Ocean-based Negative Emission Technologies

OCEAN NETs

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Author(s)	Christian Traeger & Karishma Balu
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Abstract: This report explores the future contribution of ocean-based Negative Emissions Technologies (NETs) within various climate policy frameworks, evaluating their economic and environmental viability and potential cost-effectiveness. It emphasizes the need to integrate CDR into emissions trading systems like the EU ETS. Investment in pilot projects is crucial for better cost estimation and evaluating environmental co-benefits and risks, highlighting the importance of a comprehensive portfolio of research and development and early deployment subsidies, particularly for Ocean Alkalinity Enhancement, ocean fertilization, and potentially artificial upwelling. Marine permaculture, specifically macroalgae cultivation and harvest, is identified as a promising NET, with simulations demonstrating its potential to meet Nationally Determined Contributions in regions with high abatement costs and ambitious emission targets, such as the EU, Japan, Canada, and Great Britain. Effective monitoring and compliance systems are critical for ensuring CDR project integrity, and international collaboration is essential for enhancing NET effectiveness.

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List of abbreviations, acronyms and definitions:

BECCS: Bio-energy Carbon Capture and Storage

CCS: Carbon Capture and Storage

CDR: Carbon Dioxide Removal

CO_2: Carbon Dioxide

DAC: Direct Air Capture

DACCS: Direct Air Carbon Capture and Storage

DART: Dynamic Applied Regional Trade

EEZs: Exclusive Economic Zones

ESR: Effort Sharing Regulation

ETS: Emissions Trading System

IAMs: Integrated Assessment Models

NDC: Nationally Determined Contribution

OAE: Ocean Alkalinity Enhancement

R&D: Research and Development

SCC: Social Cost of Carbon

Units:

tCO_2: Ton of carbon dioxide

$GtCO_2$: Giga ton of carbon dioxide (10^9 tons of CO_2)

$MtCO_2$: Mega ton of carbon dioxide (10^6 tons of CO_2)

MW: Mega Watts

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

1.2 Purpose and scope of the deliverable

The aim of Work Package 1 (WP1) within the OceanNETs project is to explore and evaluate the future role of ocean-based Negative Emissions Technologies (NETs) in both globally coordinated and non-coordinated climate policies. WP1 contributes to the overall objectives of the OceanNETs project by providing an assessment of these technologies, focusing on their economic feasibility and cost-effectiveness and to explore deployment options in the larger socio-economic context. The specific aim of the task addressed by this deliverable is to evaluate the future contribution of ocean-based NETs under different climate policy frameworks. This includes assessing their economic and environmental viability, potential cost-effectiveness, and the necessary policy support to promote their development and deployment. The deliverable provides detailed insights and recommendations that inform policymakers and stakeholders about the potential of ocean-based NETs. By examining the role of these technologies in both coordinated and non-coordinated climate policy scenarios, the deliverable helps to identify strategic incentives and distributional implications that are crucial for their successful implementation.

1.3 Relation to other deliverables

This deliverable builds on Deliverable 1.2 on the appropriateness of accounting schemes to assign carbon credits to ocean NETs by evaluating the role of ocean NETs in market price context. It builds on Deliverable 1.4 on operational and overall economic cost development for various ocean NETs by connecting these costs to the larger policy portfolio. It also builds on selected insights from deliverable 1.5 on NETs in strategically interacting regions based on simulation and analysis in an extended ACE model in analyzing drivers of deployment. It builds on deliverable 3.4 on public perceptions in cross-country survey in order to account for public perception in the evaluation of policy priorities and feasibility. And it connects to Deliverable 5.4 on the ecological and biogeochemical responses of a low latitude oligotrophic ocean system to a gradient of alkalinization intensities.

1.4 General Introduction

The pressing need to meet global climate goals has brought Carbon Dioxide Removal (CDR) technologies to the forefront of climate strategies. As emissions reductions alone are insufficient to achieve net-zero targets, CDR technologies have become essential to offset emissions that cannot be eliminated directly. Among various CDR approaches, ocean-based Negative Emissions Technologies (NETs) offer significant potential due to the vastness of the oceans, the permanence of storage, and the unique biological and chemical processes that facilitate carbon sequestration.

This report examines the future contribution of ocean-based NETs within different climate policy frameworks, assessing their economic and environmental viability, and potential cost-effectiveness. It highlights the necessity of integrating CDR into emissions trading systems like the EU Emissions Trading System (ETS) and underscores the importance of investment in pilot projects to better estimate costs and evaluate environmental co-benefits and risks. A comprehensive portfolio of research and development (R&D), combined with early deployment subsidies, is crucial for advancing ocean-based NETs.

Marine permaculture, specifically macroalgae cultivation and harvest, is identified as a particularly promising ocean-based NET. Simulation studies demonstrate its potential to substantially contribute to meeting Nationally Determined Contributions (NDCs) in regions with high abatement costs and ambitious emission reduction targets. The study emphasizes the need for far-sighted climate policies to incentivize these methods and the importance of linking deployment targets in wealthy nations with the potential in developing countries for more efficient and effective outcomes.

The report also explores several scenarios to understand the broader implications of deploying ocean-based NETs. It begins by establishing baseline scenarios, providing a reference point by outlining current policy trajectories and their projected outcomes without additional CDR interventions. This sets the stage for examining how consistent global carbon pricing could drive the adoption of ocean-based NETs and influence global emission reduction efforts.

Furthermore, the report delves into the complexities of heterogeneous regional commitments, reflecting the current reality of varied national policies and economic capacities. It evaluates how differing levels of ambition and capability across regions can impact the deployment and effectiveness of ocean-based NETs, highlighting the need for tailored strategies that accommodate these differences.

2 CDR Methods

This section discusses common methods suggested for the removal of carbon dioxide (CO_2) from the atmosphere. We start with ocean-based negative emission technologies (NETs) and then move on to land-based methods.

2.1 Ocean-Based NETs

The focus of our discussion will be the role of ocean-based NETs in different policy scenarios. Here, our main interest is in the novel methods that we discuss first.

2.1.1 Ocean Alkalinity Enhancement (OAE)

Ocean Alkalinity Enhancement (OAE) involves dissolving large quantities of naturally occurring minerals, such as silicate and carbonate, or using industrial waste products in order to increase the oceans capacity to absorb CO_2. This dissolution can occur directly in the ocean after processing and dispersing the minerals or be achieved in chemical reactors on land or on ships. Another method of OAE is generating sodium hydroxide (NaOH) electrochemically, which leads to the removal of atmospheric CO_2 by converting it into bicarbonate (NASEM, 2022*a*). We will look more carefully at ocean-limining and olivine-base OAE in Section 3.2. OAE can leverage the vast surface area of the oceans and can have a long-lasting impact on carbon sequestration. Research suggests that OAE could potentially sequester between 1 and 100 $GtCO_2$ annually (IPCC, 2022*a*).

OAE promises sustained CO_2 sequestration for long time horizons (exceeding centuries). Besides being a CDR method, it may help mitigate ocean acidification (Cross et al., 2023; NASEM, 2022*a*). OAE can also supply nutrients like silicate and beneficial micronutrients such as iron and magnesium. However, there are concerns about the potential toxic effects of metals like nickel, which can leach from minerals like olivine. The primary uncertainty is the impact of OAE on the biogeochemical cycling of elements and the subsequent effects on marine ecosystems, given the long-term nature of these chemical changes (NASEM, 2022*a*). For carbonate base OAE, OceanNETs Delivery 5.4 found that, in a month-long mesoscale experiment, the risk of a sustained impact on biogeochemical functioning tends to be low. It observed minor reductions in particular organic nitrogen and an increase in the carbon-to-nitrogen ratios (Paul et al., 2024; Riebesell, 2022). The delivery also found that there is a risk of secondary precipitation of carbonate under high alkalinity concentrations which would most likely reduce the durability of carbon sequestration in highly concentrated settings.

2.1.2 Marine Permaculture

Marine permaculture involves cultivating seaweed and other marine biomass, which sequesters carbon when harvested and stored. This method supports marine ecosystems and can be integrated with aquaculture, providing additional economic benefits. Seaweed farming, for example, not only absorbs CO_2 but also creates habitats for marine life, enhancing biodiversity.

One promising method of marine permaculture is nearshore macroalgae cultivation. This method involves growing large seaweeds like kelp in ocean farms. These seaweeds absorb CO_2 during photosynthesis and can grow rapidly, sequestering significant amounts of carbon. When harvested, the biomass can be processed for various uses or allowed to sink to the deep ocean, where the carbon is stored long-term, helping to reduce atmospheric CO_2 levels. Nearshore macroalgae aquaculture with harvesting can have considerable net primary production rates and the global annual removal potential is estimated to be about 5 $GtCO_2$ (Krause-Jensen and Duarte, 2016; NASEM, 2022*a*). Furthermore, required cultivation technologies are established (Buck and Buchholz, 2004; Goecke et al., 2020). This method is generally considered somewhat cost-effective since it is relatively cheap to grow algae. This makes it more accessible to a larger sample of countries who would be willing to adopt it.

Macro algal cultivation is gaining more interest because it can also be harvested for food, and the part that is not harvested sinks naturally to the seafloor where the macro-algae derived carbon can be stored for decades. However, there could be some resistance to sinking these potential viable food sources which could be used to provide human food security (Cross et al., 2023). Additionally, the cultivation of macroalgae will likely affect the ocean ecosystem in the zone where it is grown by reducing available nutrient levels as well as light. This would negatively impact the marine ecosystems. The disturbance of the ecosystem at the surface could further affect the natural balance at deeper levels of the oceans as well since the entire ecosystem is interconnected (NASEM, 2022*b*). However, a benefit to this method of carbon sequestration is that the cultivated macroalgae can be used as a fuel for bio-energy carbon capture and storage (BECCS) (Cross et al., 2023).

These methods of CDR are considered to have medium-high durability in removing CO_2 from ocean surfaces and the atmosphere for time periods between 10 to 100 years. This depends on the storage site of the sequestered biomass. Deeper discharge locations store the sequestered carbon for much longer periods of time compared to shallower sites. The time also depends on the location since the Pacific and Indian basins show longer sequestration times as compared to the Atlantic and Southern Oceans (NASEM, 2022*b*).

The dynamic scalability for macroalgal cultivation is low lying between 0.1 and 0.6 $GtCO_2$ per year (Cross et al., 2023). To get an idea for these magnitudes we rely on an illustration by NASEM (2022*b*). To sequester 0.1 Gt CO_2 per year, a seaweed farm would need to cover a 270^2km. If configured as a 100-meter-wide continuous belt of seaweed farm along coastlines, such a farm would stretch 730,000 km, covering 63 percent of the global coastline. If such a belt were placed along the coastline of the United States alone, it would form a nearly 0.5-km-wide continuous band of seaweed farms. This demonstrates the significant engineering and logistical challenges of scaling seaweed cultivation for CO_2 removal to meaningful levels.

2.1.3 Artificial Upwelling

Artificial upwelling involves pumping cold, nutrient-rich water from deep in the ocean to the surface. This process aims to enhance local marine plant growth (primary production), which can increase the capture and storage of CO_2 as these plants grow and eventually sink, carrying carbon to the ocean floor. Conversely, artificial downwelling involves moving surface water to deeper layers of the ocean. This method is proposed to address coastal water quality issues, like excess nutrients (eutrophication) and low oxygen levels (hypoxia), by increasing deep water mixing and potentially sequestering carbon by transporting it to the deep ocean.

There is, however, low confidence in the efficacy of this method since upwelling of deep water brings a course of CO_2 that can be exchanged with the atmosphere. The durability of artificial upwelling is predicted to be between 10 and 100 years. This depends on the efficiency of the biological carbon pump, which is the process by which carbon is transported from the surface ocean to the deep ocean through the sinking of organic matter, such as dead plants and animals. If the biological carbon pump is efficient, more carbon will be transported and sequestered for longer periods (NASEM, 2022*c*).

Since the deep ocean is much cooler than water at the surface the change in temperature from artificial upwelling could cause ecological imbalances and poses some environmental risks. It could lead to cooling of the lower atmosphere, reduced precipitation, promotion of ocean acidification in some regions and it could even enhance terrestrial carbon storage (NASEM, 2022*d*).

2.1.4 Ocean Fertilization

Ocean-based CO_2 removal through nutrient fertilization involves adding micronutrients like iron and macronutrients such as phosphorus, nitrogen, and silica to the surface ocean. The goal is to boost photosynthesis by marine phytoplankton, thereby increasing the uptake of CO_2 from surface waters. This process also aims to transfer the newly formed organic carbon to the deep sea, moving it away from the surface layer that directly interacts with the atmosphere. This CDR method has the potential to sequester between 1 and 3 $GtCO_2$ annually (IPCC, 2022*a*). One of the key benefits of this method is that knowledge of this method is more extensive relative to any other of the more novel ocean CDR approaches. The durability of sequestration in this approach ranges from 10 to 100 years, depending on how well the carbon is transported and stored. The intended environmental impacts of ocean nutrient fertilization include increased net primary production and carbon sequestration due to changes in surface ocean biology. However, if the method proves effective, it could also lead to significant changes in the deep ocean, raising concerns about potential negative geochemical and ecological effects. The large-scale impacts of this approach remain uncertain (NASEM, 2022*c*).

2.1.5 Established Blue Carbon

Restoring coastal ecosystems helps protect and stabilize coastlines (Duarte et al., 2013; Kuwae and Crooks, 2021). Alongside blue carbon solutions that focus on restoring ecosystems, some environmental intervention-focused applications have been termed as blue carbon capture. Large-scale farming of macroalgae can enhance the ocean's capacity to absorb CO_2, with long-term carbon storage managed through more controlled and artificial means (Krause-Jensen et al., 2018; Lovelock and Duarte, 2019).

Griscom et al. (2017) found that ecosystem restoration through coastal blue carbon applications could sequester between 0.6 and 1 $GtCO_2$ annually, with about one quarter of this amount being cost-effective at prices below \$100 per tCO_2. Of this potential, 71% is attributed to mangrove forests, 4% to salt marshes, and 25% to seagrass restoration. The IPCC (2022*a*) estimates that blue carbon management in coastal ecosystems could have the potential to sequester almost 1 $GtCO_2$ annually. Claes et al. (2022) find that about 0.4 to 1.0 $GtCO_2$ could be abated at less than \$18 per metric ton of CO_2 using blue carbon methods of carbon sequestration. Their study classifies blue-carbon solutions into three categories based on how well these methods are understood and how much their carbon abatement levels can be quantified.

2.1.6 Direct Ocean Injection

Direct ocean injection involves capturing CO_2 from industrial processes or direct air capture and injecting it into the deep ocean. In contrast with the other methods discussed, direct ocean injection is merely about carbon storage and not carbon sequestration itself. This method offers long-term storage potential but poses significant risks to marine life and ecosystem health. Long-term monitoring and risk assessment are essential to ensure the safety and effectiveness of this method.

2.2 Land-Based Methods

Ocean-based CDR technologies compete with already established land-based measures. Here, we summarize some of the main land-based carbon sequestration approaches.

2.2.1 Afforestation and Reforestation

Planting trees to absorb CO_2 remains one of the simplest and most cost-effective CDR methods. It enhances natural carbon sinks but is limited by land availability and competition with agriculture. Additionally, the permanence of carbon sequestration is uncertain due to risks such as forest fires and disease. These methods also provide co-benefits such as habitat creation, soil conservation, and enhancement of local climate conditions.

Fuss et al. (2018) estimate the global negative emissions potentials for afforestation and reforestation in 2050 are between 0.5 and 3.6 $GtCO_2$ per year. While IPCC (2022*a*) estimate the potential to be between 0.5 and 10 $GtCO_2$ annually. Nielsen et al. (2014) find that at a carbon price of $50 per tCO_2, around 200$MtCO_2$ would be sequestered annually in the US alone through afforestation, and at a price of $100 per tCO_2 an additional 100$MtCO_2$ would be sequestered each year.

The CO_2 sequestration rate of forests increases very slowly during their establishment phase and decreases to zero within less than a century once the forests reach maturity, at which point the CO_2 sink becomes saturated. Overall, the CO_2 removal efficiency of afforestation and reforestation is very high but only temporary, due to the increasing risk of natural and anthropogenic disturbances over the long term (Chiquier et al., 2022).

2.2.2 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS involves growing biomass, burning it for energy production, and capturing and storing the CO_2. This method can generate negative emissions but requires significant land, water, and energy resources, which can impact food security and biodiversity. The mititgation potential from BECCS is between 0.5 and 11 $GtCO_2$ annually (IPCC, 2022*a*). Costs for BECCS are estimated at $60 to $160 per tCO_2 (Hepburn et al., 2019). The integration of BECCS in existing energy infrastructure and the development of sustainable biomass supply chains are critical for its success.

BECCS, though land-based, offers a relatively high level of permanence since carbon stored in geological formations is less affected by management practices. However, land-use changes can threaten the physical permanence of BECCS projects, even though the captured carbon remains stored. Additionally, saturation poses a challenge due to bioenergy production rates and potential storage capacity limits (Ruseva et al., 2020).

2.2.3 Soil Carbon Sequestration

Soil Carbon Sequestration describes a growing set of techniques of managing agricultural land such that its soil holds and absorbs more carbon. Prominent methods are the application of bio char, restoration of degraded land, grazing & cropland management and 'setaside' (Paustian et al., 2016). Adoption of these practices can also enhance soil fertility, water retention and resilience to climate sensitivity.

IPCC (2022*a*) estimate that between 0.6 and 9.3 $GtCO_2$ can be sequestered annually using soil carbon sequestration in croplands and grasslands. Estimates by Paustian et al. (2016) find that total soil greenhouse gas mitigation potential at a carbon price of $20 per tCO_2 is 1.5 $GtCO_2$ per year globally. These enhancements result in an overall improvement of agricultural productivity and can be applied to many different types of agricultural land, leading to a projected annual CO_2 removal potential of 2.3 to 5.3 Gt by year 2050 (Hepburn et al., 2019). However, for this removal potential to materialize, soil carbon sequestration would need to be applied on a substantial share of the worlds agricultural area. Furthermore, the amount of CO_2 sequestered per area is modest and can be reversed by changes in land management practices. Low permanence and high saturation limit the reliability of soil carbon sequestration, making it viable only for short to medium durations. Sink saturation occurs within 10 to 100 years (with 20 years as the default), and this timeframe varies based on specific locations and practices, such as soil types and climate zones (Ruseva et al., 2020).

2.2.4 Direct Air Carbon Capture and Storage (DACCS)

Direct Air Carbon Capture and Storage (DACCS) is a chemical process where CO_2 is directly captured from the atmosphere and stored permanently. It shares its methods of transport and storage with Carbon Capture and Storage (CCS), discussed below, however, DACCS is distinct in the way it captures the ambient CO_2 from the atmosphere. This is done by capturing the CO_2 in a liquid solvent or a solid sorbent. Once captured, the CO_2 can be stored underground or utilized. The captured CO_2 can be stored for centuries and it is considered to be permanently sequestered (IPCC, 2022*a*)

The mitigation potential for DACCS is estimated to be between 5 and 40 $GtCO_2$ per year (IPCC, 2022*a*). Fuss et al. (2018) estimate the carbon sequestration potential to be between 0.5 $GtCO_2$ and 5 $GtCO_2$ annually. DAC can give the highest quality CO_2 removals since the methods are highly scalable, permanent and the quantities of carbon sequestered are more easily verifiable (Webb, 2023). However, due to the advanced technology needed to capture CO_2 directly from the air, the costs remain very high (IPCC, 2022*a*; Webb, 2023).

2.2.5 Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) involves capturing CO_2 emissions directly from industrial processes and storing them permanently. This technology, now increasingly applied to coal power plants, cement kilns and alike, captures CO_2 and transports it to storage sites, often deep geological formations with favorable mineral conditions. In some cases, CO_2 is pressurized and transported over long distances via pipelines (Bui et al., 2018). Unlike other methods, CCS does not remove CO_2 from the atmosphere but merely prevents it from being emitted.

3 Economic Comparison of CDR methods

The costs and benefits of CDR methods vary widely. Ocean-based methods, while more expensive, offer higher potential for long-term storage and, at least in principle, greater scalability. By contrast, land-based methods like afforestation and soil carbon capture are cheaper but have limitations in scalability and permanence. The measures also differ in terms of their co-benefits and potential environmental risks. Most of these co-benefits and risks have not been quantified yet. Also, cost estimates are still rife with uncertainty. As a result, we cannot provide the exact net benefits of different CDR measures. Yet, the discussions in this chapter convey a picture of the relative advantages and disadvantages of the different measures, helpful for the subsequent policy assessment.

3.1 General Discussion of Benefits

The direct benefits of CDR are based on the removal of CO_2 from the atmosphere. If emissions are permanently removed, this benefit equals the social cost of carbon (SCC). Estimates of the social cost of carbon vary widely in the literature. Moore et al. (2024) find in the most recent literature survey an expert-weighted mean SCC of $283 per tCO_2. The inner-quartile range stretches from $97 to $369 and the median lies substantially below the mean value at $185. In our view, we take this survey to indicate that the benefit of permanently extracting a ton of CO_2 from the atmosphere lies most likely above $200 per ton and under most estimates above $100 per tCO_2. The large tail of the distribution implies that the expert-weighted literature still puts more than 25% probability mass on benefits above $350 per tCO_2. The cited values reflect today's SCC. In addition, the SCC is predicted to increase roughly at the rate of economic growth.[1]

Most CDR measures do not remove CO_2 permanently from the atmosphere, we refer as well to Deliverable 1.2 for a discussion(Rickels, Koeve, Meier, Paschen, Rischer and Saldivia, 2023). In general, deep ocean sequestration is considered close to permanent removal. As a result, deep ocean sequestration, which can be achieved with the ocean-based NETs discussed here, results in benefits close to the SCC. On the other hand, the popular land-based removal methods we listed for comparison generally imply only temporary storage, which lowers the social value of removing a ton of CO_2 today using afforestation or reforestation, BECCS, or soil carbon sequestration. In principle, either of these methods could lead to close-to-permanent carbon storage. Yet, for a permanent removal, forests and, e.g., low tillage agricultural practices have to be kept in place permanently, which is hard to guarantee (see the subsequent section on monitoring and compliance). Moreover, in this case, planting trees to keep a forest area alive should not be counted as generating additional benefits. Thus, instead, the more common approach is to consider such CDR methods as non-permanent. Rickels, Koeve, Meier, Paschen, Rischer and Saldivia (2023) discuss different accounting methods for non-permanent storage, but so far this remains an area of active research. We will discuss the permanence of storage for each method below more carefully.

The SCC captures the expected damage done by an additional ton of CO_2 released today (or at a given point in the future). In order to understand this number, it is helpful to briefly discuss how SCC estimates are generated. Such estimates are based on integrated assessment models of climate change (IAMs). These models forecast the joint evolution of the economic and climate system over several centuries, predicting the future warming caused by a ton of CO_2 released today and translating this warming into a reduction of economic output, consumption, and welfare. The long time scale of several centuries is needed

[1]Different models calculate varying rates of increase of the SCC. The rule of thumb stated above results from the fact that the marginal relative value of (yet) another unit of consumption falls relative to the value of removing a ton of carbon from the atmosphere in a way that is approximately proportional to increasing consumption and, thus, economic growth.

because of the long lifetime of CO_2 and the potentially irreversible damage caused by climate change. By contrast, a typical quantitative economic model does not try to forecast economic conditions beyond a decade. Thus, IAMs take a leap of faith when they calculate the SCC forecasting so much further into the future than typical economic models. As a result, we have to acknowledge major uncertainties surrounding these estimates beyond those explicitly captured inside of the model or by comparing different models, which generally share many assumptions about future economic evolution.

At the same time, these time horizons explain why the SCC is particularly sensitive to our assumptions about the discount rate in economic models. The discount rate reduces the value of future losses as compared to the value of present losses. All economic models discount the future, and they do so for at least two reasons. First, assuming that economies continue to grow, they incorporate that future generations will be richer than present generations. As a result, the marginal unit of consumption (or the marginal loss of consumption) is less valuable in the future than it is today.[2] Second, economic models intrinsically devalue the future, which is reflected in the so-called pure rate of time preference. This assumption implies that, even if future and present individuals live in the exact same circumstances, a consumption unit given to the present generation is valued higher. There is no normative justification for this assumption, but the majority of economists believe that this assumption is required to match the observed behavior of individuals. Abandoning the assumption of pure time preference immediately propels the SCC to far higher levels Traeger (2023), but leads to a variety of issues with standard economic models. The mean and distribution of the SCC cited above uses an expert-elicited distribution of assumptions governing the (positive) discount rate.

Most SCC estimates rely on IAMs that model smooth and reversible damages from climate change. What few models incorporate is sudden or irreversible damages. Exceptions include Lemoine and Traeger (2016), Cai et al. (2016), and Dietz et al. (2021). Yet, even those models do not explicitly look at the value of a technology that can rapidly remove carbon from the atmosphere to still avoid or reverse potential long-term damages. And, similarly, this research does not explicitly estimate the added value of the option to avoid crossing a threshold by using NETs. In this sense, the SCC should be considered a lower bound for a NET that permanently removes a ton of CO_2.

3.2 Costs and Benefits of Different CDR Methods

3.2.1 Ocean NETs

OAE. Here, we have to distinguish between two different approaches. Ocean liming and the use of crushed olivine-rich rock, ocean liming involves applying calcium oxide or hydroxide, derived from lime produced from calcined chalk, to the ocean surface. Alternatively, spreading olivine-rich rock along tidal shores is less costly than lime production and offers moderate, scalable logistics costs. However, olivine sequesters carbon more slowly and less efficiently per volume than lime.

The cost of *ocean liming* is discussed in detail in Delivery 1.4 (Kooten et al., 2023). Previous studies include Paquay and Zeebe (2013) who combine the market price of quick

[2] Underlying this reasoning is the fundamental assumption in economic modeling that the benefit derived from another Euro spent on consumption is higher for a poor than for a rich person.

lime and daily operation costs of ships into an estimate of \$103-\$144 per ton CO_2 captured through ocean liming. Renforth et al. (2013) find an expected cost for capturing CO_2 via ocean liming between \$72 to \$126 per ton. Their assessment analyzes several supply chain cost elements. Moreover, NASEM (2022*a*) report \$100 to \$150 per tCO_2, Bednar et al. (2023) report \$46 to \$144 per tCO_2, and IPCC (2022*a*) report prices between \$40 and \$260 per tCO_2 removed. Yet, our project's assessment, based on a more comprehensive supply chain analysis, including various supply limitations, estimates the cost of ocean liming in the range of \$200-\$300, and even higher for near-term deployments targeting 2030 (Kooten et al., 2023). As for most technologies discussed, learning-by-doing and active R&D are predicted to slowly lower these costs over time.

By contrast, calculations based on Kooten et al. (2023) imply that *olivine crushed rock dispersion* incorporated into beach maintenance can be as cheap as \$75 per tCO_2. However, the potential in Europe will be far more limited, possibly some 50-100 $MtCO_2$ per year and maybe 0.5-1.0 $GtCO_2$ per year globally.

On the benefit side, OAE promises close-to-permanent carbon storage, aligning the direct benefits with the social cost of carbon (SCC) as discussed in Section 3.1. This method can potentially reduce ocean acidification (NASEM, 2022*a*), albeit modestly, and release beneficial micronutrients like iron and magnesium into marine environments. By counteracting acidification, OAE can benefit marine organisms sensitive to pH changes, such as coral reefs and shellfish.

However, the presence of toxic metals such as nickel in substances like olivine, and the general alteration of ocean chemistry, highlight inherent environmental risks due to the lack of larger-scale deployment experience. These include from toxic effects from the additives, bio-optical impacts, changes in functional diversity, and community composition due to altered alkalinity, and the ecological impact of increased grazing on particulates. Expanded mining activities required for OAE materials might cause local pollution and elevate CO_2 emissions, as detailed in (NASEM, 2022*c*), underscoring the complex balance of benefits and risks associated with this approach.

Marine Permaculture. According to pilot studies and assessments, the estimated cost of farming and sinking carbon in ocean areas ranges from \$200 to \$300 per metric ton of CO_2 abated, as discussed in Claes et al. (2022). However, as the same report points out, there are initiatives striving to decrease these costs to approximately \$50 to \$80 per metric ton by capitalizing on economies of scale and recent technological innovations. These innovations include the use of low-cost substrates and the implementation of nutrient circulation systems powered by wave and solar energy. Other cost estimates for coastal macro algal cultivation lie between \$25 to \$125 per tCO_2 by Cross et al. (2023) and NASEM (2022*b*), while Bednar et al. (2023) estimate costs to be between \$33 and \$133 per tCO_2.

In the case of deep-ocean sinking, sequestration would again be close-to-permanent and the benefits equal the SCC. Alternatively, cultivated macroalgae can be used as a fuel for BECCS (Cross et al., 2023). In the first case, sequestration would not be permanent but can replace fossil-fuel-combustion that would permanently increase the atmospheric carbon concentration. We return to the case of BECCS further below in this section.

Marine permaculture not only sequesters carbon but also enhances marine biodiversity by creating complex habitats. This co-benefit can boost fish populations and other marine life, contributing to food security and economic development in coastal regions. Environmental impacts of marine permaculture are also potentially detrimental, especially on local scales where seaweeds are farmed because this could lead to nutrient removal. In the deep ocean where the biomass is sequestered, some of the negative impacts could be acidification, hypoxia, eutrophication, and organic carbon inputs (NASEM, 2022*c*).

Artificial Upwelling. The costs of artificial upwelling would include the costs for the material of the pump, deployment costs, costs for development and maintenance of offshore monitoring and verification programs, energy required to run the pump as well as costs to remove the pump at the end of its lifecycle or maintain the pump during its period of use. NASEM (2022*c*) and Bednar et al. (2023) estimate that these costs would lie between $100 and $150 per tCO_2 sequestered with the largest costs arising from the development of a robust monitoring program.

The expected durability of carbon storage using artificial upwelling is less than a century, but it strongly depends on the efficiency of the biological carbon pump in sinking the carbon rich organic matter into the deeper ocean. (Siegel et al., 2021) find that methods of enhancing ocean carbon storage, like artificial upwelling of ocean fertilization, will have only short-term influence on atmospheric CO_2 levels because the ocean circulation and mixing will transport nearly 70% of the sequestered carbon back to the surface within 50 years. This means that the benefits from artificial upwelling are only a fraction of the SCC.

There is low confidence in the efficacy and co-benefits of this method. It could be used as a tool to enhance local aquaculture and fisheries, however, pumping the cooler temperature water from the deep ocean to the surface could cause ecological imbalances and negatively impact weather patterns by cooling the lower atmosphere. (NASEM, 2022*d*)

Ocean Fertilization. The costs of ocean nutrient fertilization involve several components, including the procurement and transportation of nutrients, deployment equipment, and labor for dispersal. The deployment costs for spreading nutrients in the ocean is relatively low, however, it does depend on the nutrient being added. Estimates of the total expected cost for this method are below $50 per tCO_2 sequestered (NASEM, 2022*c*). Hartmann et al. (2013) show that at a large scale deployment of artificial ocean iron fertilization could be as low at $10 per tCO_2 sequestered. Bednar et al. (2023) find that the average cost for Ocean Fertilization ranges from $66 to $158 per tCO_2 abated. While IPCC (2022*a*) estimate prices to be between $50 and $500 per tCO_2 sequestered.

The permanence of ocean fertilization depends on the location and efficiency with which the organic matter transports the captured carbon to the deep ocean. The carbon that is transported to shallower ocean depths will be stored for shorter periods of time, while the carbon that reaches the deep ocean will be safely stored for centuries. Overall, and similar to artificial upwelling, Siegel et al. (2021) find that the majority of the carbon sequestered in this method will be transferred back to the atmosphere due to ocean circulation and mixing within 50 years. This means that also for ocean fertilization, the benefits of the immediately extracted tCP_2 are only a fraction of the SCC.

The co-benefits and potential risks of this method are hard to estimate precisely. This is because it intends to increase net primary productivity at the surface ocean and carbon sequestration rates. However, ocean fertilization could impact the ecological and geochemical balance at the surface or deeper oceans through harmful algal blooms or oxygen depletion. (NASEM, 2022*c*).

Established Blue Carbon Measures. Costs vary for blue carbon measures based on the method of carbon sequestration adopted. Established blue carbon methods, including mangrove forests, salt marshes, and seagrass restoration, are the most cost-effective. Griscom et al. (2017) estimate the cost of these methods to be less than \$100 per tCO_2 sequestered. Bednar et al. (2023) find that the average cost of coastal blue carbon measures ranges from \$10 to \$50 per tCO_2 abated. IPCC (2022*a*) estimate prices to be between \$40 and \$260 per tCO_2 sequestered by coastal blue carbon. Claes et al. (2022) estimate the total potential CDR from established and emerging blue carbon solutions as approximately 3 $GtCO_2$ per year. It is most cost-effective to protect existing mangroves, salt marshes, seagrass, and kelp.

Claes et al. (2022) analyze several established and emerging blue-carbon solutions and find that all established blue carbon methods for protecting coastal environments, such as mangroves, salt marshes, seagrass, and kelp, cost less than \$10 per tCO_2 sequestered. This includes both the sequestration of new carbon and the avoidance of emissions from land-use changes. Crucially, mangrove restoration and reforestation are highlighted for their significant focus on carbon sequestration. Mangrove restoration, in particular, has an abatement potential of nearly 1.6 $GtCO_2$ annually and costs less than \$18 per tCO_2 sequestered.

The time scale for carbon storage in these blue carbon methods, such as coastal protection and restoration of mangroves, ranges from decades to centuries.

In addition to carbon sequestration, the co-benefits of blue carbon solutions also benefit coastal ecosystems. For example, as mangroves are protected or restored, fish and marine populations can expand, which would also support fisheries and the local ecology.

Direct Ocean Injection: Here we merely discuss the costs for ocean storage of CO_2, not its sequestration. The estimated price of direct ocean injection depends on the depth of injection. Chow (2014) find that costs were estimated to be \$11.9 for a 100km offshore storage site and \$13.2 for a 500km offshore storage site. They also estimate that transporting CO_2 from a 600 MW coal power plant via pipeline to a depth of 3km costs between \$6.2 per tCO_2 for transport to a 100 km offshore storage site and \$31.1 per tCO_2 for transport to a 500 km offshore storage site.

Given the storage is mostly permanent (Chow, 2014), deep sea storage would result in the full benefits corresponding to the SCC. Yet, again, these costs only include the storage and not the sequestration. The injection of CO_2 at high concentrations can lead to localized acidification and potential harm to marine organisms. A thorough environmental assessment and risk mitigation strategy would be essential for this method.

3.2.2 Competing Land-Based Measures

Afforestation and Reforestation. The costs associated with afforestation and reforestation vary depending on the location of the project, the type of trees being planted and the scale of the project being undertaken. The costs include site preparation, planting, maintenance and monitoring. Initial costs could include the cost of acquiring the land, the saplings, and preparing the soil. Subsequent costs would include the labor required in planting, irrigation, pest control and protection from disasters like fires. According to Bednar et al. (2023) the costs for afforestation and reforestation lie between \$10 and \$50 per tCO_2 sequestered while IPCC (2022*a*) estimates costs to be between \$0 and \$240 per tCO_2. A study by Hepburn et al. (2019), which includes the revenues obtained from the captured CO_2 that goes into industrial roundwood products, estimates these costs to be between -\$40 and \$10 per tCO_2.

The time scale for carbon storage in afforestation or reforestation methods ranges from decades to centuries, however, this is highly variable because the carbon storage can be affected by natural disasters like forest fires, pests, or droughts (IPCC, 2021). Therefore, given the uncertainty in the timescale of carbon storage, the benefits from afforestation and reforestation cannot be equal to the SCC.

Afforestation and reforestation have many benefits, enhancing natural carbon sinks while providing additional ecosystem services like improved biodiversity and less soil erosion.

BECCS. There are two key outcomes of BECCS that include the bioenergy produced and the atmospheric CO_2 that was removed. The costs associated with this method cover several components, including the cost of cultivating and harvesting biomass, transporting it to the processing facility, and production of bioenergy from the biomass. Bednar et al. (2023) find that the average cost for BECCS ranges from \$57 to \$145 per tCO_2 abated. IPCC (2022*a*) estimate the costs to be between \$15 and \$400 per tCO_2 abated. Fuss et al. (2018) estimate the costs to be between \$100 and \$200 per tonne of CO_2, however, they only account for the costs of CO_2 removal by the process of bioenergy production. Hepburn et al. (2019) include the revenue received from the bioenergy provided in their analysis and estimate breakeven costs to be between \$60 and \$160 per tCO_2.

The benefits from BECCS are equivalent to the SCC since the time scale for carbon storage with BECCS is potentially permanent since it is analogous to direct air carbon capture and storage (IPCC, 2021).

Soil Carbon Sequestration. The costs associated with coil carbon sequestration include the expenses for implementing methods such as no-tilling, crop rotation, or the cost of additives like biochar or compost to the land. Soil carbon sequestration has the benefit of improving soil quality and typically increasing the agricultural productivity of land. Accounting for the benefits obtained by this method, Hepburn et al. (2019) estimate the cost for soil carbon sequestration in the negative range from -\$90 to -\$20 per tCO_2 sequestered. Bednar et al. (2023) find that the average cost for soil carbon sequestration ranges from \$0 to \$83 per tCO_2 abated. While, IPCC (2022*a*) estimate the costs to be between -\$45 and \$100 per tCO_2 sequestered. IEAGHG (2005) find that at 20% of the technical potential of carbon sequestration, the price of soil carbon sequestration exceeds \$15 per tCO_2, and at 60% of the potential price approaches \$55 per tCO_2.

The benefits of carbon removal from soil carbon sequestration are not equal to the SCC. This is because the carbon is sequestered for only a few decades to a century (IPCC, 2021). After this time majority of the stored carbon would be released back to the atmosphere.

Part of the carbon taken up by land in this method leads to increased output, which is one of the largest co-benefits of soil carbon sequestration. However, impacts on yield are highly variable, depending on factors including the climatic zone.

DACCS. The costs of technologically extracting CO_2 from the atmosphere at a particular location are high. Webb (2023) estimates that the cost of direct CO_2 removal is between \$600 and \$1000 per tCO_2. Bednar et al. (2023) estimate the costs to be between \$133 to \$583 per tCO_2 abated. IPCC (2022*a*) estimate prices for DAC to lie between \$100 and \$300 per tCO_2 sequestered.

Webb (2023) argues that this method of CDR offers many advantages because it is more land-efficient and scalable than traditional land-based methods. Another advantage is that the amount of CO_2 captured is more easily verifiable in this method as compared to nature-based solutions. Direct Air Capture can sequester emissions for many centuries and store them permanently in geological formations. The benefit, therefore, corresponds to the SCC since the method only captures and stores carbon offering no other co-benefits. However, the high costs associated with this method make it more difficult for it to be widely adopted.

CCS. Analogous to direct ocean injection, we briefly discuss the mere storage costs of captured carbon with traditional storage, excluding the costs of carbon sequestration. Baylin-Stern and Berghout (2021) study the costs of capturing and storing carbon in geological deposits at the site of emissions. For pure or highly concentrated CO_2, then the costs are relatively low and are in range of \$15 to \$25 per tCO_2. Examples of these industrial processes are ethanol production and natural gas processing. However, costs are higher and lie between \$40 and \$120 per tCO_2 for diluted gas streams, like in the production of cement or during energy generation. Such storage is considered permanent, but the benefit would only correspond to the SCC if the alternative would be simply releasing the highly concentrated industrial CO_2 into the atmosphere.

3.3 Distributional Implications of CDR Methods

CDR methods have diverse distributional impacts, affecting various regions and communities in distinct ways. Ocean-based methods, such as marine permaculture and aquaculture, can benefit coastal regions by enhancing marine ecosystems and fisheries, thus providing economic opportunities. However, these methods also pose risks to marine biodiversity, which could negatively impact local communities that rely on these ecosystems. Land-based methods, on the other hand, significantly affect land use and food security, especially in developing regions. Practices like afforestation and reforestation may compete with agricultural land, potentially disrupting local food production. BECCS requires substantial land, water, and energy resources, which could reduce the availability of these resources for local communities. Conversely, soil carbon sequestration practices can enhance agricultural productivity and resilience, benefiting smallholder farmers.

Both ocean-based and land-based CDR methods offer economic opportunities but also come with challenges. Ocean-based Negative Emission Technologies (NETs) can stimulate the development of marine permaculture and aquaculture industries, creating jobs and enhancing food security in coastal regions. However, these opportunities necessitate significant investments in infrastructure and technology, which may be prohibitive for less developed regions. Land-based methods can promote rural development and provide additional income streams for farmers through afforestation, agroforestry, and soil carbon sequestration. Nonetheless, these practices may lead to competition for land and resources, particularly in densely populated areas with limited agricultural land.

The equitable implementation of CDR technologies is essential to ensure fair access to resources. Wealthier nations and regions are more capable of investing in advanced technologies, while poorer regions might favor land-based methods due to lower costs and immediate benefits. Ensuring equitable access to CDR technologies and resources is vital for global climate justice. An equitable approach to distributing CDR responsibilities is also crucial. Models indicate that regions where CDR deployment is most cost-efficient are not necessarily those with the greatest responsibility or capability. Fair-share outcomes suggest that the United States, the European Union, and China have 2–3 times larger CDR responsibilities this century compared to a global least-cost approach (Fyson et al., 2020).

Current nationally determined contributions to the Paris Agreement do not adequately address the CDR needed to meet its goals, underscoring the necessity for equitable CDR quotas based on Responsibility, Capability, and Equality principles. This results in significant variability in quotas across the European Union and highlights the importance of cross-border cooperation (Pozo et al., 2020). Many countries lack the biophysical and geophysical capacity to meet their equitable CDR shares, necessitating international carbon trading. Therefore, ensuring equity in CDR distribution is crucial due to disparities in national capacities and the need for collaborative efforts and diverse CDR technologies to achieve fair and effective climate action (?).

This synthesis of the distributional implications of CDR methods highlights their varied impacts on different regions and communities, economic opportunities and challenges, and the importance of equity and access to resources. By adopting an equitable approach to CDR responsibilities and ensuring fair access to technologies, it is possible to address global climate justice and achieve effective climate action through collaborative efforts.

4 CDR Policy

This section will first explore various policy instruments designed to promote CDR, including subsidies and market-based mechanisms such as the integration of CDR into emission trading schemes. The next section will provide an overview of current CDR policies in selected countries around the world, highlighting diverse approaches and national strategies that are being implemented to foster CDR initiatives. Finally, the section will touch upon the importance of global cooperation in scaling CDR efforts effectively.

4.1 Policy instruments

This section briefly introduces the common policy instruments that can be employed to promote ocean-based CDR.

4.1.1 Subsidies

Subsidies are an important policy instrument to promote ocean NETs and CDR in general. There are several ways to subsidize ocean NETs such as OAE, marine permaculture, ocean fertilization, and artificial upwelling, encompassing direct subsidies, tax incentives, research and development (R&D) funding, and deployment incentives to accelerate the adoption and scaling of these technologies.

In the current phase, governments and international bodies can provide (and are providing) grants and direct subsidies to academic institutions, research organizations, and private companies engaged in the early-stage research of ocean-based NETs. This funding is crucial for exploring the scientific viability, potential environmental impacts, and technological advancements needed to make these methods effective and scalable. Slowly moving towards larger experimentation can lower the financial barriers to entry, or at least more clearly establish the magnitude of those barriers. And it will be important to foster a robust research ecosystem impacts. Once technologies reach a more advanced stage, deployment subsidies can help bridge the gap between demonstration projects and commercial-scale operations. These subsidies can cover the costs associated with pilot projects, infrastructure development, and initial operational expenses. By reducing the financial risks, governments can incentivize private investment and accelerate the transition from experimental phases to widespread implementation.

As an alternative to direct subsidies, tax credits for companies that invest in ocean-based NETs can significantly enhance their attractiveness. Tax incentives can come in the form of investment tax credits, which allow businesses to deduct a percentage of the capital costs associated with deploying these technologies. Additionally, production tax credits can be given based on the amount of CO_2 successfully sequestered, thus directly linking financial incentives to performance outcomes. Another fiscal tool is allowing accelerated depreciation of capital investments in ocean-based NETs. This method enables companies to write off their investments more quickly, reducing taxable income in the early years of the project and improving cash flow. This financial relief can make investments in these technologies more appealing compared to traditional business expenditures.

4.1.2 Market-Based Mechanisms

Market-based mechanisms play a crucial role in promoting ocean-based negative emissions technologies (NETs) by creating financial incentives CDR. Integrating ocean-based NETs into existing carbon pricing systems, such as cap-and-trade and carbon taxes, can ensure a steady revenue stream for these technologies. In such a setting, companies deploying NETs can earn carbon credits, which can then be sold in carbon markets. This approach provides financial incentives while integrating these technologies into broader climate mitigation strategies, ensuring their contributions are recognized and rewarded within the global carbon economy. Most importantly, this approach would ensure that the marginal costs of removing CO_2 emissions are equalized across mitigation and CDR measures, a requirement for economic efficiency.

Standard Carbon Pricing and Trading Systems assign a monetary value to a ton of CO_2. Traditionally, these values are attached to mitigated tons of CO_2. For CDR measures, this carbon price would also be attached to a ton of carbon sequestered, thereby encouraging investment in CDR technologies and practices. Carbon credits generated from CDR projects can be traded in carbon markets, providing an additional revenue stream for project developers. These systems connect developers with buyers by certifying that carbon removals meet high-quality standards, which helps attract funding and supports the incorporation of CDR into broader climate policies. A significant issue in market-based mechanisms is the accounting for different CDR projects, especially given the varying permanence of carbon removal across methods, see Deliverable D1.2 (Rickels, Koeve, Meier, Paschen, Rischer and Saldivia, 2023). Ocean-based methods, such as OAE and marine permaculture, typically offer more permanent sequestration compared to some terrestrial methods easing this concern.

In the absence of formal cap and trade markets, Voluntary Carbon Markets (VCMs) have emerged that directly connect buyers and sellers creating economic opportunities for sellers and helping private sector buyers increase their climate ambition. Voluntary carbon markets (VCMs) face significant challenges related to verification, standardization, and transparency, which have led to skepticism about their efficacy. Unlike regulated carbon markets that are subject to stringent oversight, VCMs often rely on third-party certifiers with varying standards, resulting in disparities in the quality and reliability of carbon credits. This inconsistency can undermine the credibility of the offsets, leading to potential overstatements of carbon sequestration and uncertainties regarding the permanence of the sequestration achieved. Transparency issues further complicate the situation, as many projects do not provide comprehensive and accessible data, making it difficult for stakeholders to assess their true impact. Without robust monitoring, reporting, and verification systems, ensuring that carbon removals are real, additional, and permanent remains challenging.

Finally, governments can consider introducing subsidized financial instruments. They can establish subsidized insurance schemes and low-interest loan programs specifically for ocean-based NET projects. These financial instruments mitigate the risks associated with deploying novel technologies, making it easier for companies to secure funding and manage potential operational setbacks. By reducing the financial risks, such schemes encourage private investment and accelerate the development and deployment of ocean-based NETs.

4.1.3 Monitoring, Verification, and Compliance

Effective monitoring and compliance are critical components for integrating CDR projects into market-based mechanisms, ensuring their integrity, longevity, and credibility. These systems must account for the varying durations and efficiencies of different CDR methods, establishing a consistent framework that supports the comparability and reliability of carbon credits across various technologies. In the context of CDR, monitoring involves continuous assessment of the projects to ensure they meet their intended goals. This includes verifying that carbon sequestration is occurring as planned and that the methods used are effective and sustainable. Technologies supporting robust measurement, monitoring, reporting, and verification are essential. These technologies enable transparent reporting and accountability, ensuring that the claimed reductions or removals are real and verifiable.

However, monitoring alone is insufficient without addressing the risks associated with project failure. For example, if a reforestation project fails due to inadequate maintenance or is destroyed by fire, the carbon credits issued for the project's anticipated sequestration become invalid. This scenario highlights the importance of ex-post compliance, where ongoing verification and adjustments are necessary to account for any reversals in carbon sequestration. In such cases, financial mechanisms like insurance, buffer pools, or temporary credits can help mitigate the risks. Insurance can cover the replacement of lost credits, buffer pools can hold a percentage of credits in reserve to compensate for any losses, and temporary credits can lapse if the carbon sequestration is reversed.

International standards and protocols play a pivotal role in establishing robust monitoring frameworks. These standards ensure that activities generating carbon credits meet stringent criteria. Core integrity principles include ensuring that activities are additional (not legally required), unique (one credit per tonne of CO_2 reduced or removed), real and quantifiable (genuine impact with transparent methodologies), and validated by independent third parties. Emissions benefits must be permanent, with robust baselines to prevent over-crediting and adapt to national climate policies and technological advancements.

Credit certification standards bodies are crucial in maintaining credit integrity. These bodies govern standards with transparency and accountability, operating registries to track credit attributes and prevent double-counting. They require comprehensive and accessible information on crediting activities and ensure independent third-party verification and validation. Addressing conflicts of interest and supporting equitable participation, especially for projects in developing countries, are also essential responsibilities of these bodies.

4.2 Current Policy Incentives

This section discusses current CDR policies in selected countries. Given the lack of policy measures directly addressing ocean-based CDR, we focus on CDR in general to convey a picture of current measures to integrate CDR into the climate change mitigation portfolio.

4.2.1 Europe

Across Europe, significant strides are being made to combat climate change, with policymakers increasingly recognizing the need for CDR alongside emissions reductions. Different countries are employing different policy instruments to achieve their targets. Some countries are setting targets as a proportion of total emissions while others specify an amount in tonnes. For example, Portugal caps its CDR target at 10% of emissions to prevent reliance on CDR over decarbonization. While countries like the United Kingdom, Switzerland, and Germany, have clear numeric goals for their emission reduction targets (Manhart, 2023*b*).

The UK recently laid out its climate policy in a comprehensive policy document (Departement for Energy Security and Net Zero, 2022) and has set a greenhouse gas removal target of at least 5 $MtCO_2$ per year using CDR methods and negative emission technologies by 2030, still less than 2% of their current emissions. In 2017, the UK committed to spending 100 million GBP in funding to research and develop DACCS and other Greenhouse Gas removal technologies.

Switzerland's climate strategy also sets clear CDR goals. They plan to scale up CCS and NETs over two phases, the 'pioneering phase' up to 2030 and a 'targeted scaling phase' up to 2050. The goal is to store around 12 $MtCO_2$ annually by 2050 (Federal Office for the Environment, 2023), which is a far more ambitious target given the country's size and overall emissions (it would be about one-third of current emissions).

Germany plans to have net-zero greenhouse gas emissions by 2045 and net negative emissions by 2050 using both nature-based and novel CDR methods. The Federal Climate Protection Act targets greenhouse gas removals from land use, land use change, and forestry of at least 25 $MtCO_2$ annually by 2030, and plans to increase these amounts to 35 $MtCO_2$ and 40 $MtCO_2$ annually by 2040 and 2045 respectively (Carbon Gap, 2024*a*).

Norway's climate action plan aims to achieve a 50-55% reduction of emissions by 2030. However, it does not explicitly mention the use of CDR technologies or methods to achieve this target. According to another report by the Norwegian Environmental Agency, including CDR methods would make this target more easily achievable. The agency proposed a reverse carbon tax offering monetary rewards for every ton of CO_2 abated. They estimate a potential contribution of 1 $MtCO_2$ annually abated through DACCS and an additional 1.5 $MtCO_2$ annually using bioCCS, which includes BECCS, by 2030. Given Norway's almost entirely renewable energy sector, these measures would amount to a 55% reduction in annual emissions. (Carbon Gap, 2024*b*).

Norway also has significant potential to collaborate on bio-CCS at the Nordic level given the abundant biological sources of CO_2 present in Sweden and Finland. Norway's storage sites could be utilized to store this CO_2 from across the Nordic region and Northern European countries. This potential creates policy incentives for the Nordic countries to coordinate with each other in their CDR policies (Carbon Limits and Perspectives Climate Research, 2024).

Ocean-based projects that aim to store CO_2 in seabeds play a significant role in some countries' CDR strategies. In 2023, Denmark initiated Project Greensand, which is the world's first cross-border offshore CO_2 storage project. CO_2 from large emitters is stored underneath the seabed in the Danish part of the North Sea. Project Greensand can store 1.5 $MtCO_2$ per year in 2025-2026 but will expand to 8 $MtCO_2$ per year by 2030. This would be more than 13% of Denmark's annual CO_2 emissions. The first CO_2 to be stored in this project originated from Belgium (Project Greensand, 2024).

Germany and Norway together have launched the NOR-GE project, which is a planned CO_2 pipeline that enables safe transport, injection, and storage of CO_2 from Germany into the seabed of the Norwegian North Sea. Two CCS licenses have been awarded to Norway, giving a combined annual storage injection capacity of nearly 12 $MtCO_2$. Norway has significant experience implementing this CCS technology. Since 2008, the Snøhvit facility on Melkøya has separated CO_2 from the well stream before chilling the gas to produce liquified natural gas, transported the CO_2 back to the Snøhvit field via pipeline, and injected it into a subsea formation, storing up to 0.7$MtCO_2$ annually and totaling 4.7$MtCO_2$ captured and stored since its inception (Wintershall Dea, 2024).

4.2.2 United States

The US is a global leader for policy support of CDR. In order for the US to achieve its decarbonisation goal by mid-century, they would need to have at least one gigaton of available CDR capacity per year by that time (Jones et al., 2024).

In 2022 the US Federal Government signed the Inflation Reduction Act (IRA) which announced financial support and incentives for CCS, CDR and and CO_2 utilization primarily through enhancements to Section 45Q of the internal revenue code. Section 45Q provides performance based tax credits for carbon management projects that capture carbon oxides. The IRA raised the 45Q tax credit for CO_2 captured for utilization and Enhanced Oil Recovery from \$35 per tCO_2 to \$60 per tCO_2 for point-source capture, and to \$130 per tCO_2 for direct air capture (Goddard, 2023). This provides incentives for the deployment of carbon capture in several industries.

The regional Direct Air Capture Hubs program received \$3.5 billion in order to set up four regional DAC hubs across the US, each of which would have the potential to capture 1 $MtCO_2$ annually which would then be permanently stored in geological formations or converted to new products (U.S. Department of Energy, 2024).

CDR policies can also be implemented by individual states. The two states with the most ambitious CDR policies are California and New York. California has set an emission target of 15% for CDR or about 75 $MtCO_2$ annually by 2045. New York plans to pass the CO_2 Removal Leadership Act, which would enable the procurement of 0.01 $MtCO_2$ CDR annually with the plan to double this quantity every year over a five-year period (Manhart, 2023*a*).

Most immediately interesting for ocean-based CDR is likely a recent joint statement by U.S. Federal departments and offices on Voluntary Carbon Markets (VCMs). They emphasize the potential of high-integrity VCMs to support decarbonization efforts globally by unlocking capital and demand for verified emissions reductions and removals. The statement highlights the necessity for robust standards to ensure that credits represent real, additional, and lasting decarbonization. It acknowledges existing challenges, such as ensuring that VCMs genuinely drive additional action rather than rewarding business-as-usual scenarios and addressing barriers to market participation. Importantly, it states that the U.S. Government is taking steps to enhance market integrity through measures like incorporating carbon credit disclosure standards into securities regulation and supporting high-integrity credit-generating projects, which can boost the credibility and functionality of VCMs over time. VCMs are currently more open to incorporating CDR measures than formal cap-and-trade markets, which makes them promising for promoting ocean NETs.

4.2.3 Developing Countries

We provide a brief look at Brazil, China, and India to see how CDR policy and governance are progressing in developing countries.

In 2022, Brazil committed to achieving net-zero greenhouse gas emissions by 2050, with the government aiming to restore 12 million hectares of forest land by 2030. The Climate Change Law 12187/2009 and its regulation Decree included CDR in its target of including 15 million hectares of degraded pasture, the expansion of 4 million hectares of crop-livestock-forestry integrated systems and the expansion of 3 million hectares of planted forest area. The Low-carbon Agriculture Program (ABC+) supports carbon sequestration and trading carbon credits. Programs like the Floresta+ initiative incentivize forest conservation. While biofuel programs such as RenovaBio could support BECCS deployment, CCS developments are mostly driven by the fossil fuel industry, with limited policy support hindering large-scale deployment. Despite high innovation in the land-use, land-use change and forestry (LULUCF)-based CDR and increasing private sector interest, CCS-based CDR remains underdeveloped, though initial BECCS and DAC projects are emerging. Biochar and enhanced weathering are potential future options for carbon removal in Brazil (Schenuit et al., 2024).

China has a high level of regulation for LULUCF-based CDR, with longstanding reforestation programs and climate policies aimed at enhancing carbon sinks. The country's NDC includes pledges to increase forest stock volume and integrate carbon sink trading into the national carbon market. Despite challenges in certificate quality, voluntary emission trading schemes, such as the recently relaunched China Certified Emissions Reductions scheme, support these efforts. CCS-based CDR is still emerging, with government focus on R&D and pilot projects, but primarily linked to fossil CO_2 sources. Innovation in LULUCF-based CDR is strong, driven by voluntary markets and increasing carbon intensity targets. Although dedicated funds for CCS-based CDR are lacking, China's innovation in DACCS and BECCS is growing, with the country holding a significant number of CDR-related patents and small start-ups contributing to the field (Schenuit et al., 2024).

India has a high level of regulation for LULUCF-based CDR, with significant pledges in its INDC and NDC updates to create substantial carbon sinks. The National Action Plan for Climate Change and the Green India Mission aim to increase forest cover and contribute to these targets, though implementation and accountability issues remain. Despite India's interest in CCS due to its large coal power fleet, regulation for CCS-based CDR is underdeveloped, with no operational demonstration plants. Voluntary markets for LULUCF-based CDR are established, driven by international incentives like REDD+. Innovation in CCS-based CDR is limited but growing, with increasing research efforts and the establishment of National Centers of Excellence in Carbon Capture & Utilization. However, most initiatives focus on CCU and CCS for fossil fuel emission abatement rather than direct CDR (Schenuit et al., 2024).

4.3 Global Coordination and Cooperation

Global coordination and international cooperation are crucial for the successful implementation of CDR technologies and, in particular, ocean-based NETs. These efforts are essential to standardize methodologies, share best practices, and ensure the equitable distribution of resources and benefits, thereby enhancing the effectiveness and acceptance of CDR methods. This is particularly important for methods like OAE and direct ocean injection, which due to the transboundary nature of marine environments, require global oversight to ensure environmental safety and equitable implementation.

International agreements play a pivotal role in this landscape. Frameworks like the Paris Agreement foster global cooperation on climate mitigation and CDR, enabling countries to collaborate on setting targets, sharing knowledge, and financing CDR projects. Such frameworks also address critical issues of equity and access to resources, helping to redistribute costs and benefits to make investments in CDR more attractive (Maher and Symons, 2022). Additionally, technology transfer is vital for enabling the effective adoption of CDR technologies, particularly in developing regions. Developed countries play a significant role by providing financial aid and technical assistance, which lowers cost barriers and navigates the complexities of CDR methods. Capacity-building initiatives are equally important, as they train local professionals and establish necessary infrastructure, ensuring that developing countries can independently maintain and operate these technologies.

Ultimately, the global nature of climate issues necessitates a cooperative approach to ensure that all nations, regardless of economic status, can contribute to and benefit from efforts to mitigate global warming. This holistic approach not only helps in reducing carbon emissions but also reduces the overall costs mitigating climate change and promotes sustainable development and resilience in vulnerable regions, thus supporting a balanced and inclusive strategy to tackle global climate challenges.

5 The Role of Ocean NETs in the Larger Climate Change Policy Portfolio

5.1 Conceptual Thoughts on CDR Policy and Ocean NETs

This subsection delves into conceptual underpinnings governing CDR deployment and development, focusing on their strategic role in global climate policy. By examining these conceptual arguments, we aim to provide policymakers with a nuanced understanding of CDR's capacity to complement existing climate strategies, highlighting its value in mitigating the impacts of emissions from diverse sources and its role in the broader context of sustainable development.

CDR technologies offer significant advantages in addressing *international carbon leakage*. International carbon leakage refers to the situation where efforts to reduce greenhouse gas emissions in one country lead to an increase in emissions in another country, typically because industries relocate to regions with less stringent environmental regulations. This undermines the overall effectiveness of global climate mitigation efforts in a world with heterogenous climate action. However, by providing additional alternative means not contributing to such incentives, CDR methods can help offset residual emissions and reduce the risk of carbon leakage.

A crucial difference between ocean-based NETs and land-based CDR is their immense *storage capacities*, potential *scalability*, and the corresponding *cost response*. Most land-based measures rely on the scarce resource of land. As we discuss above, as we scale up soil carbon sequestration or reforestation projects, their cost increases as the suitability and opportunity costs for land increase. By contrast, the oceans are so vast that ocean fertilization of open ocean OAE is hardly limited in scope. Marine permaculture is more coast-bound, but the geographical potential of these coastal areas is still large. At the same time, all of these novel ocean-based NETs are predicted to have economies of scale and get more efficient with learning-by-doing. As a result, for low levels of CDR, land-based methods have a clear lead. Yet, once we require larger amounts of CDR, novel ocean-based methods become increasingly more competitive.

In scenarios where greenhouse gas emissions exceed *sustainable thresholds*, CDR technologies offer a critical advantage over traditional abatement strategies. Unlike abatement, which focuses on reducing emissions at their source, CDR can directly address excess atmospheric CO_2, providing a vital tool for mitigating irreversible environmental damages and potential tipping points. Because the capacity to act swiftly in response to escalating climate threats could become crucial in the future, CDR technologies carry an *option value* and can act as a strategic reserve; a ready solution that can be deployed to complement ongoing emission reductions or when traditional methods fall short. This argument, in particular, favors the development and testing of CDR technologies even if their deployment scope remains to be seen.

CDR will play a crucial role in offsetting the costs associated with the *most expensive emission reductions*. Recent research, such as Traeger (2024) and our project's analysis using the Dynamic Applied Regional Trade (DART) model (see below), indicate that common IAMs like DICE might underestimate the costs of reducing emissions in the final sectors of the economy. These sectors often encounter significant technological and logistical challenges in implementing abatement strategies, resulting in disproportionately high costs. Again, developing CDR today and bringing down its price will be strategically important by the time we have to address the most expensive abatement measures to succeed in a green transition.

In a similar context, but from a political perspective, many abatement strategies intended to combat climate change have encountered significant opposition across various European nations and globally. Therefore, although economically viable abatement might be theoretically possible, it may not be *politically feasible*. Moreover, in democratic societies, certain measures inevitably remain at the discretion of individuals, even if governments can implement strong financial incentives for abatement adoptions. Yet, the literature indicates that entrenched *behavioral patterns* can lead individuals to resist adopting even financially advantageous measures.[3] This reasoning amplifies the economic argument in the preceding paragraph about how CDR is a valuable option to replace the politically or behaviorally most challenging parts of the green transition.

Another interesting conceptual issue is whether it is preferable for ocean NETs to concentrate measures on more narrow areas and *localize* potential repercussions on the environment

[3] See Fowlie et al. (2018) for a discussion of the so-called energy efficiency gap. These authors also note that this issue may be less significant than previously believed.

or whether to maximize *diffusion over broad areas* to minimize local impact but therefore, potentially affect larger areas. We are not aware of careful previous considerations on this point and discuss preliminary insights in Meier et al. (2023). From the direct economic cost side, it will usually be more efficient to localize the measures, but the environmental cost-benefit ratio of diffused versus localized impact is highly uncertain. Different ocean-based NETs have different comparative advantages when it comes to localized or diffused deployment, ocean fertilization followed by some forms of OAE probably being the easiest method for diffused deployment.

Finally, CDR provides a critical capability to *mitigate* the impact of *other nations' emissions*. While we can incentivize, we cannot compel other countries to reduce their emissions. It is widely recognized that fully industrialized nations with substantial historical emissions bear a greater responsibility in curbing greenhouse gases. In pursuit of efficiency, international policies, including the Paris Agreement, advocate for collective action to limit global warming. However, when certain nations fail to collaborate, CDR offers the rest of the world a viable option to counterbalance these emissions.

One general concern governing CDR measures is that they could (i) reduce the incentive to mitigate emissions and (ii) increase gross emissions as a result of the required energy use of the CDR measures themselves (even if the net emissions impact would and should be negative). We analyze these questions in our paper Meier et al. (2022). We find that the availability and deployment of CDR has only a very minor impact on the SCC, which is the ultimate incentive for emission abatement. This result contrasts sharply with other forms of geoengineering like solar radiation management. As we show in Meier and Traeger (2022), the deployment of solar radiation management reduces the damage from a given unit of CO_2 emitted and, thus, reduces the SCC for all nations to undertake abatement efforts. That said, in practical terms, CDR of course does offset a country's pressure to satisfy given CO_2 reduction targets by means of abatement. Yet, in this context CDR does not reduce the overall incentive to lower the concentration of greenhouse gases, but it merely helps to achieve a given concentration at lower costs.

Regarding concern (ii), Meier et al. (2022) show that a large-scale deployment of highly energy-intensive CDR methods might indeed increase gross emissions notably, especially during the initial phase of the green transition when energy production is still mostly fossil-fuel-based. Of course, even in those cases the overall effect of CDR is to substantially reduce greenhouse gas concentrations. The CDR methods with the highest energy use are generally those relying on purely technological extraction of CO_2 from the atmosphere. Ocean-based NETs are typically only moderately energy-intensive. Among the ocean NETs, ocean liming-based OAE is on the slightly higher end of energy use as a result of limestone grinding and transport. Based on Deliverable 1.4's assessment (Kooten et al., 2023), the authors estimate the energy share in total production cost to be about 28% of total costs, which is still moderate. Marine permaculture and ocean fertilization would have even lower energy shares.

5.2 Benefit-Cost Driven Policy

In this scenario, we evaluate to what degree ocean-based NETs should have a place in the abatement portfolio based on their social net benefit. As discussed in Section 3, ocean-based NETs have the advantage of close-to-permanent storage, which implies that their direct benefits equal the SCC. As discussed in Section 3.1, the most recent expert-weighted mean-

SCC in the literature is \$283 per tCO_2. This estimate of direct benefits outweighs the direct costs for almost all estimates of ocean NETs. It breaks even for OceanNETs cost estimate for ocean liming of \$200-300 by 2040 (Kooten et al., 2023), and these benefits clearly dominate the other cost estimates for OAE in the literature. Thus, based on direct costs and benefits only, we find that the typical ton of CO_2 will increase global welfare with benefits dominating costs. This holds particularly if we anticipate its use in a decade or two. By then, R&D and pilot projects will have, most likely, lowered these cost estimates, whereas the SCC is increasing over time (mostly as a result of predicted economic growth).

Yet, these direct cost estimates neither include the co-benefits nor risks associated with OAE discussed in Section 3.2. These factors are marked by a high degree of uncertainty for all of the novel ocean NETs. Depending on societies' aversion to risk, see as well Section 5.5, these uncertainties have the potential to upend OAE's efficiency. At the same time, the existing uncertainties should not be viewed as deterrents but rather as an invitation to continue research efforts. Given the current landscape of theoretical studies and small-scale experiments, the next step would involve the conceptualization and execution of larger-scale experimentation. These further studies will be crucial to more accurately assess the environmental impacts and to verify the true efficacy of the novel ocean NETs in removing CO_2.

As compared to ocean liming, the case for using crushed olivine rock dispersion is far stronger. The feasibility of integrating this approach with beach maintenance activities significantly reduces costs, making it an economically attractive option. At our estimated cost of \$75 per tCO_2, this method not only breaks even but does so with such clarity that it should be regarded as a serious contender in CDR strategies. However, environmental risks must be meticulously assessed during the initial deployment phases. As noted, the potential for implementing this method in Europe is more constrained compared to ocean liming, with an estimated capacity of only about 50-100 $MtCO_2$ per year.

Marine permaculture is another strong contender in this scenario with lower risks but potentially higher costs. Our surveyed cost estimates range from \$25-300, but are generally expected to fall below \$100 with more research and economies of scale. These measures do not change the ocean chemistry and create new marine habitats. Yet, such a massive change in ocean biomass affects nutrient availability and will likely impact local marine ecosystems. Yet, under careful upscaling of deployment and close monitoring, marine permaculture is a strong candidate if our aim is to provide a positive social net benefit.

Other blue carbon CDR methods, including mangrove forest, salt marsh, and seagrass restoration, are already part of the established approaches with mostly positive co-benefits and clearly satisfy the social net benefit criterion. Ocean fertilization has the lowest cost estimates of the novel ocean-based CDR approaches. Their direct benefits clearly outweigh the direct cost of \$25-50. Yet, also ocean fertilization is surrounded by uncertainties regarding the longer-term risk both at surface level and in the deep sea (Kooten et al., 2023; NASEM, 2022*c*). As importantly, the IMO (2013) effectively bans ocean fertilization and would have to be renegotiated before such a policy could be deployed on a meaningful scale. At our cited cost "guesstimate" of \$100-200, artificial upwelling is substantially more expensive than ocean fertilization and considered at least as risky. In addition, the sequestration effectiveness of artificial upwelling and, thus, the true price estimate (rather than guesstimate) is highly uncertain; without further research and testing, we cannot evaluate the true benefit-cost ratio for artificial upwelling (or downwelling).

In summary, we find that most ocean-based NETs pass a simple benefit-cost test and that their deployment yields an expected social net benefit. Yet, except for the established blue carbon NETs, the true value is somewhat ambiguous, given that co-benefits and risks are hard to quantify. It would be natural to further test these measures carefully before any large scale deployment.

The approach above uses direct cost estimates of the social benefits of CDR policies. By contrast, international negotiations have mostly focused on quantity targets and limiting the temperature increase. The IPCC (2022*b*) has translated the 1.5°C and 2°C targets formulated in the Paris Accord into corresponding abatement cost estimates. These estimates are based on a collection of integrated assessment models of climate change and averages over a variety of socio-economic scenarios. These cost-efficiency models calculate the cheapest way to reach a given climate target by the end of the century. The report estimates that marginal abatement costs will have to be around \$90 (\$60–120) by 2030 and \$210 (\$140–340) by 2050 to reach the 2°C target; and they have to be around \$220 (\$170–290) by 2030 and \$630 (\$430–990) by 2050 to reach the 1.5°C with reasonably high probability.[4] Recent research by Gollier (2024) suggests that the employed cost-efficiency integrated assessment models might overestimate the economically efficient carbon price increase and, as a result, underestimate the optimal initial carbon prices (and similarly overestimate the required carbon prices in 2100).

These numbers suggest that, under the 2°C target, only ocean fertilization would be cost-effective in the near future apart from the already established blue carbon measures like coastal restoration and mangrove reforestation. Yet, almost all ocean-based measures will be cost-effective by 2050 given the steeply increasing carbon prices. If we can additionally commit to a slow phase-in already earlier, then also the falling deployment costs contribute to making ocean-based NETs cost-effective in the medium run under the 2°C target. Under the 1.5°C target, we should already push strongly for ocean-based NETs in the near term as even the more expensive ocean-based CDR measures are expected to break even around 2030. Of course, the need for close monitoring of environmental impacts and corresponding adjustments to potential deployment remains essential.

We have argued that each ocean-based deployment measure is likely to pass the social net benefit test (after a more careful evaluation of the environmental risks). Yet, some are cheaper than others and, as discussed in Section 3.2, some of the land-based CDR methods like afforestation and reforestation and soil carbon sequestration are substantially cheaper and without the risk attached to the novel ocean-based approaches. Thus, will it be efficient to deploy OAE and marine permaculture in the current context with far more scope for cheap abatement and cheaper CDR even in those land-based channels?

The answer to this question is twofold. In principle, from an economic standpoint, it is not efficient to deploy a more costly option when cheaper, less risky alternatives are available. However, in practice, we must acknowledge that these cheaper options are not currently being used to offset emissions sufficiently to reduce the social benefit of carbon capture to a level where other methods are no longer viable.

If the reason for insufficient mitigation and low uptake of land-based CDR is due to a lack of political feasibility, such as obstacles to further afforestation or aversion to adopt-

[4]The ranges in parentheses give the IPCC's confidence intervals and are based on simulations across many models. See Figure 3.32 in IPCC (2022*a*) on p. 360 for more information.

ing an electric vehicle fleet, then these potentially more efficient tools are not feasible, and ocean-based CDR can be considered the second-best alternative. Conversely, if the obstacle to greater mitigation and higher uptake of land-based CDR and traditional blue carbon measures is merely a lack of political willingness to commit to strong CO_2 reduction from the outset, then the novel ocean-based methods are also not viable.

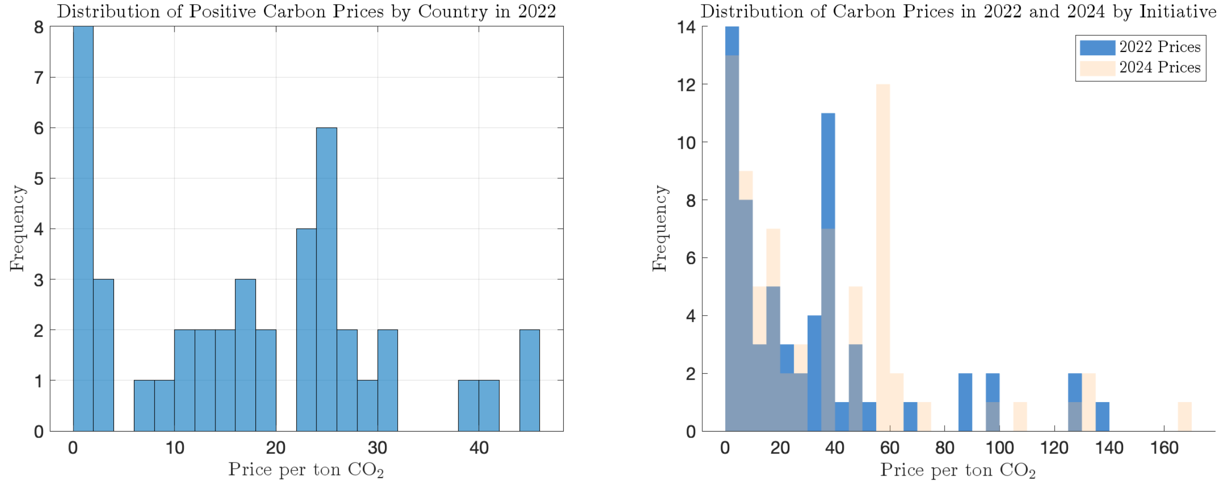
A more sophisticated answer to the question at hand is that we likely see a lack of political willingness for immediate strong action, but some commitment to future action. In this case, ocean-based CDR and classical blue carbon methods are the natural starting points to ramp up efforts. Simultaneously, investment in reducing costs and uncertainties associated with novel ocean-based measures seems advisable, given the various arguments in favor of CDR presented in Section 5.1, and the increasing urgency in addressing climate change.

The next two sections will sequentially discuss a policy assessment based on current market prices and future promises in the nationally determined contributions pledged alongside the Paris Accord.

5.3 Market Price Perspective

As discussed at the end of the previous section, there is a tension between the social value of CDR and the current actions and prices reflected across countries. We will now analyze this in more detail and translate it into the potential for ocean NETs deployment based on current market observations. Based on data from the **?** and European Commission (2024), we find the 2022 carbon price distribution depicted in Figure 1a. All countries only cover part of their emissions with a carbon price, and several countries have multiple pricing systems, including both taxes and cap-and-trade systems. The price we calculate for these countries is the emissions-weighted average price of one ton of CO_2 released by the corresponding country.

Figure 1a shows that prices vary widely across countries, but the average price of carbon lies far below the social benefits of carbon sequestration discussed in the preceding section, even in the countries with the highest carbon prices. The countries with the highest average carbon price in 2022 are Finland, followed by Germany, Estonia, and Switzerland. These all have carbon prices of (almost) \$40tCO_2 and above. Conditional on having a positive carbon price, the mean carbon price around the world is \$17.6 (which is close to the median of \$16.9). However, the standard deviation of \$13 is substantial and the 90% variation stretches all the way from 50 cents to \$43 (5^{th} and 95^{th} percentiles). Most importantly, by 2022, only 43 countries have policy instruments in place that put a positive price on carbon.



(a) Distribution of Positive Carbon Prices in 2022. This histogram illustrates the distribution of carbon prices for the year 2022 across different countries in steps of \$2. Most countries only cover parts of their emissions using carbon pricing. The histogram translates these prices into the average price of total CO_2 emissions.

(b) Price Distribution for 2022 and 2024. This histogram illustrates the distribution of carbon prices for the years 2022 and 2024 across different carbon pricing initiatives in steps of \$5. The 2022 prices are shown in blue, while the 2024 prices are shown in light orange.

Figure 1: Carbon Price Distributions

Let us, for the moment, interpret current prices as the current willingness to pay for emission reductions and CDR. Based on the prices represented in Figure 1a, the scope for CDR is limited. The CDR measure that would be considered in all countries is soil carbon sequestration, which, in some estimates, even promises negative costs due to the co-benefits. In most of the countries with positive prices, some amount of afforestation and reforestation, as well as coastal restoration projects, are still within their willingness to pay expressed by prevailing carbon prices. If we go with a low to medium estimate for the cost of ocean fertilization of \$25 and neglect potential risks (and co-benefits) then, apart from the four “high price” countries listed above, also Poland, Bulgaria, the Netherlands, the UK, Greece, Slovenia, Iceland, and France would find ocean fertilization a CDR method worth deploying. Neither the costs for OAE nor for marine permaculture would meet current average prices in even the countries with the highest average carbon price. At the high-cost estimate of \$50, also ocean fertilization would no longer compete.

A clear sign that the current average prices in a country might not reflect their willingness to pay appropriately is the large price heterogeneity even within countries. Some emissions are free and others are priced far higher than the average price suggests. In 2022, the 63 pricing initiatives listed by the **?** had an average price of \$31 per tCO_2 (median \$23.5) with a standard deviation of \$33. Three initiatives had prices above \$100 (all taxes), nine initiatives prices above \$50, and thirty initiatives had prices above \$25. Interestingly, the only coastal country with an initiative pricing CO_2 above \$100 is Uruguay, with a CO_2 tax of \$137 covering some emissions. However, if we let the market prices guide us further, all of these price statistics have notably increased from 2022 to 2024 already. For 2024, the **?**

lists 72 initiatives with a price mean of \$36 (median of \$24 and a standard deviation of \$36). Now 5 initiatives have prices above \$100, twenty-one initiatives have prices above \$50, and thirty-six initiatives have prices above \$25.

Taking a close look at the European Emissions Trading System (ETS), the carbon price has actually exceeded \$100 (and 100 EUR) at times during 2023, but prices have dropped again substantially since. To get a feel for potential developments of future carbon prices in the EU ETS, Rickels, Rischer, Schenuit and Peterson (2023) simulate various economic and political scenarios. They find that CO_2 prices around 300 EUR/tCO_2 could likely emerge in the EU ETS2 by 2030. This is due to the higher abatement costs in sectors such as road transport and buildings, which are included in the EU ETS2, and the system's design to support national targets set under the Effort Sharing Regulation (ESR).

In their "EU ETS2 scenario" and "ESR-ETS scenario," modeled in the DART framework, the authors project CO_2 prices of 297 EUR/tCO_2 and 307 EUR/tCO_2, respectively. These projections are based on the economic and policy conditions anticipated by 2030 and the EU's ambitious climate targets. As the supply of allowances is gradually reduced and demand from high-cost sectors increases, prices are likely to rise, as projected by the DART model simulations (Rickels, Rischer, Schenuit and Peterson, 2023). In these high-cost scenarios, the EU ETS emission prices would align with the benefit-cost driven policy scenario of Section 5.2, making ocean-based CDR measures relevant again.

Finally, we have to acknowledge that market prices and price signals, in general, are only one measure of the willingness to fight climate change and only related to one of the instruments discussed in Section 4.1. The recently passed Inflation Reduction Act in US is likely one of the biggest policy packages to fight climate change. However, due to political considerations, two-thirds of its volume comprises subsidies provided as tax credits and no direct carbon pricing. Bistline et al. (2023) estimate the Inflation Reduction Act's total subsidy expenditure on the green transition as amounting to about \$392 billion and the EU's Green New Deal promises over 500 billion EUR merely from the EU budget (European Commission, 2020). These numbers confirm that the willingness to commit to future action is clearly increasing, just as market prices and the social benefits of reducing greenhouse gases in the atmosphere. The next section will specifically analyze future commitment to emissions reduction and the role of CDR in nationally determined contributions alongside the Paris Accord.

5.4 Paris Agreement and Nationally Determined Contributions

We argued that we are likely in a world with insufficient present action but a stronger commitment to future action. Therefore, we will evaluate the role of CDR measures under the assumption that countries will comply with their Nationally Determined Contributions (NDCs) agreed upon as part of the Paris Agreement. For this purpose, the present Ocean-NETs study by Siebert et al. (2023) employs the Dynamic Applied Regional Trade (DART) model to assess the abatement costs and quantitative requirements for CDR under the NDCs. We connect these results with a tentative exploration of meeting these CDR needs through marine permaculture. We chose marine permaculture due to its lower risk and higher public acceptance compared to Ocean Alkalinity Enhancement (OAE) (see Section 5.5), and the strict limitations on ocean fertilization imposed by the London Protocol (IMO, 2013). The indispensable inclusion of atmospheric CDR as a critical component of comprehensive climate policy is underscored by IPCC (2022*b*). This analysis aims to provide a clearer understanding of the economic and environmental implications of implementing marine permaculture as a substantial part of the required by international commitments.

Siebert et al. (2023) establish a demand for CDR by employing the computable general equilibrium model DART to simulate the economic impacts of climate policies. The DART model integrates data on emissions, abatement costs, and economic activities across different regions. By inputting the NDCs submitted by countries under the Paris Agreement, the model projects the future emissions reductions required by each region to meet their climate targets. The model then calculates the marginal abatement costs associated with these reductions, considering both conventional emissions reduction measures and CDR technologies.

Using this framework, the study generates demand curves for CDR by evaluating how much CO_2 each region needs to remove to comply with their NDCs under different cost scenarios. The demand for CDR is derived by comparing the costs of achieving the necessary emissions reductions with and without the inclusion of CDR. The model simulates various unit costs for CDR (\$50/tCO_2, \$100/tCO_2, and \$150/tCO_2) and assesses the cost-effectiveness of incorporating CDR into the regions' climate strategies. This approach determines the additional amount of CO_2 removal required to meet the NDCs, given the projected abatement costs and emissions. The resulting demand for CDR reflects the economic trade-offs between traditional emissions reduction methods and the adoption of CDR technologies across different regions, highlighting the role of CDR in achieving global climate goals.

Examining both the case with and without international emissions trading is crucial to understanding the full spectrum of potential demand for CDR. International emissions trading allows regions to buy and sell emissions reduction credits, lowering the overall cost of meeting climate targets by leveraging cost-effective reductions available in other regions. However, focusing on the case without trade is particularly important because it highlights the self-sufficiency required for each region to meet its NDCs independently. This scenario provides a clearer picture of the intrinsic demand for CDR within each region, emphasizing the necessity for local investment in CDR technologies and infrastructure when external trading options are not available. This scenario aligns more closely with current global policy, which often features differential pricing and fragmented markets rather than a unified trading system.

The study finds that the demand for CDR varies significantly across different regions and cost scenarios, as highlighted in Table 1. One of the main findings is that the demand for CDR is highly sensitive to the unit cost of removal. At a lower cost of \$50 per tCO_2, regions such as the EU29 and the United States exhibit substantial demand for CDR, with mean values of 333 MtCO_2 and 252 MtCO_2, respectively. However, as the cost increases to \$150 per tCO_2, the demand significantly decreases, indicating that high costs may deter regions from investing in CDR technologies. Additionally, the study underscores the variability in demand across regions, with some, like Brazil and Canada, showing consistently high demand across all cost scenarios, while others, such as South Korea and Australia/NZ, have negligible demand at higher costs. The findings also illustrate that without international emissions trading, regions must rely on local CDR measures to meet their NDCs, emphasizing the need for cost-effective and region-specific CDR strategies to achieve climate goals.

To understand how these CDR demands could be met, the study further analyzes the potential of blue carbon solutions, specifically through macroalgae cultivation and harvesting. For this purpose, it utilizes simulations employing the University of Victoria Earth

Country/Region	Unit cost 50 USD/tCO_2 Mean (Std) MtCO_2	Unit cost 100 USD/tCO_2 Mean (Std) MtCO_2	Unit cost 150 USD/tCO_2 Mean (Std) MtCO_2
EU29	333.10 (232.09)	79.41 (123.37)	0
United States	252.47 (286.31)	0	0
Japan	225.71 (118.69)	99.53 (94.15)	32.43 (52.99)
Brazil	143.11 (61.82)	91.46 (53.88)	56.53 (38.97)
Canada	123.06 (45.78)	61.39 (39.95)	20.73 (26.87)
South Korea	18.88 (46.24)	0	0
Australia/NZ	14.40 (22.38)	0	0
Great Britain + Ireland	1.10 (2.70)	0	0
Russia	0	0	0
China	0	0	0
India	0	0	0
Middle East	0	0	0
Other Asia	0	0	0
Other Americans	0	0	0
Africa	0	0	0
Rest of Europe	0	0	0
Sum	**1111.83 (398.11)**	**331.79 (169.07)**	**109.69 (10.90)**
With international emissions trading	0	0	0

Table 1: Average demand for CDR in dependence of CDR unit cost in the year 2030.

System Climate Model version 2.9, which was adapted to include a macroalgae component. This component, based on the Nearshore Macroalgae Aquaculture for Carbon Sequestration framework, simulates the growth of macroalgae under various limiting factors such as nutrient availability, light, and temperature. Macroalgae farms were assumed to be deployed along coastlines between 60°S and 60°N, with grid boxes extending up to 200 nautical miles from sovereign state coasts. The cultivation was modeled to begin in 2020, and the cumulative yield over time was converted into potential carbon sequestration values (in tons CO_2 per km^2) for different regions by the fifth deployment year, assumed to be 2025. These values were then assigned to the Exclusive Economic Zones (EEZs) of respective countries.

Figure 2 illustrates the regional variation in the potential supply of CDR via macroalgae cultivation and harvesting, depicting the carbon sequestration yields in metric tons of CO_2 per square kilometer. The results highlight significant regional disparities in carbon sequestration efficiency, driven by local environmental conditions such as nutrient availability, water temperature, and solar radiation. The data reveal that while some regions, like the coastal waters of Asia and Africa, show high potential for macroalgae-based CDR, others are limited by lower natural productivity or existing infrastructure constraints. Additionally, the figure underscores the necessity for far-sighted climate policies that incentivize the development of marine CDR methods in regions with high sequestration potential to meet future CDR demand effectively.

Table 2 connects these results to the surface area of macroalgae cultivation required to fulfill the demand in the three different cost-demand scenarios under the NDCs, for each the short run (or immediate) deployment or the build-up over 5 years. It details the percentage of a country's Exclusive Economic Zone (EEZ) that would need to be allocated to macroalgae cultivation to fulfill the regional CDR demand identified in Table 1. This analysis considers two different timeframes for deployment: a short-term strategy starting in 2030 and a far-sighted strategy starting in 2025. The findings from Table 2 provide a comprehensive view

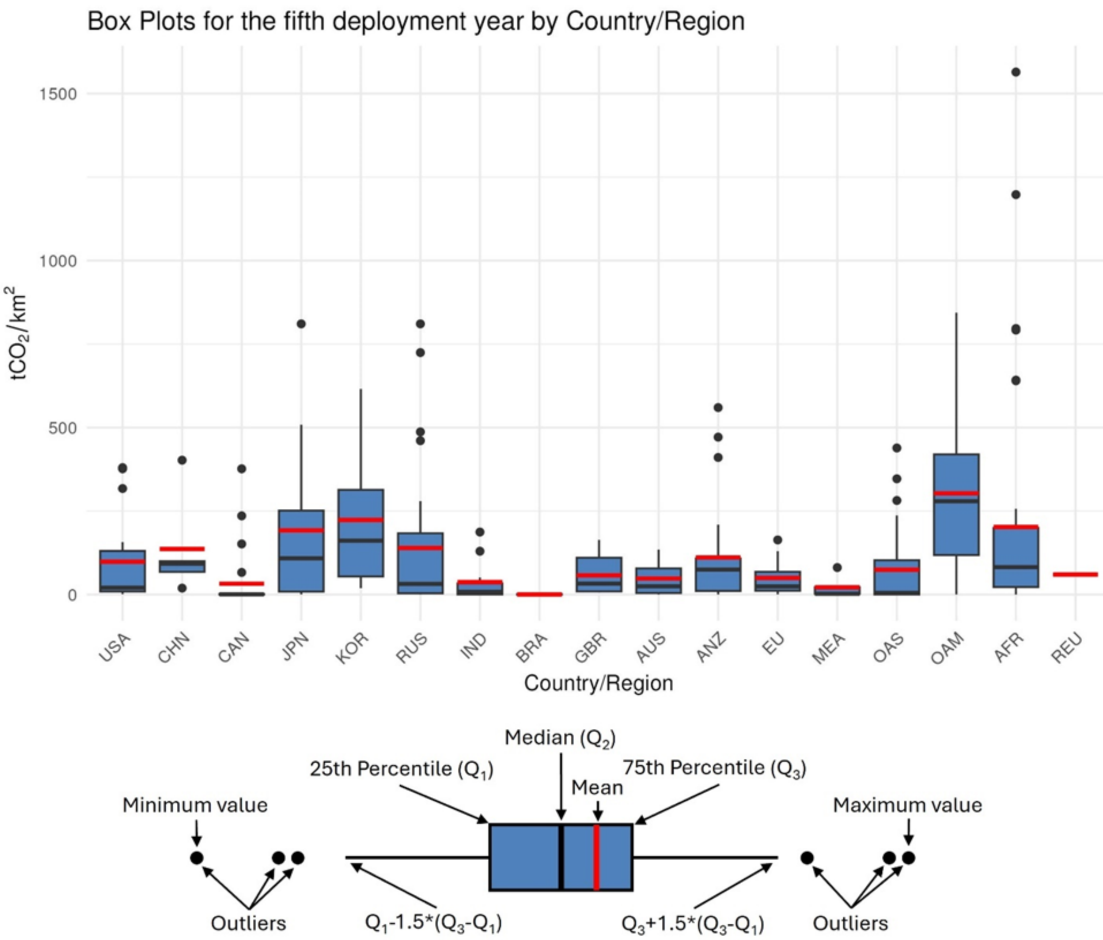


Figure 2: Regional Variation in potential CDR supply via macroalgae cultivation and supply. Regional variation in potential CDR supply via macroalgae cultivation and supply. Box plots representing the carbon sequestration yields of nearshore macroalgae aquaculture in metric tons of CO_2 per square kilometer (tCO_2/km^2) for different countries and regions. The CDR capacity is given by the carbon contained and securely stored within the harvested macroalgae biomass. The yields are aligned with the Exclusive Economic Zones (EEZs) extending to 200 nautical miles from the coasts of sovereign states. The data is derived from the University of Victoria Earth System Climate Model version 2.9 and pertains to the fifth year of macroalgae cultivation deployment, where each data point corresponds to a pixel of horizontal resolution, measuring 3.6° longitude by 1.8° latitude.

of the spatial and temporal requirements for macroalgae-based blue carbon solutions, highlighting the feasibility and challenges of relying solely on this method to meet the substantial CDR demand projected for 2030.

Country/Region	**Unit cost 50 USD/tCO$_2$**		**Unit cost 100 USD/tCO$_2$**		**Unit cost 150 USD/tCO$_2$**	
	short (1 y)	**far (5 y)**	**short (1 y)**	**far (5 y)**	**short (1 y)**	**far (5 y)**
EU29	>100	68.46	94.41	16.32	0	0
United States	>100	21.97	0	0	0	0
Japan	>100	22.07	55.21	9.73	17.99	0
Brazil	>100	>100	>100	>100	>100	3.17
Canada	>100	>100	>100	>100	>100	>100
South Korea	71.71	13.98	0	0	0	>100
Australia/NZ	28.92	1.21	0	0	0	0
Great Britain + Ireland	4.71	0.85	0	0	0	0
Russia	0	0	0	0	0	0
China	0	0	0	0	0	0
India	0	0	0	0	0	0
Middle East	0	0	0	0	0	0
Other Asia	0	0	0	0	0	0
Other Americans	0	0	0	0	0	0
Africa	0	0	0	0	0	0
Rest of Europe	0	0	0	0	0	0

Table 2: Average area of EEZ required for macroalgae harvest and cultivation to meet CDR demand in the year 2030.

Specifically, the columns labeled *short (1y)* represent a short-sighted strategy where macroalgae cultivation and harvesting are considered to start in the year 2030, and the harvest rates of the first deployment year are used to determine the CDR supply. This scenario reflects a situation where there is little to no advance planning or preparation, and macroalgae cultivation begins immediately when the demand for CDR arises. In contrast, *far (5y)* represents a far-sighted strategy where macroalgae cultivation is assumed to start earlier, in the year 2025, allowing for a five-year lead time. The harvest rates of the fifth deployment year are used to determine the CDR supply. This scenario reflects a situation where there is advance planning and preparation, resulting in more mature and potentially more efficient macroalgae cultivation and harvesting operations by the time CDR demand peaks in 2030.

The different numbers in the columns under *short (1y)* and *far (5y)* represent the percentage of a country's Exclusive Economic Zone (EEZ) required to meet the national CDR demand using macroalgae cultivation and harvesting. For *short (1y)*, the percentages are typically higher because the efficiency of carbon sequestration is lower in the first year of deployment. The short-sighted strategy reflects a rushed or immediate response without allowing time for the cultivation system to reach optimal efficiency. In contrast, the *far (5y)* strategy, with a five-year lead time, generally shows lower percentages, indicating that less of the EEZ is required due to improved efficiency. This demonstrates the significant impact of planning and lead time on the effectiveness of macroalgae cultivation for CDR.

For example, in the case of the EU (United States), the *short (1y)* strategy would require more than 100% of the EEZ, indicating that even if the entire EEZ were utilized, it would not suffice to meet the national CDR demand. However, with the *far (5y)* strategy, only 68% (21.97% for the United States) of the EEZ would be needed, reflecting the higher efficiency and effectiveness achieved through early and proactive planning also emphasized by **?**.

These insights underscore the importance of adopting a far-sighted approach to marine CDR methods to optimize their contribution to national and global carbon sequestration goals.

5.5 Public Perception

Public perception plays a crucial role in the acceptance and deployment of CDR technologies. Public perception is important for any climate policy, as we have learned from recent protests and polarization over climate policies, which highlight how public opposition can hinder policy implementation and lead to significant political challenges. Ocean NETs might not directly affect distributional concerns to the same extent as other climate policies like fees and taxes, but they directly affect the natural environment and the public generally has strong opinions on altering the natural environment. Therefore, the political feasibility of Ocean NETs will crucially depend on public perception and acceptance of these technologies.

As Working Package 3 found in their surveys, the public is generally skeptical about more technical approaches like OAE and ocean fertilization (Merk et al., 2023). Concerns include the feasibility of scaling these technologies, their long-term impacts, and the potential for unforeseen ecological consequences. By contrast, blue carbon management enjoys higher public support as it is often considered a restoration of natural ecosystems. This method is perceived to have co-benefits for biodiversity and coastal protection, making it a more attractive option for stakeholders and policymakers.

Working Package 5 did not identify significant negative environmental impacts of OAE, but clearly, more research is needed to ensure safe deployment. Plans to deploy OAE or ocean fertilization must engage with communities, provide transparent information, and address public concerns through rigorous research and pilot projects. These steps would have to overcome significant concerns about the deployment of ocean fertilization and OAE, primarily due to their potential negative environmental impacts and the complexity of controlling such interventions. Building public trust requires transparent communication about the benefits and risks of Ocean NETs. Policymakers should involve stakeholders in decision-making processes and ensure that the deployment of these technologies is accompanied by stringent monitoring and regulation.

It stands to reason that aligning Ocean NET strategies with public preferences can enhance their acceptance and effectiveness. Emphasizing natural and less intrusive methods like blue carbon management is likely to facilitate broader support for CDR initiatives. For OAE, a preferential focus on blue carbon methods, such as marine permaculture, aligns with our economic evaluation. Although ocean fertilization may be one of the cheapest scalable options for ocean-based NETs, the environmental risks and their public perception do not support deployment in the near future. Instead, they support prioritizing further research to explore its safety.

6 Conclusion

The analysis and discussions presented in this report lead us to a nuanced conclusion regarding the potential and role of ocean NETs in various climate policy scenarios. If a globally uniform carbon price aligned with current NDCs is implemented, the role for CDR would likely limited to a few $GtCO_2$ annually, which could be cost-effectively managed by land-based measures for a considerable period. These NDCs are not in line with the more stringent Paris Accord's temperature targets.

Yet, the global landscape is far from homogeneous regarding commitments to net-zero emissions and adherence to the Paris Accord's temperature targets. We currently observe significant disparities in carbon pricing and commitment levels, with many regions lacking decarbonization incentives anywhere close to the globally socially efficient level. Meanwhile, there is a clear willingness for more serious future commitments in many of the wealthier regions, including and perhaps particularly within the EU.

If regions such as the EU focus solely on addressing their emissions and, for this purpose, borrow from the global CDR potential, land-based CDR methods can deliver the necessary scope at affordable prices. However, if these regions take on a responsible leadership role, they must contemplate the following possibility: the high carbon prices prevailing in affluent regions are largely infeasible to implement in developing countries without significant repercussions on consumer welfare. These repercussions cannot be easily mitigated by financial transfers, even if such willingness for transfers existed in the wealthier parts of the world. Consequently, the EU might need to either compensate for more than its emissions or assist in reducing global CO_2 concentrations beyond its emissions.

In the absence of high carbon prices in developing countries, CDR emerges as a major, and potentially optimal, opportunity. While high abatement costs could depress the local economy and reduce consumer welfare, cooperative efforts on novel ocean-based CDR methods can offer a contrasting benefit by creating new job opportunities. This collaborative approach not only contributes to global CDR efforts but also supports economic development in these regions. Such a strategy necessitates a broader scope of CDR than what established coastal restoration and land-based measures can provide. Ocean-based CDR, particularly novel methods like Ocean Alkalinity Enhancement (OAE) and marine permaculture, should form a significant part of the CDR portfolio. Compared to Direct Air Capture (DAC), which is the only other method that could promise a comparable volume, these ocean-based methods are more cost-competitive and hold the necessary promise for scalability.

Among the novel ocean-based CDR methods, marine permaculture, particularly macroalgae cultivation, stands out as particularly promising. It not only sequesters carbon but also enhances marine biodiversity and offers economic benefits through aquaculture integration. Our simulation studies underscore the significant potential of marine permaculture to meet NDCs, especially in regions with high abatement costs and ambitious emission reduction targets. This potential would be even more efficiently realized if deployment linked the targets of wealthy nations with the CDR potential in the developing world. However, effective implementation requires far-sighted climate policies to incentivize these methods. Investment in pilot projects is crucial for better cost estimation and evaluation of environmental co-benefits and risks. Early deployment subsidies and a comprehensive portfolio of R&D are essential to advance these technologies.

If we foresee a scenario where significant CDR is needed beyond what land-based measures can provide, we should commit today to seriously exploring ocean-based NETs. This commitment should manifest in supporting pilot projects at increasing scales, with careful environmental monitoring. These projects are critical to understanding actual costs, co-benefits, and risks, and to building public trust in the technologies' efficiency and safety, thereby helping to make them politically viable. As these projects scale up, observing cost trends over time will provide valuable insights into the actual cost declines through learning by doing, even though true economies of scale might only become apparent with large-scale deployment.

Effective integration of CDR methods into cap and trade markets, conditional on robust monitoring, can be an important step for ensuring economic efficiency.[5] Ocean-based NETs have an inherent advantage due to their generally permanent sequestration, reducing the need for verifying ongoing storage as might be required for many land-based methods. Integrating CDR into emissions trading systems, such as the EU ETS, and organizing more effective Voluntary Carbon Markets can pose crucial steps towards signaling commitment to supporting CDR in general, and fostering ocean-based methods in particular. A comprehensive portfolio of research, development, and early deployment subsidies, coupled with strict mandates for environmental risk evaluations, is necessary. This is especially true for methods like OAE, ocean fertilization, and potential artificial upwelling projects. Among the novel ocean-based projects, marine permaculture appears the most timely for early deployment due to its manageable environmental risks, potential for cost decline, and higher public acceptance.

Finally, continuous assessment of CDR projects is essential to verify that carbon sequestration occurs as planned and that the methods used are effective and sustainable. Robust monitoring, reporting, and verification systems are vital for ensuring the integrity, longevity, and credibility of CDR projects. By committing to these strategies now, we can pave the way for scalable, efficient, and politically feasible ocean-based CDR solutions that contribute significantly to global climate mitigation efforts.

In conclusion, ocean-based NETs can play a significant role in achieving a sustainable and resilient future. By committing to strategic investments, robust monitoring systems, and international cooperation, these technologies can substantially contribute to global climate mitigation efforts. The EU and other affluent regions should consider leading by example, taking bold steps to integrate and support ocean-based CDR, ensuring that they not only address their emissions but also contribute to global efforts to mitigate climate change effectively. Achieving these ambitious goals will require coordinated efforts, significant investment in research and pilot projects, and a willingness to adapt policies based on emerging scientific and economic insights. With the right commitment and leadership, ocean-based NETs have the potential to become a cornerstone of global climate strategy, especially in the case when theoretically efficient more homogenous abatement trajectories fail to meet the urgent challenge of reducing atmospheric CO_2 concentrations and limiting global warming to safe levels.

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[5] In the longer-run future, if CDR in a regional market might dominate emissions, the government would have to step in as an additional buyer of certificates paying for global CO_2 reductions.

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