing practice. On the other hand, for example ocean liming entails a new activity, without predecessors, even though the constituent elements of its value chain do exist. Generally, innovation-based extension of the scope of applications of an existing product tend to produce less extra benefits, but has a lower failure risk, whereas genuinely new products with new applications can produce larger benefits, but have higher failure risks. The various innovations within the group of ocean-based NETs are spread out over the Ansoff matrix (Figure 1). Some blue carbon options and possibly localized ocean fertilization can be regarded already being beyond early innovation stages and mainly entailing smaller improvements within existing product-market combination or rather in the case of NETs within existing purpose-solution combinations. In the case of seaweed cultivation new applications/markets are explored.

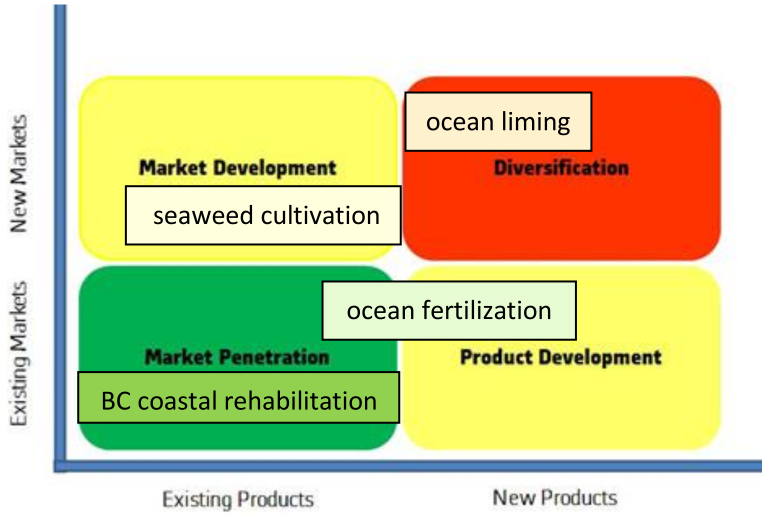

Figure 1. *The Ansoff matrix applied to ocean based NETs innovations*

Early-stage cyclical evaluation of NETs properties

As the realization of ocean-based NETs is predominantly dependent on public policies and – at least in early stages – on public funding, the acceptability of the options is an important aspect, not necessarily only for those living or working in the vicinity of the physical intervention, but for society at large. This also means that acceptability is already relevant in earlier stages than indicated in the scheme used by Nemet et al (2018). In the scheme by Nemet et al. (2018) acceptability comes in at a rather advanced stage of innovation development. Yet, many ocean-based NETs entail large scale interventions in natural environments within a public resourcing context. Such features call for much earlier activation of the acceptability stage. In fact, as long as the precise technical design and organization of the solution is not clearly established the acceptability question may re-emerge, as is illustrated in Figure 2,which depicts innovation and its policy framework as a cyclical system. The start of the first cycle is from the top, identification of meaningful solutions (for an acknowledged problem). During later rounds of the cycle it may be that acceptability and consequent regulatory propositions guide to short cuts to other stages in the cycle.

At very early stages the decision to explore a certain type of technological solution will often be driven by (expected) theoretical or experimental effectiveness and efficiency. Yet, after a first stage of results acceptability issues such as side-effects and fitness for international and national legislation have to be addressed convincingly. Otherwise continuity in funding further development gets increasingly uncertain. Acceptability often plays a central role, meaning that solutions to bolster performance and reliability and reduce negative effects will be scrutinized on external effects in the social, environmental and governance realm.

In fact, a distinction is made between the eventual technical specification of the solution and the instruments used to promote the realization of the solutions. A(s|i) etc. In early stages of policy preparation the effectiveness of the actual solution is often first assessed. Once the most sensible technical options are known the assessment shifts to instruments in combination with given solutions. A(s) means acceptability of a solution s, regardless of the pathway of promotion/realization; A(i) means acceptability of instrument i, regardless of its purpose; A(s|i) means acceptability of solution type s given realization through instrument i, and A(i|s) means acceptability of instrument i given solution type s

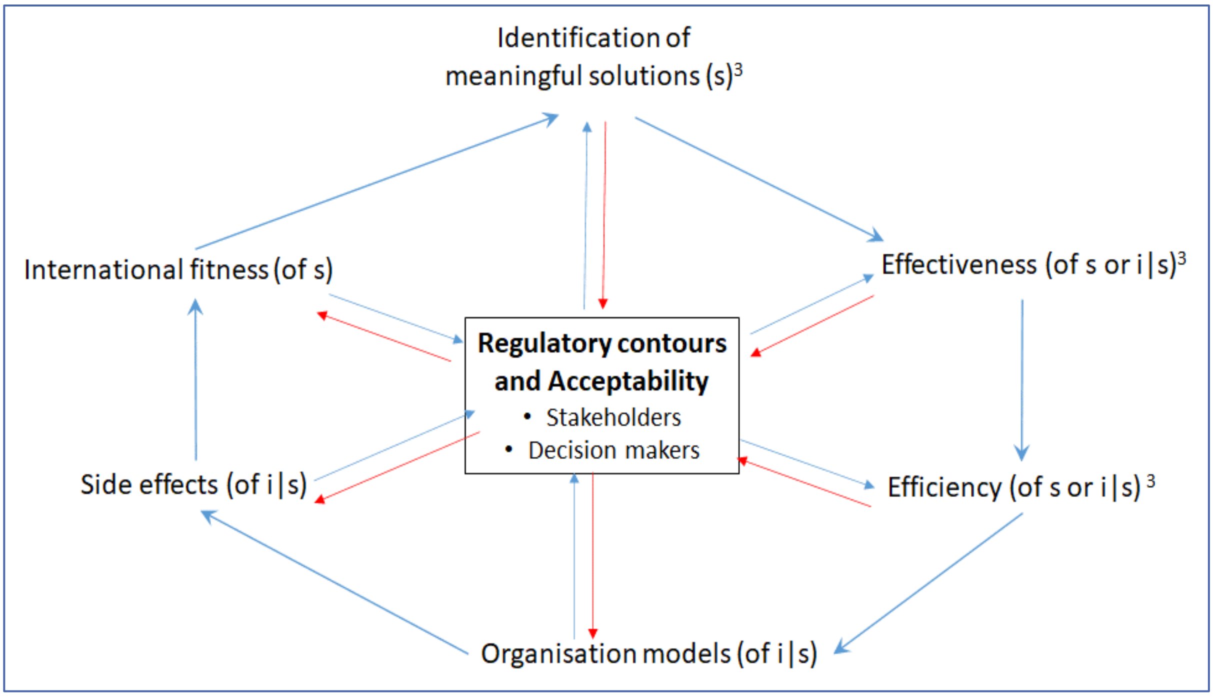

***Figure 2**. Factors driving progress and failure in innovations in repetitive cyclical system (derived from Stegmaier and Perrels 2019)*

Linking Evolutionary Economics views on innovation with cost-focused concepts

Since there may be several competing NETs emerging, the creation of support and knowledge sharing networks for a particular innovation is important for enabling upscaling and evidencing the management of side effects. These processes can indeed altogether be seen as evolutionary in which several NETs are partly competing and partly cooperating regarding the securing of new sources and cycles of funding. Over time a diverse knitwork of niche solutions, broader applied solutions as well as global solutions emerges, inter alia depending on the political and institutional underpinning of the innovations. New solutions may remain confined to niches or expand 'only' in a few sectors and/or world regions or become indeed globally applied in many sectors. These outcomes are the result of interactions between societal and juridical acceptability, degrees of economic protectionism, enablement of control and oversight, and technical-economic effectiveness and efficiency. (Geels & Schot, 2007) refer to such emergent systems as 'multi-level perspectives' (MLP) and cast such processes as a *transition*, rather than just a few innovations. In this case the development and uptake of several ocean-based NETs are innovations that support the transition to a carbon neutral economy. Yet, the overarching favorable context of intended strong reductions in greenhouse gas emissions eventually works out differently for different NETs for the reasons mentioned above, and not the least for reasons of internal competition for development and deployment funding between NETs.

When the management of an innovation process applies comprehensive and continuous monitoring of the innovation development as suggested by the review cycle depicted in Figure 2 surprises tend to be smaller and consequently the learning curve expressed in unit-cost at subsequent times T will show less serious interruptions of the overall downward slope as compared to less comprehensive development monitoring, e.g. when being merely efficiency focused. This is illustrated in Figure 3 by means of hypothetical learning curves showing unit-cost development over time[3]. The left-hand example starts at higher unit-cost levels reflecting a more comprehensive approach. Small surprises are still encountered along the development path, but the comprehensive approach prevents large (upward) shocks. The right-hand example illustrates a process and its monitoring strongly focused on cost-efficiency. It starts at a lower unit-cost level, but faces larger costs shocks when it has to integrate not foreseen new aspects (e.g. due to acceptability issues and regulatory decisions). For each NET unfolds such a unit-cost pathway, with different patterns of shocks and different slopes, whereas some of these pathways will get aborted when development prospects worsen considerably.

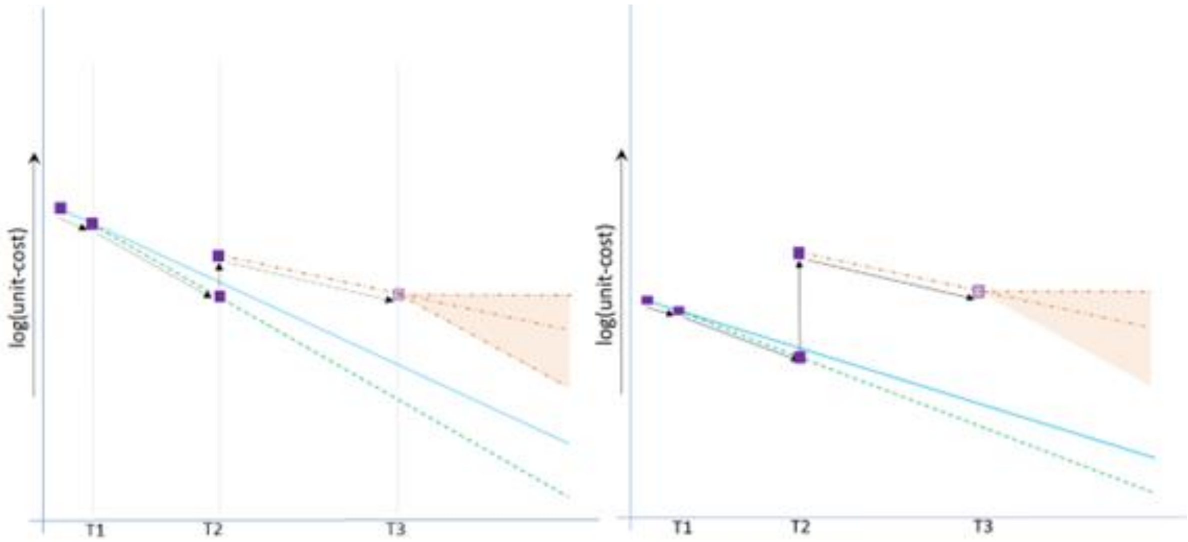

Figure 3. *Illustrative unit-cost pathways in alternative innovation trajectories, being more (left) and less (right) anticipatory regarding acceptability*

The preceding considerations on the unfolding and success factors of innovations can all be understood as elements from Evolutionary economics, in which the emergence of innovations is understood as an evolutionary process, somewhat similar to the evolution of natural species. Steedman & Metcalf (2013) present a theoretical underpinning why this evolutionary representation of innovation and purely cost-efficiency driven representations of innovations can be linked. Holm et al. (2016) provide an outline of the methodological operationalization based on replicator dynamics with which the evolution of bundles of innovations can be analyzed, with unit-cost as one of the performance attributes of each innovation. Progress in the development of a cluster of partly competing innovations is steered by the different innovations' multi-attribute weighted relative advantage compared to the others. New knowledge and new obstacles can affect the merit order as illustrated in figures 1 and 2.

[3] . In fact, *unit-cost development is explained on the basis of cumulative experience*, which associates closely with *cumulative quantities produced*. Yet, when we consider emerging innovations, these are often projected against time. Lafond et al (2017) show that both cumulated output and time can be used in formal analysis.

Gradually for the more vital options expanding niche markets occur and cost-efficiency starts to get more important for upscaling.

An important insight from evolutionary economic studies is also that initial conditions and initial unit-cost levels have a quite limited predictive value for eventual competitive position of a new technology. This means that projections of learning curves cannot be straightaway inferred from the – anyhow scarce – data. Instead, a more exploratory approach is called for. Systematic scenario-based exploration is the option that we propose and implement in this report. In conjunction with scenario exploration or separately a detailed technical-economic analysis of the main drivers of uncertainties of key components can be conducted, inter alia involving effects of progress in material and process control technologies as well as effects of choosing different business model and regulatory regimes that frame the innovation. These notions are used in the design of the deployment scenario tool.

3.2. Definition and significance of unit-cost in the project

In the context of OceanNETs unit-cost refers to the total cost per net ton abated CO_2 considered over the entire value chain which enables the abatement. Cost components per consecutive segment in the value chain can concern costs specifically incurred for the NETs function as well as costs of which a part is attributable to the NETs function. The notion of net ton means that attributable CO_2 emissions of the NETs itself are deducted from the achieved abatement. The amount of abatement is measured in the year of realization. Limitations to permanence of the abated CO_2 are considered separately when comparing alternative NETs.

The theoretical underpinning for a focus on unit-cost of NETs is based on the assumption that the unfolding of the portfolio of greenhouse gas emission reduction measures is to a significant extent driven by the expected and realized cost per ton abated CO_2 of different abatement options. Several studies on realized policy portfolios also indicate this (Best et al 2020). Admittedly, the cost driving effect is bounded by policies referring to environmental and social protection, which are expected to be part of the regulatory context in which NETs will be operated. Furthermore, in absence of perfect foresight an iterative corrective system emerges in which options that seemed very cost effective for some time may face extra cost to contain negative effects and hence may lose competitive edge, while other initially more expensive options may get more attractive as side effects get better understood. This was discussed in the preceding section. It is plausible that after initial development stages unit-cost will get a more influential indicator. With reference to footnote 1 (page 17) it is reiterated that unit-cost development expressed through learning curves depict the cumulative effect from experience through cumulating *quantities* produced. The underlying mechanisms for unit-cost are:

- learning-by-doing
- learning-by-research
- economies of scale (at sector or macro level)
- market form / business model

By assessing the approximate unit-cost of a NET at different points in time one can on the one hand compare to the cost levels of other NETs, and on the other hand review the pace of decrease of the unit-cost and its underlying factors. However, many of the considered NETs are novel and therefore often too few datapoints are available for any meaningful estimation. The different NETs can however be compared with other technologies which are more mature and have similar characteristics in terms lumpiness, substitutability, measurability of performance, and ancillary effects. This implies that some NETs could be compared to unit-cost development of selected large equipment, e.g. wind turbines, and other NETs e.g. to cropping innovations.

Next to and in conjunction with the above-mentioned four factors, the scale of operations affects the unit price. Scale of operation refers here to the typical size of single technical units used. To a significant extent, scale of operations is a result of the above listed four factors, but it also constitutes an own factor, which can privilege larger countries or countries with large stocks of the relevant natural or manmade resources (e.g. lengthy coastline; engineering industry). In conjunction with overall economies of scale (macro-level) a larger scale of operation often enables the actors to get lower prices for inputs.

Learning by doing is a factor which is active when already (some) activity exists and depends on the cumulation of experiences. It typically leads to lower unit-costs and, depending on the degree of competition among suppliers, also to lower product prices. Unit-cost reduction may be precipitated when actors can share information. Learning-by-research is a kind of extension of the learning by doing mechanism during the development phase, e.g. getting a better understanding of critical design features. Also in that phase information sharing can precipitate unit-cost reduction. However, various innovators may not recoup their investment cost, as information sharing will help some innovators more than others. Hence the social optimal outcome in terms of number of successful NET innovations may well be unequal to the eventual number if only commercial interests of each (separate) innovator are optimized. The market form and business model have a significant effect on the strength of continued incentives for cost efficiency, as well as on the ability to expand quickly if necessary.

3.3. Assessment of unit-cost development in the project

In sections 3.1 and 3.2 was explained that the predominantly early development stages of most NETs imply a lack of cost observations and large uncertainty about their prospects due to major uncertainties of various constituent factors, such as feasible and allowable scales and manageability of side-effects. Under those circumstances an exploratory approach which allows the assessment of alternative deployment scenarios is a better choice than trying to infer a unit-cost pathway from insufficient cost estimates and/or from analogues of partially comparable technologies.

Based on literature review the principal factors steering the scale and quality requirements of a NET are identified. These factors can influence one or more segments of the value chain of a NET. At the level of segments, e.g. related to quarrying, raw material processing, and dispersion, there is often information about current technologies and the likely consequences of additional quality requirements, new logistics, etc. By means of literature review, interviews and expert workshops at least some degree of specification per segment, including ranges of plausible levels under certain circumstances, can be produced. By investigating the alternative chains of choices in consecutive value chain segments and for some overarching contextual choices a collection of unit-cost estimates can be produced, whereas also the contributions per value chain segment and their uncertainties are shown. Within the collection of results more plausible pathways and/or weighted averages of unit-cost estimates can be indicated depending on the nature of the collected data and deliberative processes in the workshops. In addition, in as far as possible, comparisons can be made with estimated learning curves for (partially) comparable sectors or products. Dosi (2016) (see chapter 5 and Appendix 4) estimated empirical learning curves of unit-cost of products for selected sectors and product groups, of which some can function as reference for estimates in this study.

4. Scenarios for the unit-cost development for ocean alkalinization

Ocean alkalinity enhancement was already briefly introduced in section 2.1 as part of an overview of ocean-based NETs. This chapter presents a deployment scenario approach applied to ocean liming, based on the theoretical and methodological underpinning presented in chapter 3. Prior to the explanation and application of the deployment scenario approach it first reviews two (clusters of) NETs in more detail, being electrochemical carbon dioxide reduction (CDR) technologies and ocean liming. Initially electrochemical CDR was also considered as a second application option for exploring the deployment scenario approach. In the review of section 4.1 is explained that the immaturity obstructs such an exploration. Ocean liming is described in more detail in section 4.2.1 as basis for the scenario deployment presentation in the rest of section 4.2.

4.1. Electrochemical CDR

A wide range of technologies utilizing electrochemistry has been proposed to increase the uptake of carbon dioxide from the atmosphere (National Academies of Sciences Engineering and Medicine, 2022; Sharifian et al., 2021). These techniques can be divided into a group of technologies that extract carbon dioxide from ocean water (de Lannoy et al., 2018; Eisaman et al., 2018) and a group of technologies that enhances alkalinity to absorb more carbon dioxide into the ocean (La Plante et al., 2021; Rau et al., 2013). Here we will jointly discuss these sets of techniques as they face similar challenges in terms of scaling potential and fungible business models.

Electrochemical techniques hold large potential as they do not necessarily require a large supply chain, but instead can be based on existing technologies and industrial processes such as the desalination industry. The scaling of such preexisting applications serves as an indication for the scaling potential of electrochemical carbon removal approaches (National Academies of Sciences Engineering and Medicine, 2022). As preexisting electrochemical applications such as desalination plants are already in use on a local scale, it seems plausible that electrochemical carbon removal would also be able to function on a more local or national scale, simplifying governance issues surrounding large scale applications such as ocean liming (see Section 4.2).

At this point, it remains unclear which type of electrochemical technique would be most beneficial for carbon removal. Techniques aiming at the direct removal of CO_2 from seawater for storage in geological storage sites are severely limited by the limited concentration of CO_2 in seawater. It is estimated that if the same amount of seawater is processed for CO_2 removal as is currently being processed for desalination, an annual capture of 1-2 Megaton CO_2 could be achieved. Electrochemical alkalinity enhancement would allow for a manifold increase of CO_2 captured for the same amount of seawater processed (National Academies of Sciences Engineering and Medicine, 2022).

On the other hand, alkalinity-based approaches tend to create a stream of acids that would need to be discharged. Several applications consider the use of minerals to neutralize this by-product (Rau, 2008; Rau et al., 2013). This would in turn create a complicated supply chain. Moreover, some approaches propose the neutralization of substances such as hydrogen chloride or chloride gas (House et al., 2007). As these substances are extremely hazardous, strict handling regulations could impose high costs. Moreover, the suggested sale of such substances could work on a limited scale to generate additional revenue. However, on a scale which would be meaningful for global CO2 abatement, most by-products would have to be safely processed nonetheless, because the market for these products is limited. The generation of hydrogen as a by-product appears more promising.

The utilization of reject brines from desalination plants has also been proposed, focusing on the application of magnesium oxides and hydroxides for carbon capture (Davies, 2015; Davies et al., 2018), but using brines faces the same problems as other electrochemistry-based carbon removal techniques. Desalination brines have also been proposed for the capture of carbon from industrial flue gases (Choi et al., 2021; Gálvez-Martos et al., 2020; Mustafa et al., 2020). We do not consider these to be negative emission technologies, but rather a means of industrial carbon capture to reduce overall emissions.

For all electrochemical approaches the required electricity input per ton of CO_2 captured is very high. A (nearly) fully decarbonized electricity supply would be required to maintain a negative carbon balance. Operations restricted to times of day with excess electricity production seems improbable as this would strongly increase the capital costs (National Academies of Sciences Engineering and Medicine, 2022). Therefore, it seems unlikely that an impactful scale, if achievable at all, would be possible in an electricity grid that is not decarbonized. Given the large energy requirements per ton of CO_2 captured, it seems also probable that renewable energy as is could be more efficiently utilized in the decarbonization of other types of industry.

Cost estimates for electrochemical carbon removal range anywhere between $150-$2355/t CO_2 captured, with large variations between techniques. Current estimates fail to fully incorporate all required processes, related emissions, possible carbon capture and storage and tend to focus solely on the energy costs (National Academies of Sciences Engineering and Medicine, 2022).

As renewable electricity generation technologies are maturing and deployed in increasing quantities their unit cost go down and generally have become quite competitive (IRENA 2022). Yet, at system level the requirement to have steady delivery of electricity pushes up costs in a renewables dominated and partly dispersed system. Especially for industrial bulk production facilities the reliable continuous supply of electricity is crucial. So, in real price terms unit-cost of power may be higher than now. Cost levels vary greatly across countries. In as far as electrochemical weathering technology is applied in conjunction with desalination the arid conditions hint at fairly high future electricity prices for reliable bulk use despite the solar energy potential.

At this stage, electrochemical approaches for carbon removal are as yet quite immature and in various respects not well developed. Further research, including pilots and trials, would be required to allow for meaningful assessments of potential impact and the associated cost.

4.2. Ocean Liming

4.2.1. A brief review of ocean alkalinity enhancement options

Ocean alkalinity enhancement refers to a set of negative emission technologies with the same underlying principle: creating a change in the existing alkalinity-acidity balance in the ocean. The naturally existing balance would be distorted through an emulation of accelerated natural processes, in particular weathering. Weathering releases mineral particles into the oceans which increases alkalinity and thus allows for the increased uptake of carbon dioxide. Besides the potential contribution to reducing atmospheric greenhouse gas concentrations, ocean alkalinization enhancement in general has received attention for the possible stabilizing effects on ecosystems affected by ocean acidification such as coral reefs ((Bach et al., 2019; Feng et al., 2016).

Several minerals have been proposed for enhanced weathering. However, at this time, the only form having received a formalized technoeconomic analysis is ocean liming (National Academies of Sciences Engineering and Medicine, 2022). For this reason, the main focus for discovering the cost structures has been put on enhanced weathering with calcined lime, also called ocean liming. A rudimentary investigation into electrochemical weathering and other electrochemical approaches has been performed as well, since this range of techniques might not require large rock extraction efforts and would thus not cause the same amount of direct environmental damage through mining as other techniques could. Moreover, electrochemical weathering could be employed to diminish the environmental effects of desalination brines if combined with a desalination plant.

Since the concept of ocean liming as a type of ocean alkalinization enhancement through the addition of alkaline minerals was introduced by Kheshgi (1995), several aspects of this promising technology have been analyzed. Various studies have been conducted analyzing its feasibility while focusing mostly on techno-economic assessments (Foteinis et al., 2022). The potential contribution and required scale of ocean liming to offset carbon emissions was evaluated as well (Paquay and Zeebe, 2013).

Research and development for ocean liming has initially focused on the addition of calcium oxide as alkaline mineral to the ocean because the procurement of this material is largely based on existing industrial processes. Therefore, at least part of the supply chain for ocean liming possesses a high technological readiness level (Foteinis et al., 2022; Gattuso et al., 2021b). However, calcium oxide is highly reactive complicating large-scale handling of the mineral. So, it appears that calcium hydroxide is more likely to be employed for ocean liming applications due to calcium hydroxide's higher stability. As this mineral is heavier but would achieve the same carbon capture effect, using that mineral will incur additional costs per unit of carbon dioxide captured (Caserini et al., 2022). Several technological challenges still exist in the production process of the calcium minerals as described by Renforth et al. (2013). Specifically, the capture and storage of carbon released and emitted during the calcination process is a necessity to apply ocean liming as a carbon negative technology, yet this process is currently insufficiently incorporated into lime production processes. A practical consequence of the inevitable need to capture the released CO2 from the calcination process is that the ability to realize *affordable* carbon neutrality of the lime production will become a significant location factor for the future liming industry.

For the dispersion of alkaline materials in general, Bach et al. (2019) summarized the proposed platforms into three categories, namely: stationary deployment from marine constructions such as offshore platforms, coastal release of minerals, and dispersion along commercial shipping routes. Ship based deployment possibilities for calcium hydroxide utilizing either partial capacity of merchant vessels or dedicated ships were described by Caserini et al. (2021). Moreover, the possibility to employ aircraft for the spreading of lime has been explored (Gentile et al., 2022).

The potential scale of ocean liming deployment remains little explored. Existing scale predictions tend to focus on the required impactful scale and link that scale with process and operations requirements. Renforth et al. (2013) suggest that a dedicated fleet of 101 ships would lead to a deployment scale of 4.5 gigaton of discharged materials, allowing for 3.7 gigaton CO_2 captured annually. Caserini et al. (2021) propose a fleet of 1000 dedicated ships for the discharge of 1.3 gigaton of materials, whereas they assess that utilizing 15% of the cargo space of existing bulk and container ships would lead to a discharge potential of 1.7 – 4.0 gigaton of calcium hydroxide. Within which time frame these scales are attainable, remains unexplored.

A few cost assessments for ocean liming have been made.Paquay and Zeebe (2013) combined available data on the market price of quick lime and daily operation costs of ships, leading to their estimate of \$103-\$144 per ton carbon dioxide captured. A technoeconomic assessment included several categories of cost for individual components of the ocean liming supply chain and reported expected costs of \$72-\$126 [4] per ton carbon dioxide captured (Renforth et al., 2013). More recently, Caserini et al. (2019) estimated the carbon capture cost at \$98 per ton of CO_2, with the potential to reduce these costs if hydrogen generated in their proposed process would be valorized. The explored dispersion method using aircraft yielded a dispersion cost between €30 and €1846 per ton of CO_2, which was deemed too high compared to ship-based transportation costs (Gentile et al., 2022). All the listed cost assessment assumed the large-scale application of ocean liming, and cost levels for the scaling up process remain unidentified.

In the approach presented below, all crucial supply chain elements and their interconnectedness are assessed. Particular attention is paid to constraining factors that could limit the scale of deployment over time. Moreover, additional external factors that could hinder or support the deployment of ocean liming have been included in the analysis. The combination of state-of-the-art literature with introduced constraints reflects the current best estimates for the cost and scale of ocean liming in the three decades following 2030.

4.2.2. Approach for deployment modeling of Ocean Liming

For the assessment of the potential cost, scale and learning effects of ocean liming, the entire supply chain was considered. The primary components of the supply chain are the production of slaked lime and the sea-based dispersion through shipping. The analysis has focused on shipping as this is currently the only non-stationary means available. Ship based dispersion allows more flexible management of the scaling and tuning of the system compared to the stationary options. Therefore, it seems most likely that through shipping an impactful scale can be reached without surpassing local alkalinity saturation points.

Even though it was indicated in figure 1 in chapter 2 that ocean liming entails *both* a new market *and* a new product, which is usually regarded a high-risk innovation, the value chain of ocean liming contains mostly quite settled industries, such as the lime industry (including quarrying), shipping, ship building, and bulk product and port logistics. In fact, only carbon neutral large-scale electricity and heat production and especially CCS for the CO_2 from the calcination process can be regarded as less and not at all settled respectively. Even though there are technical challenges regarding CCS and lime dispersion technologies in ships a significant part of the cost reduction potential is related to smooth cooperation between quite distinct sectors and the associated creation of effective governance structures. Within each main strategic pathway cost reduction will remain important, but the uncertainty around strategic choices and strategy ‘flipping’ risks is likely to cause jumps in the unit-cost pathways (cf. figure 3 in chapter 2). Hence next to learning in terms of technology and scientific understanding, it also strongly refers to effective collaborative abilities, as will be shown in the next sections.

Initially, reflections from the lime and shipping industries were explored through deliberative discussions with individual stakeholders, being representatives from the liming sector, innovative liming technology producers, shipping companies, marine transport experts, port authorities, environmental NGO’s, marine environmental experts, experts in international environmental legislation, and researchers and evaluators of various NETs. These early

[4] Results are here reported in the denomination used in the referred publication. In 2013 the exchange rate was €1.00 ≈ \$1.35, in 2019 €1.00 ≈ \$1.12, and in 2023 €1.00 ≈ \$1.09

discussions served to identify the incentives for stakeholders to participate in a possible ocean liming supply chain and to uncover any strong barriers that would have to be overcome. The information material gathered, was used as input for a workshop in cooperation with WP6. This first workshop attempted to evaluate plausible configurations of the ocean liming supply chain and the influence of a broad range of factors on the possibilities of deployment (Lezaun and Valenzuela 2021).

In conjunction with an initial understanding of the key drivers and interactions based on literature review and interviews the lessons from the first workshop on plausible configuration possibilities were transformed into a tool for ocean liming deployment scenarios (for tool description see Appendix 1). This tool utilizes a combination of literature and knowledge accumulated during stakeholder interactions to simulate cost and scale outcomes given selected ocean liming supply chain configurations (for a complete documentation of the tool see Appendix 3). During the second workshop, participants discussed how they expected the supply chain to be configured and participants reflected on the outcomes of the tool[5].

A few follow-up discussions were held to clarify various details with participants. Reflections were used to improve the tool. All selected and preferred scenarios were used as input for the amended tool. The equally weighted configuration input was used for generating the final cost and scale predictions for plausible future ocean liming deployment.

4.2.3. Scenario building blocks and scenario realization

4.2.3.1. Identified building blocks

This section describes the six identified building blocks and their role within the ocean liming supply chain. These six building blocks correspond with the selected choice categories in the ocean liming configuration tool. The available choices for each of the building blocks are covered in the description of the tool (see Appendix 1).

International Regulation

As ocean liming will depend on the large-scale discharge of minerals into the world's oceans, regulatory restrictions will not just be determined by national laws, but more importantly by international conventions on the marine environment. The London Protocol and London Convention will have to be amended to accommodate future ocean liming operations. The extent up to which ocean liming would be allowed within these international treaties strictly determines an upper bound for the scale of plausible operations. Next to environmentally inspired restrictions, the upscaling of ocean liming could be significantly influenced by the kind of monitoring regime to be put in place to assure calculated amounts of abated CO_2. The required accuracy and transparency of the monitoring system will also depend on the financial sourcing and the organizational form and associated business models of the involved sectors.

Financial Sourcing

Ocean liming would require substantial financial means to reach an impactful scale. The source of such financial means can influence the possible scale and resulting cost levels. In particular, external financial means would be required if the supply chain would not be self-sustaining. This could be in the form of public support mechanisms or by organizing it as a public service, or conversely link the activity to a permitting system, such that it becomes self-financing. It is

[5] The second workshop was seperately documented and published prior to this report, see: van Kooten et al. (2023).

also conceivable that the system would be started on the basis of public funding, while after some stage of upscaling, when uncertainties have decreased, private funding is included as well.

Organizational Form

Aside from the source of financial means, the conditions under which entities would execute ocean liming could determine price levels. The mechanism for procurement of “orders” or allowances for ocean liming activities can determine the market dynamics and whether any form of competition would be possible in a future ocean liming market environment. For example, the further development of the EU Emission Trade System (EU-ETS), so as to make it more reliable and resilient to economic and technical changes, took many years. Also, even not so large changes in regime designs of e.g. EU-ETS and green certificates caused significant changes in outcomes (e.g. Friedrich et al 2020).

Dispersion Design

The dispersion design refers to the platform of operations for the dispersion of slaked lime into the ocean. Roughly, there are two ship-based strategies possible to reach an impactful scale. A dedicated fleet could be equipped to disperse materials across the globe through specialized operations. Alternatively, a significant part of the merchant fleet would dedicate part of its cargo space to ocean liming and contribute to operations by dispersing materials during their voyages. In essence, the dispersion strategy touches upon a key choice in the business model for ocean liming, as it addresses the preference for a specialized approach. How the precise dispersion technology (the actual application to the sea) may be developing is also considered. See the last item on Operational Effectiveness.

Land operations

The spatial distribution of available limestone deposits and lime kilns influences the connection between land-based operations and sea-based dispersion. The current market for lime can be described as spatially segregated, implying that currently no large, concentrated, supply exists. Loading large ships with lime regularly could therefore imply significant logistical costs. Moreover, the carbon neutral production of lime would require significant long term carbon storage capacity. The availability of this service could strongly influence where and how land-based operations would take place in the future. Various major ports are already developing CCS strategies, e.g. the Port of Rotterdam (https://www.porthosco2.nl/en/) and of Gothenburg (https://www.portofgothenburg.com/the-project-of-the-port/cinfracap/).

Operational Effectiveness

The effectiveness of ocean alkalinity enhancement has not been sufficiently investigated to guarantee that full operational capacity can be utilized in every maritime location. Potentially, discharge rates of lime would have to be adjusted dependent on the location of operations. The operational effectiveness of ocean liming would evolve as more knowledge is acquired on the effects of alkalinity enhancement on overall ocean alkalinity, carbon uptake and the risks of run-away secondary precipitation of lime materials, or when more advanced dispersion technology would become available.

4.2.3.2. Interaction of the Building Blocks

Figure 4 depicts the interaction between the different building blocks in the deployment scenario tool and how these building blocks influence the price and capacity of ocean liming deployment. External societal influences are also included.

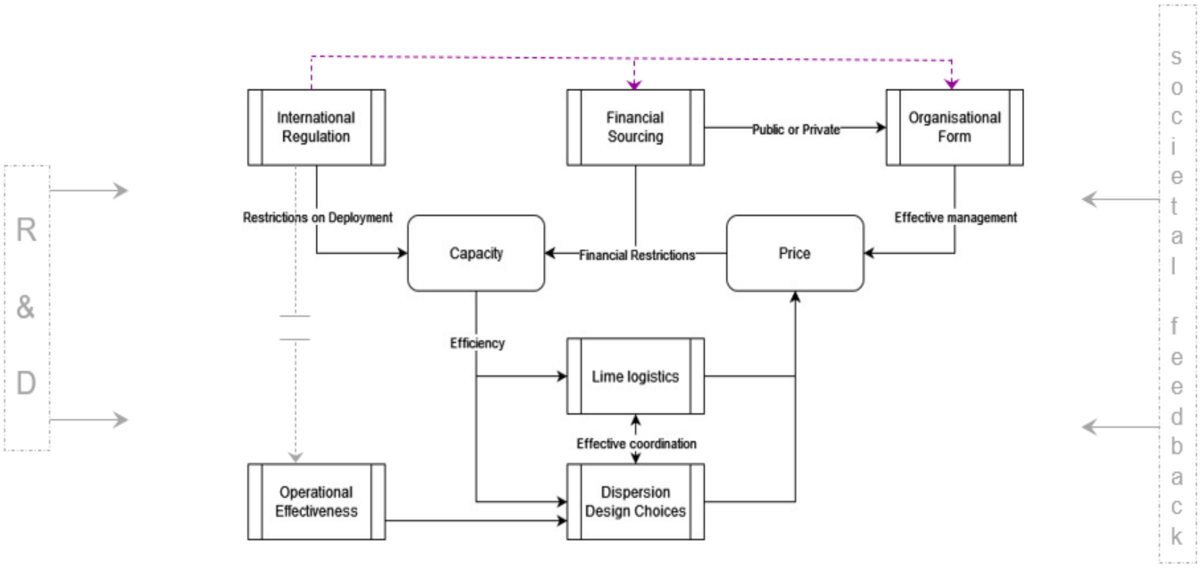

***Figure 4**: Scenario building blocks in a broad societal context*

This figure is not exhaustive and additional factors could influence the deployment of ocean liming. With the current knowledge it seems to capture the most crucial elements that affect the prospects of ocean liming. On the far-left hand side of the figure, research and development is included as an external driver to the building blocks. Research and development largely determine the state of knowledge on ocean liming. This body of knowledge will inform decision makers to formulate policies that would regulate ocean liming. International regulation allowing for ocean liming would require the availability of monitoring and verification methods. Appropriate methods will only exist if research progresses sufficiently. Thus, research and development form a crucial factor that steers the building block of international regulation. Moreover, the operational effectiveness depends on the availability of advanced discharge, handling and shipping techniques that would facilitate the controlled dissolution of slaked lime into the ocean. Developments in the field of carbon capture and storage are instrumental for facilitating the availability of sufficient carbon neutral slaked lime. Advancing the development of any relevant technique can lead to more efficient and cost-effective operations.

Societal feedback influencing ocean liming is visible on the far-right hand side of Figure 4. Societal discourse informs political and regulatory decision-making processes. If ocean liming were to be put into practice, it is likely that societal groups will form opinions on ocean liming in general and the way it should function, if at all. Decision makers could be susceptible to input from society. The social feedback plays a role at the global level, concerning the question whether ocean liming would be in principle allowable or not, and at the regional/local level regarding spatial restrictions to its application.

International regulation by itself could have a dominating influence on the eventual deployment possibilities for ocean liming. Prohibitive regulation will halt the entire deployment and restrictive regulation could impose strict capacity constraints on a potential ocean liming supply chain. At the same time, regulatory restrictions could also impose certain organizational models or financing schemes. Moreover, the rate of deployment would also depend on the regulatory conditions, so regulation would also influence the operational effectiveness.

For modelling purposes, the interactions of **Figure 4** are simplified. In **Figure 5**, the scenario tool's implemented building blocks and their considered interactions are shown. The above discussed external factors have been omitted as building blocks in the tool, but the available choices do reflect the possible states that these influences could lead to. Therefore, their respective influences are more implicit.

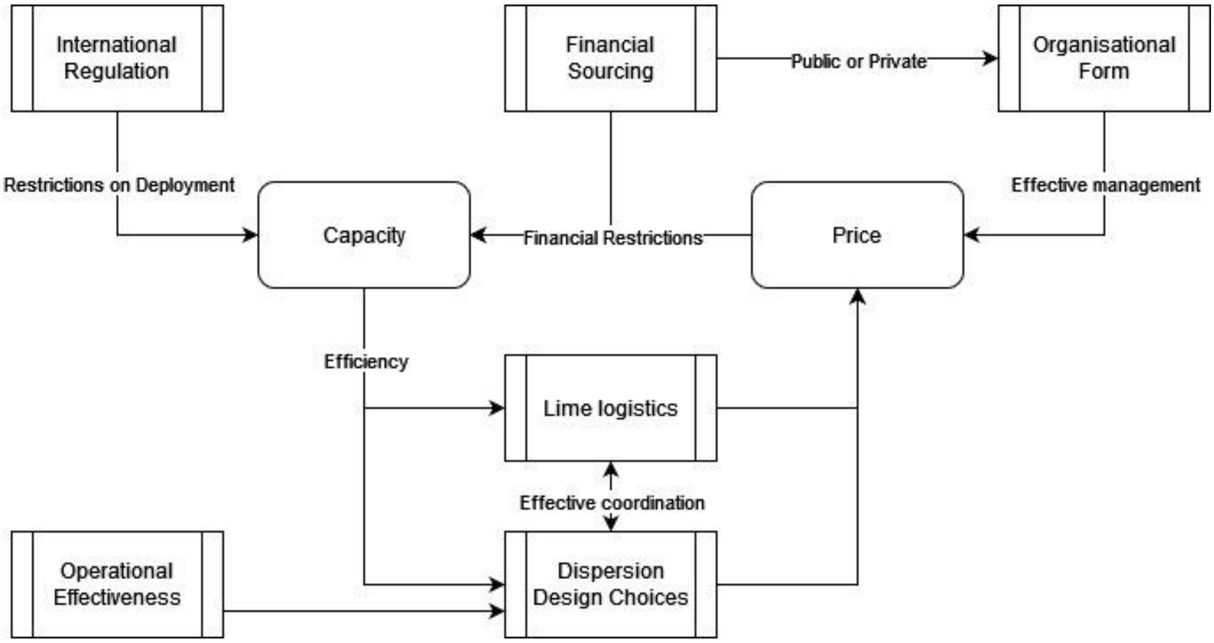

***Figure 5**: Scenario building blocks as modeled in the tool*

As mentioned above, international regulation has a dominating effect on potential ocean liming supply chains. In the tool this is modeled by strict capacity constraints belonging to restrictive or prohibitive scenarios for regulation. Financial sourcing could also cause strong upper boundaries if ocean liming is to be entirely publicly financed. For this, the tool has included budget ceilings for publicly sourced supply chains.

A key distinction is applied between the lime supply and the shipping discharge of alkaline materials in the tool. The lime industry has been modeled as an external supplier of materials since this industry already exists and no specific innovation within the liming process would be necessary, even though admittedly the energy used should be carbon neutral and CCS facilities should be available. Increase in the demand for lime may also cause upward pressure on the price for lime, if only temporary. The merchant fleet on the other hand does exist, but pursuing ocean liming would require disrupting changes to some business models and basic designs. Therefore, the shipping side of the supply chain is modeled more extensively.

The exact functioning and interaction of the building blocks within the tool is documented in Appendix 3: Tool description and documentation.

Presentation of most plausible scenarios and unit-cost prospects

Table 3below presents the results of the scenario configuration exercises. A total of 12 distinct scenario configurations were obtained in consultation with experts. From **Table 3** can be inferred that for some supply chain building blocks expert views diverge more than for others, especially when observing the preference for scenario choices over time

Table 3: *Selected scenarios for the deployment of Ocean Liming*

		2030	2040	2050
International Regulation	Prohibitive	0%	0%	0%
	Restrictive	100%	33%	0%
	Facilitating	0%	67%	100%
Financial Sourcing	Private	33%	75%	67%
	Collective	67%	25%	33%
Organisational Form	Public Enterprise	50%	25%	25%
	Public Tender	17%	0%	8%
	Tradeable NE rights	33%	75%	67%
	Auction NE rights	0%	0%	0%
Dispersion Design	Dedicated Ships	92%	42%	50%
	Partial Capacity Use	8%	58%	50%
Lime Logistics	Centralized Hubs	42%	75%	67%
	Scattered Supply	58%	25%	33%
Operational Effectiveness	Low	25%	8%	0%
	Medium	75%	50%	25%
	High	0%	42%	75%

Stakeholders seem to generally agree about the development of international regulation, gradually developing from a restrictive scenario in 2030 to a facilitating one in 2050. No prohibitive scenario was chosen for any time period. This might partially be caused by the setting of the workshop as it considers deployment scenarios. In case of a prohibitive scenario no supply chain would exist, and no deployment would occur. Nonetheless, this option was available for participants to select. It must be noted that the selection of an international regulation configuration alternative indicates the preference or expectation of stakeholders rather than of the decision makers. This means that the observed expectation for these regimes does not necessarily reflect the actual developments that would take place within the governing bodies. Nevertheless, this factor was included as it has a strongly deterministic influence on the plausibility of ocean liming deployment. Furthermore, even though not explicitly modelled in this case, there is also feedback between the technical-economic prospects of an option and the political inclination to support or oppose it. In other words, if ocean liming would appear to have a significant CO_2 reduction potential that is technically feasible and socioeconomically affordable, there is a larger probability that governance discussions are about the degree of limitations and obligations rather than about prohibition.

No strong pattern can be observed with regards to the financial sourcing mechanisms of plausible ocean liming deployment. Participants did express a slight preference for initial public sector investment. Proposed reasons for this preference mainly addressed proof-of-concept demonstrations by publicly financed organizations. A more privately financed system was preferred for the later periods as ocean liming would supposedly be able to generate revenue.

In case a collectively financed system was preferred, stakeholders indicated a strong tendency to select public enterprises as organizational form for entities deploying ocean liming. Moreover, in case a privately financed system was preferred, stakeholders opted exclusively for tradeable negative emission rights. Clearly, the two options including more public-private partnerships seemed less desirable. This could possibly be explained by the complexity and/or lack of explanation of the latter two choice options. The former two options are more straightforward and could thus be preferred for that reason.

As a deployment platform, dedicated ships are strongly preferred in the initial stages. This links to the earlier mentioned proof-of-concept. Commercial parties would only dedicate part of their cargo capacity if sufficient evidence for the effectiveness of ocean liming has been obtained. Therefore, partial capacity use gets more preferred in later stages of deployment. However, dedicated ships appear to remain a viable possibility over time as well. Dedicated ships would possibly be more efficient in their operations and able to reach a larger share of the oceans. In the next section is shown that in mature (upscaled) stages this choice seems to matter much less with respect to unit-cost.

For the block Lime Logistics, stakeholders did not express a strong preference for 2030. However, centralized supply was more frequently chosen for the 2040 and 2050 periods. Scattered supply was often combined with Partial Capacity Use, as the latter would require broad availability of minerals to maximize the utilization of Ocean Liming capacity. No exclusive combinations between the Dispersion Design and Lime Logistics options were observed due to differences in emphasis for the Lime Logistics alternatives. However, in the current version of the tool the combination of dedicated ships and scattered supply results in very high unit-costs in the first decade (2030). That result is logical, as the number of ships is initially anyhow small, making scattered supply pointless. The large difference of the first decade reduces significantly in the next decade and gets small after 2050. Some expert stakeholders expressed that large scale carbon neutral lime production would be centered around limited geological carbon storage facilities and thus enforcing the centralized hubs option. Others expressed that transporting limestone is relatively expensive, and thus opting for calcination near the quarry. As quarries tend to be scattered, this would naturally lead to a scattered supply of ocean liming minerals.

Selected scenarios for the operational effectiveness of ocean liming exhibit a transformation over time from medium-low to high-medium. Such a development could be expected if it is assumed that ocean liming as a technology will mature over time. However, as for the International Regulation, this process is at least partially beyond the control of expert stakeholders included in our deliberative process and therefore more speculative. An important note was made that both International Regulation and Operational Effectiveness might be tightly linked. Namely, if the effectiveness is low, it seems less likely that International Regulation would facilitate ocean liming operations, even at a limited scale.

4.2.4. Discussion of scenario outcomes

The aforementioned twelve scenario selections were used to simulate outcomes with the tool. This resulted into a range of outcomes for the scale of deployment and associated cost levels. **Figure 6** presents the results for unfolding scale and **Figure 7** shows the results for unit costs.

Scale estimates

In **Figure 6**, it is visible that the 2030 scale level is close to zero, compared to outcomes for 2040 and 2050. Clearly, a more experimental phase is expected for 2030, meaning that only few ships would be equipped for ocean liming operations. This would lead to a limited capacity. This ties in with the exclusive selection of the restrictive scenario for 2030. The scale appears to be increasing exponentially afterwards over the next two decades.

In the tool and choices available, this exponential scale growth was facilitated by allowing for an increase in ship building capacity with increasing capacity, as well as increasing effectiveness given a development of scientific standards. The occurrence of this exponential trend is the result of the tendency to select high operational effectiveness and facilitating international regulation scenarios for the tool configuration.

From **Figure 6** can be inferred that the range of scale outcomes is large for 2040 and 2050. The broad variety of scale outcomes is a result of the development of organizational form scenario selections for these time periods. Especially the choice between a smaller fleet of dedicated ships or a larger number of adapted cargo ships entails a significant difference in unit-cost in the 2040 decade. In case a restrictive scenario was chosen for 2040, there would be large differences with the outcomes of the facilitating scenario in 2040. Moreover, these differences would continue into 2050, as the acceleration of deployment caused by a restrictive scenario for 2040 is delayed by a decade compared to a facilitating scenario choice for 2040. Moreover, collectively financed scenario outcomes are restricted by the available public means, which in this tool would lead to lower deployment levels than for privately funded scenarios.

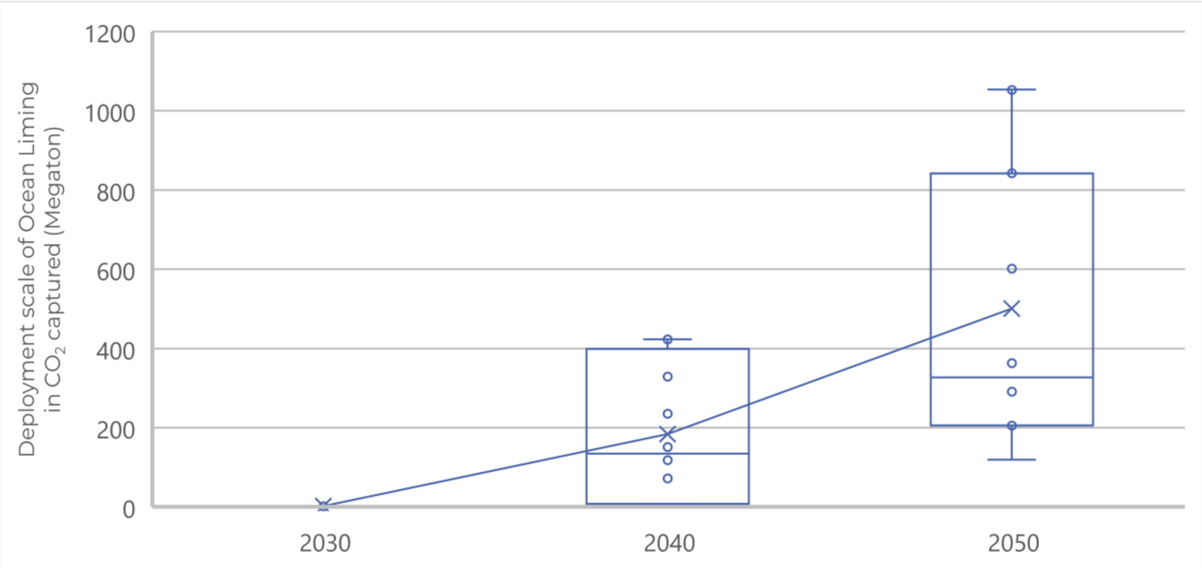

Figure 6: *Deployment scale of ocean liming in megatons of CO_2 captured. The scale of slaked lime discharged can be obtained by multiplying the captured amount of CO_2 by a factor 1.321 (see Appendix 3).*

Cost estimates

Figure 7 visualizes the estimated development of the unit price for ocean liming. In 2030 the average cost per ton of CO_2 was found to be relatively high compared to 2040 and 2050. This is directly linked to the experimental deployment phase that was predominantly reflected in the selected scenarios for this period. An experimental phase would imply that investments are made for limited deployment, and unit-costs don't matter still so much in that phase. In fact learning how to get these unit-costs down matters more. Moreover, lower levels of operational effectiveness cause additional costs because more equipment is needed to achieve the same volume of abatement. On top of that, technologies that are crucial for ocean liming deployment would be in their early operational phases, which implies that no learning or scaling up has happened for these technologies yet.

For the two later decades, the unit price decreases compared to 2030. In general, the maturation of different technologies would reduce the unit cost. In 2040, however, there is a large margin of uncertainty, and some extreme values trump the highest cost figures for the 2030 period. This is caused by some selected restrictive scenarios in combination with partial capacity usage in the fleet. The deviations from the average scale level in 2040 and 2050 do not affect the cost uncertainty as much for the scale having reached large levels in either decade anyhow. This hints at the crucial importance of the first decade of upscaling, i.e. moving from a workable (extended) pilot phase to serious global investment levels. This usually entails a transition from (predominantly) public funding to predominantly private funding, where the latter funding approach will face more competition with other investment options (within the mitigation portfolio and beyond).

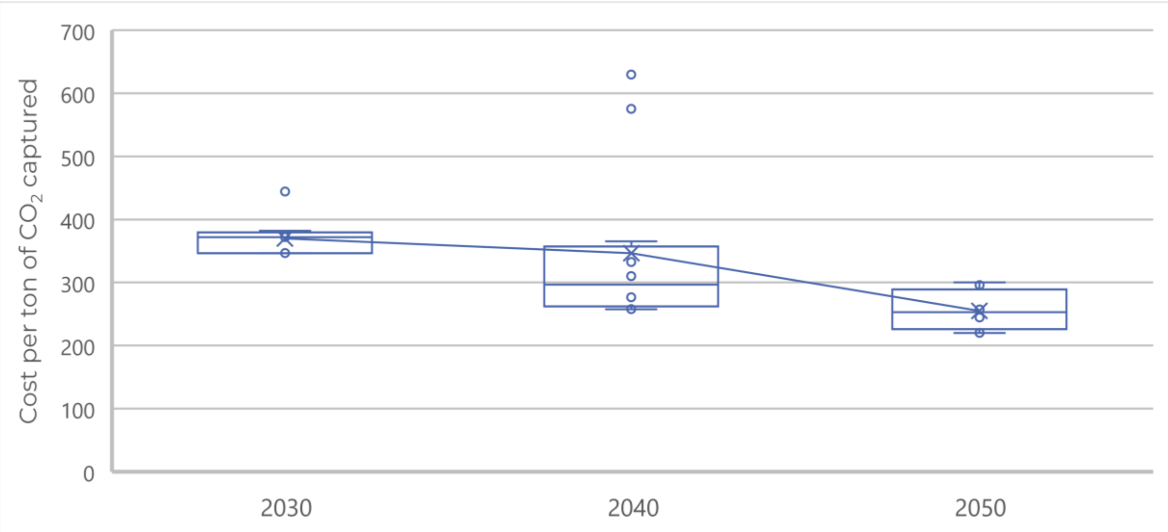

Figure 7: *Cost of deployment for ocean liming based on the scenario outcomes*

The cost breakdown per component as included in the tool is presented in Figure 8. Slaked lime production contributes consistently for a large share to the cost of ocean liming. Since the lime industry is well established, the cost per unit does not decrease much over time. Carbon Capture and Storage unit costs decrease over time due to the assumed further development of this technology in the decades to come in combination with scale effects. The uncertainties with respect to CCS are however quite large, both in terms of unit-cost and in terms of achievable capacity. The land logistics costs on the other hand do not exhibit any clear price development because this is largely based on existing infrastructure and technologies which are not expected to drastically change due to the deployment of ocean liming. In fact, in large ports, competition for space may even raise these costs. Furthermore, the required global expansion of limestone quarries may be challenging. Use of quarry locations with the best logistic features may not always be acceptable. The overhead shrinks strongly from the first decade from 2030 to the next decades starting in 2040 and 2050 as the regulatory and resourcing conditions for operations is expected to be better defined and operational effectiveness increases.

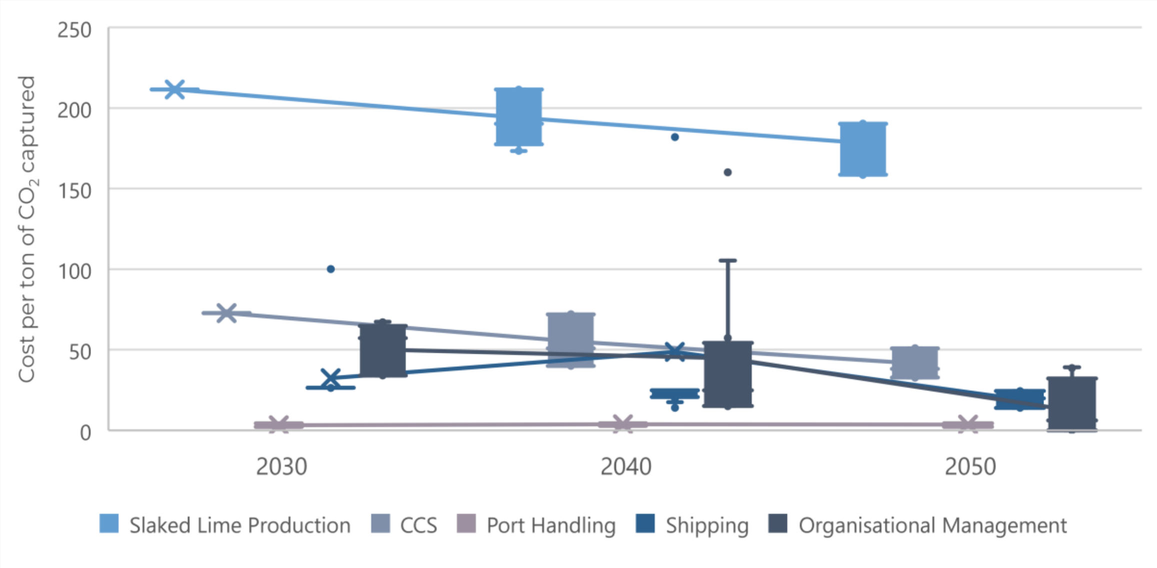

***Figure 8**: Cost breakdown of ocean liming based on scenario outcomes. Note, the unit cost of CCS and Lime production here does not reflect the unit cost of these elements in their respective processes, but is rescaled to the cost per ton of CO_2 by a factor 1.321.*

Interpretation and Discussion

The means of point estimates for the scale and cost levels by decade are summarized in Table 4. These mean values must be interpreted with care. The results of this scale and cost assessment are not specific predictions for either. Rather, these estimates serve as indications for the development of the scale and cost and must be interpreted as the mean of a range within which the expert panel of the workshop foresees the deployment scale and cost to fit, based on currently available information.

***Table 4:** Summary of the scale and cost estimates for 2030, 2040 and 2050 based on average across expert based scenario choices in the workshop and based on the dominant choice per item in the workshop*

	Deployment scale (Megaton)		Average (Median) Cost per unit of CO2	
decades starting	average of choices	dominant choice	average of choices	dominant choice
2030	1.6	1.9	€370 (€372)	€ 542
2040	183	190	€346 (€297)	€ 265
2050	500	1180	€255 (€253)	€ 197

The development of the deployment scale as presented in this research cannot be compared to earlier research as those studies did not consider the development of the scale over time and were mostly based on technically feasible capacities. The scale estimated here can be interpreted as the average maximum achievable scale for the respective decades. The estimated scale for the 2050 period lends itself best for comparison with earlier studies. It is significantly lower than the proposed scale by Caserini et al. (2019) and Renforth et al. (2013). The deployment scale is hindered by two factors in this research, causing the stark differences. Firstly, the restrictive perspective for the international regulation in the 2030 decade postpones the large-scale deployment of the technology to the next time-period because of an initial experimental phase. As the deployment of technology accelerates later, the total attainable capacity in the last decade is lower than proposed scales in earlier studies. The deployment of ocean liming is moreover limited by the available shipping capacity in the accelerating phase. The potential output of shipyards imposes an upper bound on the deployable scale of ocean liming. Even though not explored in the current version of the tool, it seems likely that further reduction of the unit-cost after the 2050 decade can be achieved, especially owing to learning effects (see below).

At first sight, the cost estimates resulting from this research appear significantly higher than the estimates made by earlier studies, especially at low deployment scales. As previous studies did not provide a cost estimate for the start-up phase of ocean liming operations, the figure for at least 2030 and 2040 must not be compared to earlier articles. Nonetheless, the estimate for 2050 remains above earlier provided cost figures. Differences with Renforth et al. (2013) originate in the application of quick lime, a lighter material than slaked lime and thus reducing the transportation cost, the higher carbon absorption rate of discharged alkaline minerals (1.7 vs 1.27 here) and lower geological storage costs ($5 per ton CO_2 vs €33 - €73 per ton CO_2). The utilization of biomass and the addition of removed carbon by the generation of biomass in the carbon budget of ocean liming more than doubles total the amount of carbon removed per ton of discharged quick lime and thus more than halves the price of ocean liming in the study by Caserini et al. (2019).

Apart from the predicted levels the implied pace of change of the unit-costs, i.e. the *learning curve*, is of interest. A problem is that the estimated abatement volumes in the first decade lie in a very narrow interval (1 to 5 MT) as compared to the other estimations for volumes in the next two decades. Following empirical work by Dosi (2016) a simple power function is projected on all observations as well as on a curtailed set including volumes of at least 8 MT abatement (**Figure 9**). Interestingly, Dosi's estimate for pollution control equipment has a parameter value of -0.071, which is close to the parameter for the entire series (Figure 9 left). For pipe fitting Dosi obtains a parameter value of -0.11 just halfway the parameters presented here. Yet, not too much value should be attached to these correspondences. Nevertheless, the deployment scenario tool seems to produce unit-cost series that are not implausible in terms of pace of learning.

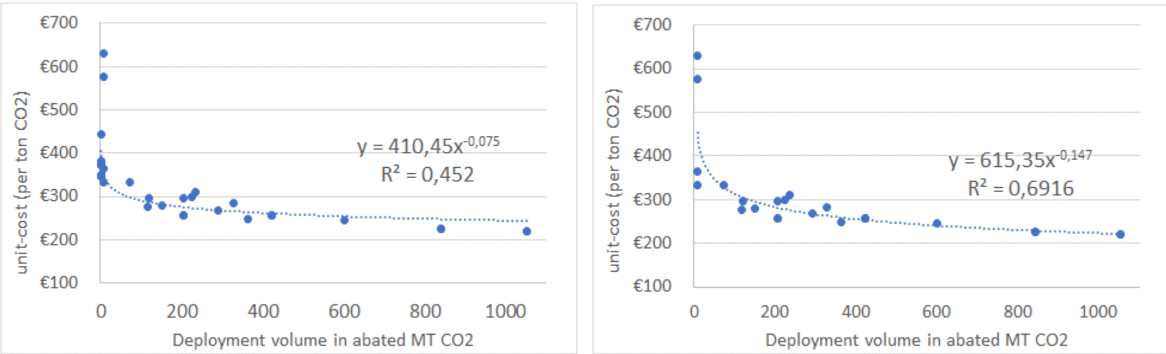

***Figure 9**: Development of price of CO2 captured given the scale of CO2 capturing, using all observations (left) and those with at least 8 MT abatement (right)*

Another angle is to provide more understanding about the most critical choices in the deployment scenario tool in terms of their unit-cost effect. Using the dominant choice per item as a point of departure a selection of choice switches is shown in Table 5.

After the decisions on the global regulatory and governance framework of a global ocean liming system the strategic choices regarding fleet approach (dedicated ships or adapted cargo ships) and choices regarding port oriented supply structures at national and continental levels (centralized hubs or more scattered supply structure) can steer the development notably. Interestingly, if global use of this NET is abounding notably (say beyond 0.5 GT / year) these choices start to matter less in terms of unit cost effects, as most of the scale effects are already reaped at that level. For financial resourcing decisions it is rather the other way around, which is understandable as at smaller scales the absolute risks are smaller from a financial perspective.

Table 5. *Indicative changes of unit-cost due to switches in choices*

Change	Other relevant co-choice	2030	2040	2050
Centralized hub instead of scattered supply *	Dedicated ships	-179	-140	-82
Centralized hub instead of scattered supply *	Partial capacity use (private + tradable NE rights)	+168	+25 (+4)	+4
Private + Tradable NE rights vs. Collective + Public tender		+11	-56	-105
Operational effectiveness Low instead of High**	Financial sourcing: private or collective	+145 +145	+10 +26	+4 +4

*) The dispersion strategy based on dedicated ships has an appreciably larger abatement capacity in the decades of 2040 and 2050 as compared to the option based on partial capacity use.

**) The achieved amount of abatement varies with the effectiveness, meaning that overall capacity is not adapted upward if operational effectiveness is lower than expected. If more capacity would be built, unit-cost reactions would be smaller due to economies of scale, but total cost would obviously increase.

By means of figure 10 it can be clarified why unit-cost matter less in early stages, provided these are not prohibitively high. When at the beginning of the pilot phase is arising a global agreement on the attraction and acceptability of ocean liming the financing of a few billion euro should not be a problem. In the subsequent decades investments and annual operation cost become much larger, and thereby the cost efficiency starts to count more. When an international agreement arises on such a joint effort an interesting flipping point is the attitude towards financing the endeavour. Initially, caution and cost critical inclination tend to prevail, but once an investment programme starts to arise attitudes may flip as at country level very substantial engineering contracts are at stake.

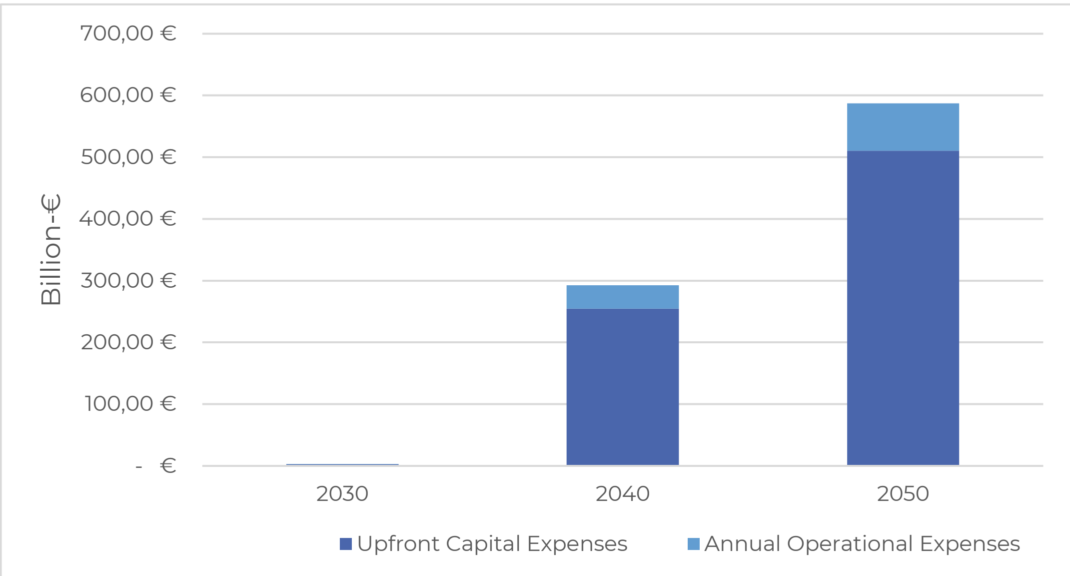

Figure 10: *Overview of expenditure structure for deployment of Ocean Liming in the deployment scenario based on average choices (table 4)*

4.2.5. Competitiveness of Ocean Liming

Compared to various other NETs, both marine and terrestrial, ocean liming seems fairly expensive. It should be realized however that learning processes will continue beyond the horizon of tested deployment scenarios. Furthermore, ocean liming seems so far to be the only marine based NET which can offer a more significant CO_2 abatement potential, while not causing significant negative environmental effects, or even some positive ones (reducing marine acidification).

In cooperation with VTT, the coordinator of the related project NEGEM, part of the same Horizon project cluster on NETs, a scenario run was conducted with the TIMES model to check whether ocean liming would enter the emission reduction technology mix. In some strategy varieties of a 1.5 degree target scenario it starts to appear from 2060 onwards, reaching 2 GT abatement contribution around 2080 and gradually declining again after 2090. These results seem compatible with outcomes of the scenario exploration (in which runs up to 2050-2060)..

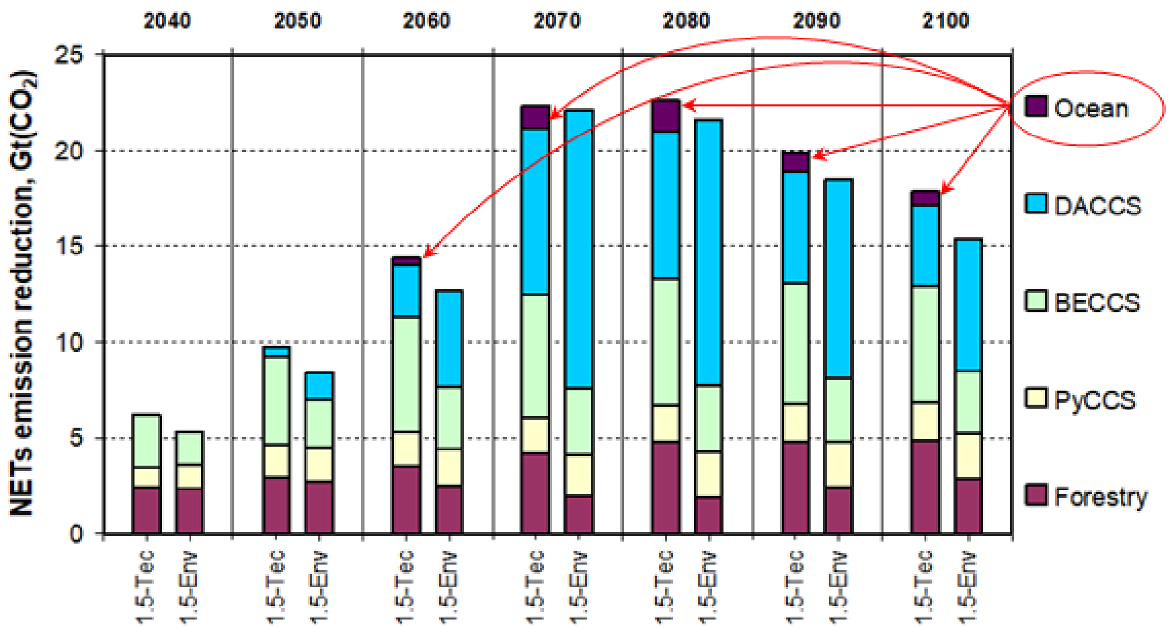

Figure 11. Times model-based projection of contribution of NETs to CO2 emission reduction in 1.5 degree scenario (source: Lehtilä et al 2022)

Last but not least from the interviews and workshop deliberations could be inferred that another significant challenge is the necessity of a mutual alignment of the climate strategies of the lime industry and the shipping industry, if not globally than probably at least at continental level. How are the liming industry and the shipping industry willing to (re)define their strategic goals and their ways of implementing these? For example, the shipping industry focuses now on own emission reduction, but the consequent investment need for renewing the propulsion competes with funding needs for building ocean liming capacity. What would be the reasons to change or diversify the operationalization approach. Reasons could be:

- buying time for fleet conversion (if technical challenges larger than expected)
- introduction of tradable carbon reduction certificates may make the resource input vs. carbon reduction output more efficient (less conversion cost for given goals; yet equalization of own emission reduction and CDR may be contested)

- creation of an auction based dedicated liming fleet operating under a set of conditions; this is similar to a public service contract used in several (originally) public services aimed at production of a public or merit good against minimal cost.

5. Blue Carbon Prospects

All forms of organic carbon sequestration in the ocean environment, particularly in coastal areas, are included in the term blue Carbon (Macreadie et al., 2019). The concept of blue Carbon as a means of carbon sequestration was introduced by the United Nations Environment Programme (2009) to divert some of the attention focused solely on natural terrestrial carbon sequestration to the marine environment. Since then, many studies have explored the potential of marine ecosystem conservation and restoration for carbon capture purposes (Song et al., 2023) .

Potentially, blue carbon sequestration could function as a double-edged sword in the struggle against climate change as it can contribute to both climate change mitigation *and* adaptation. The restoration of ecosystems in coastal areas helps protecting and maintaining coastlines (Duarte et al., 2013; Kuwae & Crooks, 2021). Next to the ecosystem restoration based blue carbon solutions, more environmental intervention-focused applications have been coined as blue carbon capture. Large scale aquaculture of macroalgae could artificially increase the uptake capacity of oceans while the securing of long-term carbon storage would happen more synthetically (Krause-Jensen et al., 2018; Lovelock & Duarte, 2019).

For the remainder of this chapter, we will distinguish between local and global blue carbon solutions. The scope of applicability is mainly determined by the scale of applications. Ecosystem restoration and rehabilitation are considered local solutions because these solutions are usually location dependent and do not require broad-based approval before they can be implemented. Of course, particular ecosystem restoration approaches can be replicated in similar ecosystems elsewhere, but these remain separate projects and decisions, even though there can be some degree of learning which is portable. Such local blue carbon solutions are discussed in 5.1. Ecosystems engineering approaches could have more transboundary effects, are likely to require a broader governance approach and are probably only viable at a large scale. These more intervening applications are covered in section 5.2.

5.1. Local Solutions

Coastal ecosystems such as mangrove forests, salt marshes and seagrass meadows, contain large carbon stocks and generate significant value by sequestrating carbon continually (Bertram et al., 2021). However, coastal ecosystems have degraded significantly over time, a sizeable proportion of the initial habitat has been lost. Restoration and regeneration of coastal habitats could not only provide an expansion of carbon sink location, but also contribute to other ecosystem service enhancements and biodiversity conservation.

Roughly, three categories of coastal wetlands are recognized for their potential in terms of carbon sequestration, namely seagrass meadows, salt marshes and mangrove forests (Macreadie et al., 2019) These three types of ecosystems function differently and possess distinct characteristics. Here we will treat these types uniformly as we are not focusing on biological conditions, but rather interested in the overall potential and associated incentives for the deployment of the whole range of blue carbon applications. In general, these incentives tend to apply to all types.

The potential contribution of the individual coastal biotopes to carbon capture and storage has been assessed in a range of studies. Overall, Griscom et al. (2017) find that the contribution of all coastal blue carbon applications aiming at ecosystem restoration to be between 621 and

1,064 Megaton carbon dioxide equivalent annually, it is reported that only 24% of this capacity is cost effective (below $100 per ton CO_2 equivalent). Of the total potential, roughly 71% would be attributed to mangrove forest, 4% to salt marsh, and 25% to seagrass restoration. One main restriction of blue carbon applications in wetlands is that the total deployable scale is much more limited than for other nature-based solutions (Griscom et al., 2017). Consequently, the overall contribution level of blue carbon applications to reaching a global net zero emission remains limited.

The effectiveness of blue Carbon applications in terms of carbon sequestration strongly depends on local factors. For instance, biological and non-biological factors influence the functioning of seagrass meadows, leading to differences across and within estuaries Hatje et al. (2021) concluded that the range of carbon uptake for mangrove forests within the same estuary in Brazil ranged between 62 and 1073-gram organic carbon per square meter per year. This result demonstrates that it is complicated for indirect measurements or models to assign carbon uptake and carbon stocks to blue carbon ecosystems with large uncertainty ranges to be accepted. Clearly simple global averages for types of blue carbon applications cannot be used to estimate the carbon sequestration potential of a blue carbon site (Williamson & Gattuso, 2022). Consequently, each site might require its own on-site measuring and verification process. This is highly costly and strongly reduces the cost-effectiveness. Moreover, it emphasizes the complexity of assessing the unit price of blue carbon projects per unit of carbon dioxide captured. Possibly, the expanding application of remote sensing for carbon sequestration monitoring, also of wetlands, may help to arrive at affordable monitoring solutions of acceptable quality(Campbell et al., 2022).

A direct consequence of the unreliable sequestration rates is that the current body of knowledge cannot provide a concrete and well accepted estimate of the potential contribution of blue carbon applications to reducing greenhouse gas emissions, nor is it possible to give an accurate cost price as the results in terms of carbon dioxide storage remain uncertain.

On the other hand, the total value of coastal ecosystems has been elaborately studied when it comes to the provided ecosystem services in terms of coastal protection. Several studies have explored the physical benefits and related economic value of these ecosystem services (Blythe et al 2020). Next to that, the value of coastal wetlands for eco-tourism has also been well documented. The value of coastal ecosystems extends beyond its current role in coastal protection, as these ecosystems have been found to hold substantial climate change adaptation value. Coastal wetlands can reduce the effects of waves by absorbing and spreading the impact of incoming waves. Moreover, the root systems of the vegetation create a more stable sediment that is more resistant against erosion. These two characteristics will aid the resilience of coastal areas against increasing sea water levels (Duarte et al., 2013; Jacquemont et al., 2022). In particular, mangroves have been found to significantly reduce the flood risk in coastal areas across the globe (Losada et al., 2018). Moreover, the conservation and restoration of coastal natural habitats can be crucial in maintaining or improving local biodiversity levels (Williamson & Gattuso, 2022).

The acknowledgement of the significant and highly beneficial role of coastal ecosystems in the protection against storm surges and coastal erosion has effectively created a market for the maintenance and restoration of such ecosystems. Inherently, these projects also generate carbon storage capacity within the ecosystems. Consequently, the generation of so-called blue carbon credits would supplement the existing market by expanding aggregate demand for coastal ecosystem enhancement. It does not seem obvious that these demand components are competing, rather the blue carbon element seems largely supplementary. If that also means supplementary resourcing (from carbon reduction credits), a larger share of the global coastal rehabilitation potential could be realized sooner.

The effect of blue Carbon credits can be illustrated rather straightforwardly using basic microeconomic methods, as is done in Figure 12**Error! Reference source not found.**. Initially, there is a supply of coastal wetlands available for restoration. The supply of global coastal wetlands is limited hence the steeply upward-curving supply line near the limit. The demand for coastal wetland restoration is depicted by the initial (lower) demand curve. This represents the current situation in which the only values incorporated in the market for coastal wetland restoration are coastal protection and eco-tourism values. In equilibrium, the quantity of coastal wetland restoration (q1) is found at the intersection of the supply and demand curve (A).

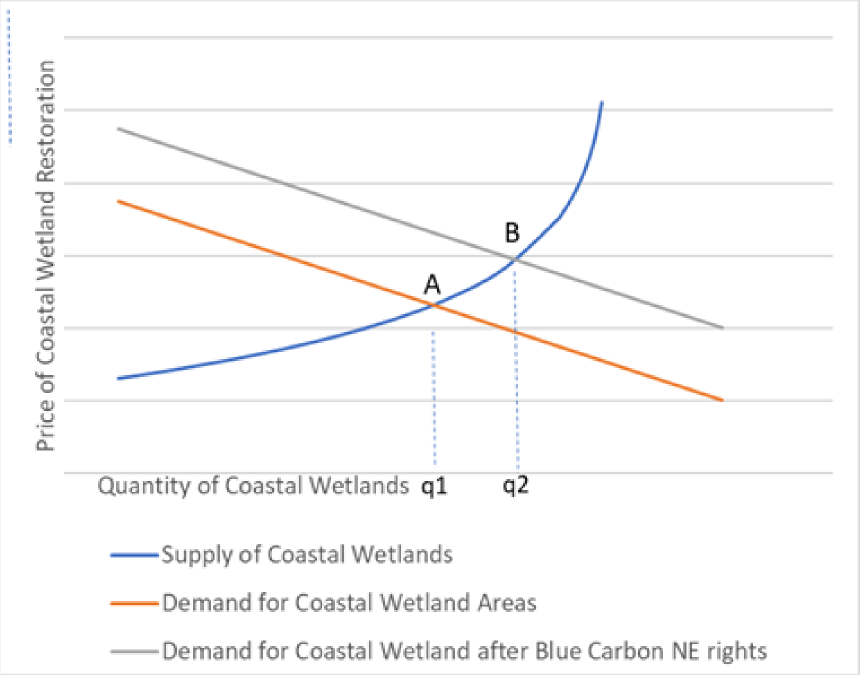

***Figure 12**. Stylized representation of the effect of negative emission (NE) rights on the maximum acceptable unit-cost (price) of blue carbon prjects and consequent realizable volume of rehabilitation* (q1 → q2)

When the value of blue carbon can be valorized by project realizers, such as by means of tradable negative emission (NE) rights, the same wetland will generate larger tangible benefits. As a direct consequence, the demand for coastal wetland areas shifts up by the additional value of blue carbon per unit of coastal wetland, the additional benefit per unit of coastal wetland. The new equilibrium would be found at the intersection of the supply curve and the new demand curve (B). Evidently, more coastal wetlands will be restored (q1 ⟶ q2), especially those that had initially been deemed too expensive to restore. Importantly, blue carbon action must make a clear distinction between coastal wetland protection and rehabilitation. Annually, coastal wetland areas are still lost to be converted for aquaculture, agriculture or are threatened for other reasons (Rogers et al 2019). Preventing such land use change impacts prevents the release of carbon dioxide from sediments and maintains the carbon uptake mechanisms of those locations, but does not yield any increase in the locations of blue carbon lands. Therefore, protection measures alone do not provide additional negative emissions.

In addition to challenges to distinguish between human influenced changes in the quantity and quality of coastal blue carbon ecosystems these ecosystems undergo effects caused by climate change. In some cases, the deterioration can be very significant. Overall climate change seems to cause far more negative than positive change in coastal blue carbon ecosystems (Reed et al 2022). This class of effects has not been taken into account in this chapter.

At large, we underline the suggestion by Williamson & Gattuso (2022), that restoring coastal blue carbon ecosystems for the sake of carbon sequestration only might be ineffective, while blue carbon restoration is a purposeful investment when all other benefits are considered. The expansion of the restoration of coastal ecosystems thanks to supplementary benefits blue carbon generation will hinge upon the reliable monitoring of the additional carbon storage attributable to the restoration efforts. The extra cost of reliable monitoring may have a prohibitive effect on the expansion, hence the significance to reduce the cost of monitoring without compromising the reliability.

5.2. Global Solutions

The global seaweed aquaculture sector is well developed. Output approximately tripled between 2000 and 2019, with 360 000 ton of seaweed in 2019 (Zhang et al 2022). In Asia it is mainly produced in aquacultures, whereas in the Americas and Europe natural sources prevail. Seaweed, and macroalgae in general, are rapid growers when subjected to suitable climatic conditions. These species can therefore rapidly absorb carbon dioxide. When seaweed is harvested for (human) consumption, no stable storage of carbon is achieved, hence no sequestration occurs (Troell et al., 2022). However, a significant expansion of the current seaweed industry in combination with the development of a large-scale long-term storage solution for seaweed debris could yield significant carbon capture potential rapidly. The most prominently discussed storage option in the literature is biomass sinking. During such operations, seaweed biomass is pumped, or otherwise transported, into the deep ocean from where carbon can hardly escape to the atmosphere, thus safeguarding stable storage. An alternative would be the production of marine Biochar, in which process seaweed biomass is turned into stable carbon through pyrolysis. Both proposed processes are still in the development phase. If seaweed plantations were to be located in zones affected by eutrophication, the cultivation would contribute to reducing the nutrient surplus in these environments and help return ecosystems to a healthy nutrient balance.

Conceptually, large scale seaweed cultivation sounds like a high potential solution for carbon capture. However, some major issues have so far not been properly addressed, yet these issues could significantly affect the suitability for large scale deployment. Firstly, seaweed cultivation is considered a form of marine geoengineering rather than a nature-based solution, because its aim is to sequester carbon (Proelß & Steenkamp, 2022; Webb et al., 2021). At the moment, seaweed cultivation as a carbon removal technique is not (yet) included in the list of techniques that could be approved for research purposes under the London Protocol (Proelß & Steenkamp, 2022). A long chain of approval and further research would thus be required before field experiments could be performed. Moreover, the cultivation of seaweed for carbon storage will undoubtedly affect the nutrient streams in the upper layers of the ocean. Furthermore, large scale seaweed cultivation could affect marine biodiversity negatively, even though various authors seem to suggest that such effects may not be dramatic if precautionary measures are taken (Eggertsen and Halling 2020; Forbes et al 2022).

It is estimated that 7.3 million hectares of aquaculture would yield 0.1 Gigaton of CO_2 captured annually (National Academies of Sciences Engineering and Medicine, 2022). To prevent a depletion of nutrient streams, this scale of deployment could require artificial upwelling to resupply the created nutrient deficits (National Academies of Sciences Engineering and Medicine, 2022). The consumption of nutrients is expected to also affect other ecosystems, in particular the Net Primary Production of plankton is expected to be reduced, lowering the plankton carbon capture potential (National Academies of Sciences Engineering and Medicine, 2022), and potentially affecting the vitality of plankton based marine ecosystems. In case seaweed biomass sinking will be employed, the ecosystems on the deeper ocean floor could be affected while these ecosystems are the least studied on the globe. Moreover, the lack of knowledge of these ecosystems and their environment causes a sizeable lack in the certainty of the behaviour of biomass debris and actual long-term carbon storage potential of seaweed materials.

The concerns over using seaweed biomass for long-term carbon storage, especially in the deep ocean, are numerous. The effects of a large-scale deployment on marine ecosystems are likely to be distorting. At this point, we deem it impossible to make an accurate assessment of the potential scale and the associated cost for the deployment of this technology because of the lack of knowledge on the actual achievable effects and potential negative consequences. We recognize that seaweed as a food source could develop further. In that case, cultivation in locations suffering from eutrophication, could contribute to healthier seas. Moreover, seaweed as a food or feed source could substitute agricultural land for aquaculture, such that fields could be transformed into terrestrial carbon sequestration areas trough for instance afforestation (Troell et al., 2022).

6. Conclusions

The development of the unit-costs appears to be an important factor for significant deployment of a NET, but in early phases of NET development it is not necessarily a critical factor, as long as the expected unit costs are not extremely high. The prime factor for an ocean-based NET to have a significant role is to become a formally recognized and approved technology in international marine, coastal and naval regulations, in particular the London Protocol. Once that acknowledgement is secured many actors will have a higher willingness to invest in the development of an ocean-based NET. In turn that acknowledgement will probably require more evidenced assurances that ocean liming can be conducted without significant environmental effects at sea.

In case of ocean liming the next important layer about which should be achieved broad, if not global, agreement is the spatial and technical organization of lime logistics and delivery at sea (fleet characteristics). In this stage unit-cost prospects will play already a role. These prospects are also influenced by the financing structure of the build-up of the liming logistics and delivery fleet, especially during the upscaling phase following successful pilots.

Based on the scenario exercises conducted in this study ocean liming may be able to contribute to global mitigation efforts at a level of 0.5 to 1 GT abated CO_2 per year by 2060 ~ 2070. That would be probably at a cost level which is above current estimates of future carbon prices in EU-ETS. In an associated EU funded study called NEGEM a TIMES model-based exploration of emission reduction options including ocean liming yielded prospects of maximum 2 GT abated CO_2 per year by 2080. It should be realized that these estimates are subject to quite large uncertainties.

As regards the prospects of different NETs, ocean based and terrestrial, it is important to nurture diversity for the time being, as many options are still at quite immature development stages. Tradable negative emission rights would probably promote the emergence and expansion of at least some of the ocean-based (and terrestrial) NETs. Many options may have some application potential, albeit locally. A part of the blue carbon potential has moderate unit-cost. The realizable potential would increase in case of tradable negative emission rights, as well as through resilience bonds for the adaptation function (e.g. coastal protection) of a part of the blue carbon projects.

Learning curves, i.e. cost efficiency as leading factor in innovation, are an helpful indicator, but their significance should not be overrated. Innovations, especially in earlier stages are driven by many other factors. In the case of various ocean-based NETs for example acceptability and prospects for significant potential are equally important. A combination of evolutionary economics approach and learning curve theory seems to provide a more fruitful basis for analysis and provided the underpinning for a deployment scenario tool meant for NETs – more in particular applied to ocean liming.

On the basis of literature study, interviews and an expert workshop a deployment scenario tool was devised, which was subsequently tested in a second expert workshop. The tool provides indications for the development of the scale of deployment of ocean liming by decade from 2030 to 2060. The results should be understood as being only indicative and intend to provide understanding of the order of magnitude of effects of various types of decisions on deployment scale and (unit) costs, as well as of the interaction effects between some of the variables.

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Appendix 1: Tool description as shared with workshop participants

OCEAN NETs

Ocean-based Negative Emission Technologies

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].

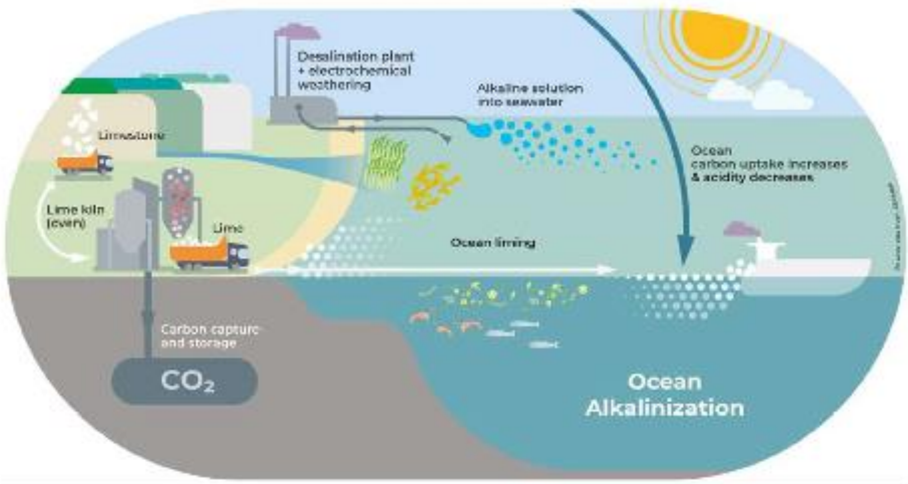

Image 1. Representation of possible paths for OAE

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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Ocean-based Negative Emission Technologies

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/8C76017EE72F07CF. 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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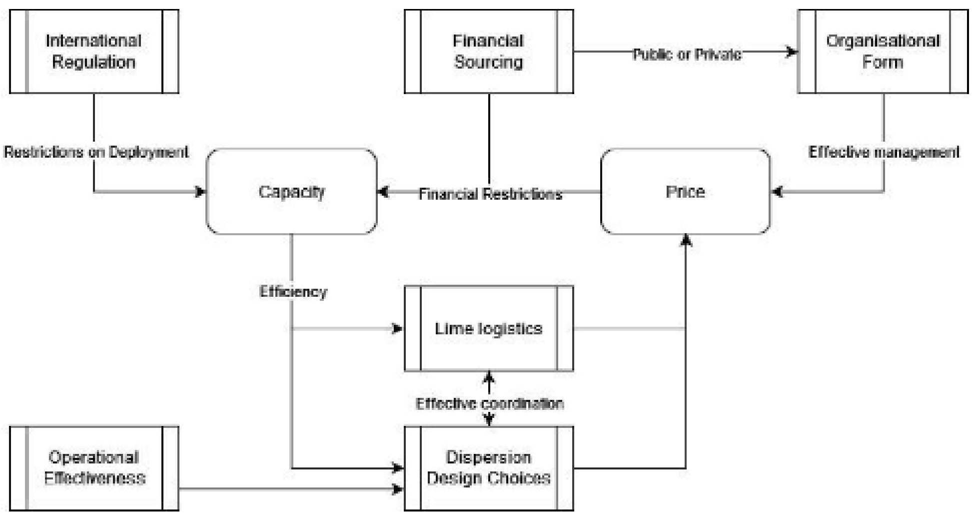
Detailed description of the tool

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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Ocean-based Negative Emission Technologies

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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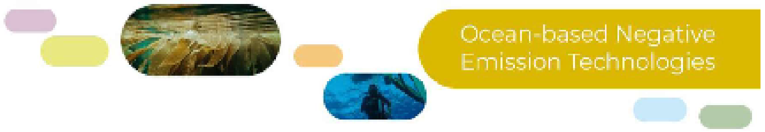
Appendix 2: Tool entry tables as shared with the workshop participants



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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Appendix 3: Tool description and documentation

A general description of the Tool, its purpose and options are documented in Appendix 1: Tool description as shared with workshop participants. In the preceding Appendix 2 the scenario simulation module of the tool has been displayed. In the first half of the decision table, scenarios can be selected for the six building blocks. This would then generate a certain output. The output is summarized in the bottom half of the decision table and the figure below the decision table. The setting of key parameters is displayed in the “Key Parameters” table at the bottom of the document.

This appendix explains and justifies all the computations underlying the output generation of the tool. Each of the sections below deals with one of the building blocks that were identified. Some building blocks contain computations that are explained for one year only since the computations are identical for the other time periods, except for some differing input values (as indicated in the explanations).

NOTE: Point estimates have been used in the tool as much as possible to simplify the estimation procedures. We acknowledge that those point estimates could vary, but we allow for these fluctuations as the goal of this tool is not to provide accurate point predictions but rather indications of intervals.

International Regulation Building Block

For each period, three scenarios are available for International Regulation:

- Prohibitive: No ocean liming is allowed.
- Restrictive: A limited, experimental scale of ocean liming is allowed.
- Facilitating: International regulation does not impose restrictions on the scale of ocean liming deployment.

In each time period, the selection of a scenario option generates a capacity constraint, the legal maximum capacity. This is a capacity constraint for the maximum amount of dischargeable alkaline materials. This capacity constraint is an intermediate output and used by other building blocks in further computations. It is also communicated in the Decision Table. As ocean liming is a novel technology, no real-life data was available to translate the scenario options into numeric capacity constraints. As an alternative, the capacity follows a certain logic. Prohibitive scenarios restrict the legal maximum capacity of ocean liming to zero. Restrictive scenarios allow for an experimental scale of ocean liming, which implies that several megatons are allowed, assuming that one dedicated ship could discharge already 1.3 megaton of alkaline materials ((Caserini et al., 2021). Facilitating scenarios have legal capacity restrictions that should not influence the deployable capacity otherwise. Over time, it is assumed that the restrictive and facilitating scenarios allow for increased capacity, as it is assumed that the state of research will develop over time as well. Moreover, choices from earlier time periods influence the capacity outcomes in later time periods. The possible legal maximum capacity outcomes as parameterized in the tool are visible in Tables 3-5. Table 6-Table 8.

Table 6: Legal maximum capacity for 2030 in megaton

Scenario	Capacity 2030
Prohibitive	0
Restrictive	5
Facilitating	1000

Table 7: Legal maximum capacity for 2040 in megaton

		Scenario and Capacity 2040		
		Prohibitive	Restrictive	Facilitating
Scenario in 2030	Prohibitive	0	5	500
	Restrictive	0	15	1500
	Facilitating	0	5	2000

Table 8: Legal maximum capacity for 2050 in megaton

			Scenario and Capacity 2050		
		Scenario in 2040	Prohibitive	Restrictive	Facilitating
Scenario in 2030	Prohibitive	Prohibitive	0	5	250
		Restrictive	0	15	500
		Facilitating	0	5	2000
	Restrictive	Prohibitive	0	5	250
		Restrictive	0	25	2000
		Facilitating	0	15	5000
	Facilitating	Prohibitive	0	5	250
		Restrictive	0	15	1500
		Facilitating	0	5	10000

Financial Sourcing Building Block

For each period, two scenarios are available for Financial Sourcing:

- Collective, indicating a publicly financed supply chain.
- Private, indicating a privately financed supply chain.

The main difference between these two scenarios is that in a privately financed system, the deployment capacity is not necessarily capped by fixed financial means. Rather, if the technology is competitive, the market would determine the price and cover all expenses. In the collectively financed scenarios, a cap on the product of capacity and end price of ocean liming is introduced. As there is no real literature available on the financial means that could be disposable for this technique, educated guesses have been made. The disposable amount increases progressively over time, assuming that increasingly proactive climate action will lead to larger willingness to finance. The amount is assumed to be made available by large cross-country coalition(s) on a pan-continental or global level. The following amounts are included in the tool: €2 billion per year for the 2030 period, €25 billion per year for the 2040 period and €75 billion per year for the 2050 period.

Organizational Form Building Block

For each period, the following four scenarios are in principle available for the Organizational Form:

- Public Enterprise: A public organization directly under supervision of an international organization is responsible for the deployment of ocean liming and coordination of the different actors across the supply chain.
- Public Tender: A public organization selects the deployers/coordinators of ocean liming by means of a tender in which private organizations can propose ocean liming execution given an available budget.
- Auction of Negative Emission Rights: Permits to operate ocean liming are auctioned to the most competitive parties. Operations are limited to the acquired permit but generate negative emission rights for verified amounts of carbon captured. The negative emission rights then be traded to generate funds.
- Tradeable Negative Emission Rights: Ocean liming would generate tradeable negative emission rights. This means that free ocean liming operations can occur, and that operators obtain negative emission rights for verified amounts of carbon dioxide captured. The negative emission rights can then be traded to generate funds.

The availability of these scenarios in each time period depends on the selected scenario for financial sourcing in the same time period. Public Enterprise and Public Tender are funded through public means and thus only available if the Collective scenario for Financial Sourcing is selected. The other two scenarios generate private funds and are thus only available if the Private scenario is chosen for Financial Sourcing.

The type of organizational form determines the organizational costs that will be included in the price of ocean liming. No exact data is available for the justification of specific organizational costs, especially for varying scales of operations. Therefore, the organizational costs are determined as a mark-up of the total ocean liming costs. These mark-ups have been formulated based on the assumed efficiency of the individual organizational models. Over time it is assumed that ocean liming increases in scale, and therefore the mark-ups of the organizational models evolve accordingly. In Table 9, the mark-ups applied in the tool are displayed. The mark-ups are a percentual increase on top of the gross estimated cost of ocean liming.

Table 9: Mark-ups to the ocean liming costs given the Organizational Form

Organizational Form	Mark-up 2030	Mark-up 2040	Mark-up 2050
Public tender	5 %	5 %	5 %
Public enterprise	5 %	15 %	15 %
Auction NE rights	10 %	0 %	0 %
Tradeable NE rights	15 %	5 %	0 %

Public enterprises, especially large ones, tend to run less efficient and therefore would incur more organizational costs given increasing quantities of operation. Public Tenders allow for a certain level of competitiveness but do restrict market access by limiting operations and thus create a certain level of market power, which could allow for a limited mark-up for organizational costs. Auctions for negative emission tenders force market participants to make competitive offers. Similarly, tradeable emission rights are only sold by the most competitive market players. The latter two options would thus have restricted organizational costs. However, in initial phases a limited amount of ocean liming operators would be able to exert significant market power and could thus generate a mark-up for organizational costs or profits. This is more limited for auctions as operators would still need to be selected.

Dispersion Design Building Block

Dispersion Design has the following scenario options for each time period:

- Dedicated ships: A fleet of purpose-built ships will be dedicated to the operations of ocean liming.
- Partial Capacity Use: existing or new merchant ships will dedicate a share of their cargo space to ocean liming.

These two scenario options cover the most scalable options for the large-scale deployment of ocean liming. Alternative options mentioned by (Bach et al., 2019) such as the application of minerals in river estuaries or from fixed marine structures were not considered as the deployment scale was assumed to be too limited while avoiding localized negative environmental impacts.

This building block computes the gross transporting cost per ton of alkaline material discharged. These costs are based on computations detailing the discharge capacity of a ship (Table 10), the required fleet size (Table 11), the investment and operating cost (Table 12) and learning benefits (Table 13). The tables provide the metrics for computation in each of the three periods that are assessed with the tool.

The discharge potential of a ship dedicated to ocean liming is computed in Table 10. These computations largely follow the computations made by .Caserini et al. (2021). A 100,000-ton dead weight tonnage ship has been used as reference point for the ocean liming fleet. A relatively low discharge rate compared to some earlier papers (Renforth et al., 2013) has been applied to include some prudence regarding the dissolvability of lime. A longer loading time has been used than in Caserini et al. (2021) as the ship is larger. Moreover, we expect that ships need to be at sufficient distance from ports or coastal areas before performing ocean liming and have therefore included a 2 times 2 hour steaming time at the beginning and end of each journey. The ship building capacity has also been included in Table 10. This capacity indicates the potential output of ocean liming ships (provided that normal ship construction will continue). The capacity for construction partial use ships is much larger, as it is assumed that this will hardly cannibalize ship construction capacity for merchant ships. Moreover, with the upscaling of ocean liming, it is assumed that the construction capacity will increase over time (provided sufficient demand). The estimates for the construction capacity are based on the current global fleet size of ships with a ~85,000+ dead weight tonnage, assuming a fleet renewal period of 25 years with a construction capacity not exceeding 25% of existing capacity initially[6], and have been adjusted with help of stakeholder engagements.

[6] From https://agtransport.usda.gov/stories/s/Bulk-Vessel-Fleet-Size-and-Rates/bwaz-8sgs/ and https://agtransport.usda.gov/stories/s/pjaw-nxa9 the fleet has been estimated at ~4000 ships, excluding crude carriers, with a 25-year renewal period, there ought to be a yearly output of 160 ships annually.

Table 10: Basic information for computations of ship capacity

Basic ship		
Ship Dead Weight Tonnage	100,000.00	a
Ship Dead Weight Cargo Capacity	85 %	b
Load available for lime materials	85,000 ton	c = a×b
Discharge rate	50 kg/s	d
Discharge time	472.2 hours	e = c/d×1000/3600
Travel time w.o. operation	4 hours	f
Journey time	19.84 days	g = (e+f)/24
Loading time	2 days	h
Operational days p.a.	330 days	i
Trips per year	15,1	$j = i/(g+h)\times 10^{-6}$
Liming capacity	1,28 Megaton	k = j×c
Ship building capacity dedicated (per year)	40 (2030), 48 (2040), 60 (2050)	
Ship building capacity partial use (per year)	150 (2030), 170 (2040), 200 (2050)	

The fleet size computations are visible in Table 11. The ship capacity usage refers to whether a ship is a dedicated ocean liming ship, or whether it is a partial use ships, with values of 100% or 10% respectively. The maximum allowed capacity comes from the international regulation building block. The existing capacity refers to the outcome of the computations for the previous time period (hence zero in 2030). The 10-year construction capacity is a 10-fold of the ship building capacity for the given periods (see Table 10). The computations provide the increment of the fleet, restricted by building capacity, resulting in an overall practically attainable capacity of ocean liming in terms of dispersion logistics.

Table 11: computations and required information for fleet size and expansion

Computations for fleet size and possible expansion	
Ship capacity usage (%)	a
Ship capacity (Megaton)	b = 1,28×a
Max allowed capacity (Megaton)	c
Existing capacity	$d = i_{t-1}$
Ships required	e = max{(c-d)/b, 0}
Construction 10y max capacity	f (see Table 10)
Ships to be constructed	g = min{e,f}
Fleet size	$h_t = h_{t-1} + g$
Practical Capacity	$i = i_{t-1} + h_t \times b$

The unit cost computations for ocean liming sea logistics are provided in Table 12. The ship investment base and interest expenses have been set based on (Hakulinen, 2015). The investment base has been adjusted given time passed and with feedback from stakeholders. The cost rate refers to whether the ship is built specifically for ocean liming or whether the ship has a dual purpose. For dual purpose ships the rate is 25%, and 100% otherwise. Here it is assumed that equipment for dual purpose ships per unit of dischargeable capacity is higher than for singular purpose ships. The learning and scaling benefit are found in Table 13, for explanation see below. The lost tonnage is 0% for singular use ships, and 5% for dual purpose ships as it is assumed that dual usage would result into a loss of cargo capacity on top of the dedicated cargo space. The usable tonnage refers to the share of cargo space dedicated to ocean liming, so either 100% or 10%. The lime cost rate is the share of lime costs covered by liming operations, with 100% for purpose-built ships and 50% for partial capacity use ships. Here it is assumed that partial capacity usage will allow merchant ships to offer customers a premium sustainable cargo service, which would cover part of the costs of ocean liming. This assumption has been established with input from stakeholders.

The estimated daily operational costs (excluding liming capex) as a result from the assessment here are higher than the suggested standard by Bernacki (2021). However, the difference is assessed as acceptable since the figures by Bernacki (2021) date back to 2010.

Table 12: Computations and required informatuion for unit price computation of shipping (alkaline material)

Computations for unit price shipping	
Ship Investment Base (€)	a = 70,000,000.00
Scale benefit rated (%)	b (see Table 13)
Ship cost per unit (€)	c = a×b
Liming investment base (€)	d = 15,000,000.00
Cost rate (%)	e
Learning benefit (%)	f (see Table 13)
Liming equipment cost per ship (€)	g =d×e×f
Capital Rate of Return (%)	h = 8 %
Payback period	i = 10 years
Write-off period	j = 15 years
Scarp rate value (%)	k = 20 %
Lost tonnage (%)	l
Usable tonnage (%)	m
Initial investment (€)	o = c + g
Liming specific interest (€)	$p = g×h×(1+h)^i/((1+h)^i-1)$
General interest (€)	$q = c×h×(1+h)^i/((1+h)^i-1)$
Scrap value (€)	r = a×k
Net Ship Investment (€)	s = c+q-r
Net Liming Investment (€)	t = g+p
Net total Investment (€)	u = s+t
Annual capital expense (€)	v = s/j
Annual Lime capex (€)	w = t/j
Annual Opex (€)	x = 20,000,000.00
Lime Cost rate (%)	y
Lime share Opex (€)	z = y×x×m/(1-l)
Lime share Capex (€)	A = w + y×v×m/(1-l)
Lime share expenses (€)	B = z+A
Ship capacity (ton)	C
Price per tonne no usage correction (€/ton)	D = B/C

It is assumed that over the course of deployment of ocean liming, some significant scale and learning benefits can be attained for the maritime logistics part of the supply chain. In particular, the standardization of design, large scale orders of raw materials and repeated actions could lead to reductions in the construction prices of ships. Moreover, the advance of discharge techniques as ocean liming will mature could lead to improved equipment and better designs, which could lead to lower costs as well. This is accounted for in Table 13, in which the assumed scale and learning benefits are displayed. The scale benefit is based on the annual demand for new ships (a tenth of the ships to be constructed from Table 11), each row contains a range of annual ships constructed, and the belonging price level. Similarly, the learning benefit contains a cumulative number of ships constructed for ocean liming (the total fleet size) and belonging price levels.

Table 13: Scale and learning benefits for ship construction and required liming equipment

Scale benefit ship production		Learning benefit liming equipment	
Quantity	Price Level	Quantity	Price Level
0	100 %	1 – 3	100 %
1 – 5	100 %	4 – 6	90 %
6 – 29	95 %	7 – 15	80 %
30 – 54	85 %	16 – 25	70 %
55+	75 %	26 – 50	60 %
		51+	50 %

Land Operations Building Block

For each period, two scenario options are available for the Land Operations:

- Centralized Hubs: Several large logistical hubs are created for the transfer of materials onto ships.
- Scattered Supply: Many smaller logistical hubs are created across major port locations for the transfer of materials onto ships.

This building block addresses how the shipping and lime industry will be connected with each other. At this point it is complex to indicate whether centralized hubs or scattered hubs would imply the same spatial distribution for the lime calcination, and thus more generally refers to the loading aspect. This means though that slaked lime could be produced at decentralized locations before being transported to large transfer hubs in port locations.

As in the tool lime is externally sourced from producers, an external price is assumed. This level results from interactions with stakeholders from the lime industry and is supposed to reflect the production with more advanced kilns. The price used is €160 per ton calcium hydroxide. Similarly, a price for the carbon capture and storage of all CO_2 emissions in the calcination process is included. Predictions of $62 - $100 (Pisciotta et al., 2022) and €62 - €73 ((Shogenova et al., 2022) are available as estimates for the carbon capture, transport and underground storage per ton of CO_2 for the cement industry. As the processes from the lime industry are largely similar to the cement industry, the cost in this study is selected within the proposed cost ranges. The unit cost is transformed to cost per ton of slaked lime using the average CO_2 emissions of the calcination process as described by Foteinis et al. (2022). The resulting price is €55 per ton of calcium hydroxide.

As the lime industry is well established, a limited scale benefit curve is included. Carbon capture and storage in general and applied to the lime industry is rather novel, therefore a learning curve is included. Both curves function similar to the curves described in Section 0. The curves are presented in Table 14: Scale and Learning Benefits for lime production and carbon capture and storage.

Table 14: Scale and Learning Benefits for lime production and carbon capture and storage

Scale Benefit Lime Production		CCS Learning Benefit	
Annual Scale (MT)	Price level	Cumulative Scale (MT)	Price level
0 - 49	100 %	0 - 4	100 %
50 -149	95 %	5 - 14	99 %
150 - 499	90 %	15 - 49	95 %
500 - 899	82 %	50 - 149	85 %
900+	75 %	150 - 399	70 %
		400 - 699	55 %
		700 - 999	50 %
		1000+	45 %

The cost of handling slaked lime loading the material onto ships is assumed to differ between dedicated hubs and scattered supply points. Centralised hubs are assumed to be larger and to be located in larger ports. In that case, the port handling costs are assumed to be higher because of the competition for land in large ports. Table 15 contains both the used port handling capacity and handling cost. The cost for scattered supply is based on the listed price for bulk handling with a mark-up of 50% for other port costs (Port of Helsinki, 2023). The price in the centralized hubs is assumed to be double.

Table 15: Port Handling cost and capacity for the different scenario choices

	Centralised Hubs	Scatterd Supply
Annual Capacity (ton)	6,000,000	1,250,000
Port handling cost (€/ton)	3.30	1.65

Ships that are used for ocean liming operations are required to visit ports with available alkaline minerals to continue operations after a load has been spread. For dedicated ships it is assumed that journeys are generally designed to have both a port of origin and destination with liming facilities. Ships with partial capacity for ocean liming are assumed to generally pursue routes that are driven by their merchant operations. In the routing process, the availability of liming facilities in ports is less prioritized. This means that it is unlikely that a merchant ship will visit ports with liming facilities if there are only few of such facilities available. As the number of ports with liming facilities increases, so does the chance that a merchant ship will find liming facilities in any port it visits. In Table 16, the chance that a visited port has liming facilities for a given number of ports with facilities is presented. The rate of ports is used to account for the utilization rate of the cargo space dedicated to ocean liming. The number of ports required for liming is computed by taking the ratio of the maximum capacity as computed in 8.3.4 over the annual capacity of the chosen port strategy. The resulting figure is rounded up.

Table 16: T rate of arrival of partial capacity use ships to ocean liming ports given the amount of ports available

Rate of arrival to port with a facility	
Number of ports with liming facilities	Rate of arrival to a port with liming facilities
0	0 %
1	4 %
2	8 %
3	15 %
4	20 %
5	30 %
6	40 %
7	45 %
8	55 %
9 - 11	65 %
12 - 19	70 %
20 - 34	80 %
35 - 49	85 %
50 - 69	90 %
70 - 79	95 %
80 - 99	98 %
100+	100 %

Operational Effectiveness Building Block

For the Operational Effectiveness, the following three scenarios are available in each time period:

- Low: Uncertainty on the exact discharge techniques and discharge effectiveness persists. This means that the utilization of ocean liming equipment and materials is restricted regularly.
- Medium: Advances have been made to improve the discharge techniques available and the discharge effectiveness tends to be largely safeguarded. The utilization of ocean liming is restricted from time to time.
- High: In general, techniques applied for ocean liming are effective and available equipment can be utilized at capacity.

These scenarios are formulated to cover the management of secondary precipitation risks as a consequence of ocean liming. Large uncertainty still exists in this domain. The maximum rates of discharge are unknown at the moment, and the effect of the sea water conditions on the attainable solubility of slaked lime remain insufficiently investigated. Consequently, no point estimates are available for the chemically possibly discharge rate. The operational effectiveness therefore includes a rate of operations. This percentage indicates the share of the installed capacity that can be utilized in practice. It is assumed that over time discharge techniques will improve, reducing uncertainty on the attainable discharge rates and increasing the share of installed capacity that can be used in practice. The utilization rates that are applied in the tool are visible in Table 17. Utilization rates only affect dedicated ships in the tool as ships that utilizes maximum capacity are assumed to be more flexible in their discharge rate.

Table 17: Utilization rates of available ocean liming capacity as a result of Operational Effectiveness

	2030	2040	2050
High	80 %	90 %	100 %
Medium	60 %	70 %	80 %
Low	40 %	50 %	60 %

The general uptake factor of carbon dioxide given discharged calcium hydroxide (slaked lime) has the following weight ratio: 1 ton of CO_2 will be absorbed by the ocean for every 1.321 ton of slaked lime discharged. This is the same rate as applied by Foteinis et al. (2022).

Overall computations

Here the overall computations leading to the point estimates for the price and capacity are estimated. The used input originates from all the individual building blocks.

The capacity is set by the minimum of the practical capacity (the practical capacity already accounts for the legal maximum capacity, see *Max Allowed Capacity* in Table 11) and the financial capacity. The practical capacity is first corrected by the rate of arrival to ports with facilities (for partial capacity usage) by multiplying the capacity with the rate of arrival. Next, it is corrected for the utilization rate of operational effectiveness (for dedicated ships) by multiplying the capacity with the utilization rates. The financial capacity is computed by dividing the financial means available by the assessed cost of deployment of the previous year (€400/ton lime in 2030). The CO_2 capture scale is obtained by dividing the capacity by 1.321 to correct for the rate of uptake.

The price is estimated by the addition of the port handling, lime production and CCS cost estimates from the land operations building block. In addition, the shipping cost is corrected first for the rate of arrival and then the utilization rate in a similar way as for the capacity, but instead of multiplications, divisions are performed. The sum of all cost inputs is then multiplied by one plus the mark-up obtained from the organizational form to give the price per ton of lime discharged. The cost of capture per ton of CO_2 is obtained by multiplying the cost with factor 1.321 to correct for the uptake rate.

Appendix 4: Empirical estimates of paces of learning

Estimates of learning curve coefficients (the pace of learning) were obtained from Dosi (2016).

Table 3: Equations representing Linear, Exponential, Logarithmic and Power functions

Function Type	Equation
Linear	$P = a - \beta Q$
Logarithmic	$P = a - \beta \log Q$
Exponential	$P = (a)e^{-\beta Q}$
Power	$P = (a)Q^{-\beta}$

Table 4 reports the learning rates estimated using the power law function. *First*, note that the learning coefficient vary a lot among products. *Second*, we observe that for quite a few products, the learning coefficient is positive, and thus, hints at an upward sloping cost-quantity curve. Figure 1 plots

Table 4: Learning coefficients using Power function

Product name	Power Coeff.	Std error
Mineral Water	-0.551***	(0.050)
Detergent Soaps	-0.217***	(0.055)
Writing & Printing Paper	-0.235***	(0.043)
Passenger Cars	-0.062***	(0.016)
Portable Electronic Typewriters	-0.249***	(0.067)
Automotive Diesel Engines	-0.169***	(0.062)
Pollution Control Equipment	-0.071**	(0.032)
Cranes	-0.264***	(0.059)
Road Construction & Maintenance Machines	-0.251***	(0.057)
Washing Machines	-0.170***	(0.025)
Refrigerators	-0.150***	(0.020)
Air Coolers	-0.044**	(0.021)
Wiring Accessories	-0.205***	(0.043)
Electrical Porcelains And Insulators	0.714***	(0.139)
Tyre Pressure Gauges	0.257***	(0.056)
Can Making Machinery/Industrial machinery	0.619***	(0.123)
Coke Oven	0.403***	(0.084)
Sprocket Wheels	0.219**	(0.044)
Food Processing Machines	0.549***	(0.200)
Metal Cutting Incl. Grinding Machines	0.738**	(0.264)
Oil Purifiers	0.218***	(0.083)
Perfumery Compounds Aromatic Spices & Herbal Etc.	0.262***	(0.081)
Stainless Steel Forging,Flanges & Allied Pipe Fitt	0.011***	(0.004)
Radio Sets,Tape Rec.,Combination Sets & Rec.Player	0.165***	(0.016)
Hand watches& manufactured components-watches	0.799***	(0.196)