NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Literature assessment of ocean-based NETPs regarding potentials, impacts and trade-offs

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Executive Summary

Negative emissions technologies and practices (NETPs) play a significant role in the mitigation pathways projected by the IPCC to limit global warming to 1.5 °C. Marine Carbon Dioxide Removal (CDR) strategies such kelp farming and ocean alkalinization can enhance the ocean's CO_2 sequestration potential.

Ocean-based NETPs include such as enhancement of kelp forests (wild and cultivated) complementing current actionable 'blue carbon' ecosystems (seagrasses, saltmarshes, and mangroves). Their impacts on biodiversity and ecosystem services have been reviewed and assessed in the present NEGEM Deliverable.

In addition, artificial ocean alkalinisation (AOA) and their impacts on ocean biogeochemistry (including acidification) and on pelagic and deep ocean ecosystems have been assessed, based on literature review. Likely or possible marine ecological impacts of subsea CO_2 storage was also summarised, as CCS is component of some NETPs like BECCS.

Several marine NETPs hold a potential to draw down large amounts of CO_2 from the atmosphere to the ocean in the context of CDR. However, none of the key technologies like blue carbon and ocean alkalinization have been tested and proven to work on a large scale.

It is still expected that marine NETPs will have negative environmental consequences, even if they help to mitigate climate change, avoiding possible detrimental ecosystem effects. These consequences may be minor or significant, depending on the type on NETP, and the location and scale.

Weighing the impact on reducing climate change by the NETPs against their negative environmental effects is not within the scope of NEGEM but may be pursued in follow-up studies.

Numerical modelling is the best tool available to assess the scale of the consequences of marine NETPs under various scenarios. Experimental work in-situ like in mesocosms can help to improve parametrization of geo-biochemical processes. Both approaches should be focused on in follow-up studies, to help improve the precision of predictions by models.

Other technologies like conventional CCS that are relevant for NETPs as well, are being heavily investigated already with several industry-scale pilot projects on-going, and more to come. In the framework of NETPs, these may therefore not require particular attention, as consequences are dealt with elsewhere like under the IEA-GHG programme.

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1 Introduction

Carbon dioxide removal (CDR), alternatively phrased as Negative Emissions Technologies and Practices (NETPs), are treated in the NEGEM project. NETPs constitute a supplement to another mitigation technology, carbon dioxide capture and storage (CCS). The CO_2 from biomass processing can be captured and securely stored underground in geological formations. As such, in BECCS or Bio-CCS, the emissions from produced biofuel will be characterised as net negative because of the storage of biogenic CO_2.

Some NETPs like Bio-CCS actually rely on CCS, while most stand alone, without CCS required. According to the IEA-GHGT (IEA 2022) the highest CO_2 removals are achieved in NETP pathways that maximize the capture of CO_2, have low energy conversion efficiencies, or have access to low-carbon energy.

In the present task 3.1.3 we have treated selected marine NETPs as the (CDR) strategies aiming to maximize the long-term storage of carbon in the ocean or on/in the seabed. Marine NETPs can be divided into nature-based methods, and engineered methods. The former usually causes less controversy than the latter, that, wrong or right, tends to fall under the term “geoengineering”. Marine geoengineering options are calling for marine geoengineering governance (Brent, 2019).

The objective of this study is to assess the sustainability performance of marine NETPs with emphasis on environmental impact. The present understanding of the environmental consequences of such technologies relies mostly on small-scale experiments and numerical modelling. Only a few large-scale experiments in the ocean have been performed, notably with iron fertilization.

As technologies being low on the TRL-scale and far from implementation, ocean NETPs are generally not prohibited under international law. However, despite this general legality, individual technologies may prove to be incompatible with the requirements arising from relevant international agreements or customary international law, depending on the specific activity in question. Any examination of the negative environmental consequences of a particular ocean NETP, therefore, has to account for whether the activity in question itself is legal or illegal. In this context, it must be highlighted that the realisation of environmental damage does not necessarily indicate an illegal activity (OceanNETs 2021a, p. 3).

In Deliverable 1.3 a selected subset of marine NETPs was described and identified in terms of KPIs, key Performance Indicators. Those were:

- Kelp farming and sinking. Macrocystis pyrifera is grown and subsequently sunk, thereby sequestering the CO_2 captured during the photosynthesis process in the deep ocean.
- Ocean liming. Calcium oxide (CaO) particles are added to the surface ocean and react with CO_2 to form bicarbonate ions.
- Coastal enhanced weathering. Olivine particles are spread over beach environments to promote the naturally occurring weathering reactions between CO_2 and silicate minerals.

The Specific Objective SO2 of NEGEM takes into the consideration of the sustainable potential of marine NETPs relative to Earth system feedbacks. This particular deliverable highlights the key environmental impacts of the selected technologies, based on available literature.

1.1 Scope of this Deliverable

From the NEGEM proposal, Subtask 3.1.3:

> Assessments of global and selected regional impacts of ocean-based NETPs on marine biogeochemistry and fisheries will be produced. Ocean-based NETPs include analyses of enhancement of kelp forests (wild and cultivated) complementing current actionable 'blue carbon' ecosystems (seagrasses, saltmarshes and mangroves) and their impacts on biodiversity and ecosystem services. In addition, ocean fertilization (iron, other limiting nutrients) and artificial ocean alkalinisation (AOA) and their impacts on ocean biogeochemistry (including acidification) and on pelagic and deep ocean ecosystems will be assessed. Lastly, marine ecological impacts of subsea CO_2 storage will be summarised.

1.2 Marine NETPs treated in WP1

Many technologies and practices can contribute to artificially sequestering CO_2 in the ocean. Figure 1 illustrates some of those. Most of them can be part of a NETP solution, although they were described as regular mitigation methods before the concept of NETPs was brought forward. Some NETPs have been tested, and some are still on the drawing table. Ocean Iron Fertilization that seems to be the only thoroughly investigated open ocean NET, has been met by public opposition, partly due to environmental concerns (Keller et al. 2021).

Table 1 lists the marine NETPs reviewed in NEGEM Task 1.1. As discussed in Deliverable 1.1 (Cobo et al. 2020), blue carbon and ocean alkalinization were selected for the present study.

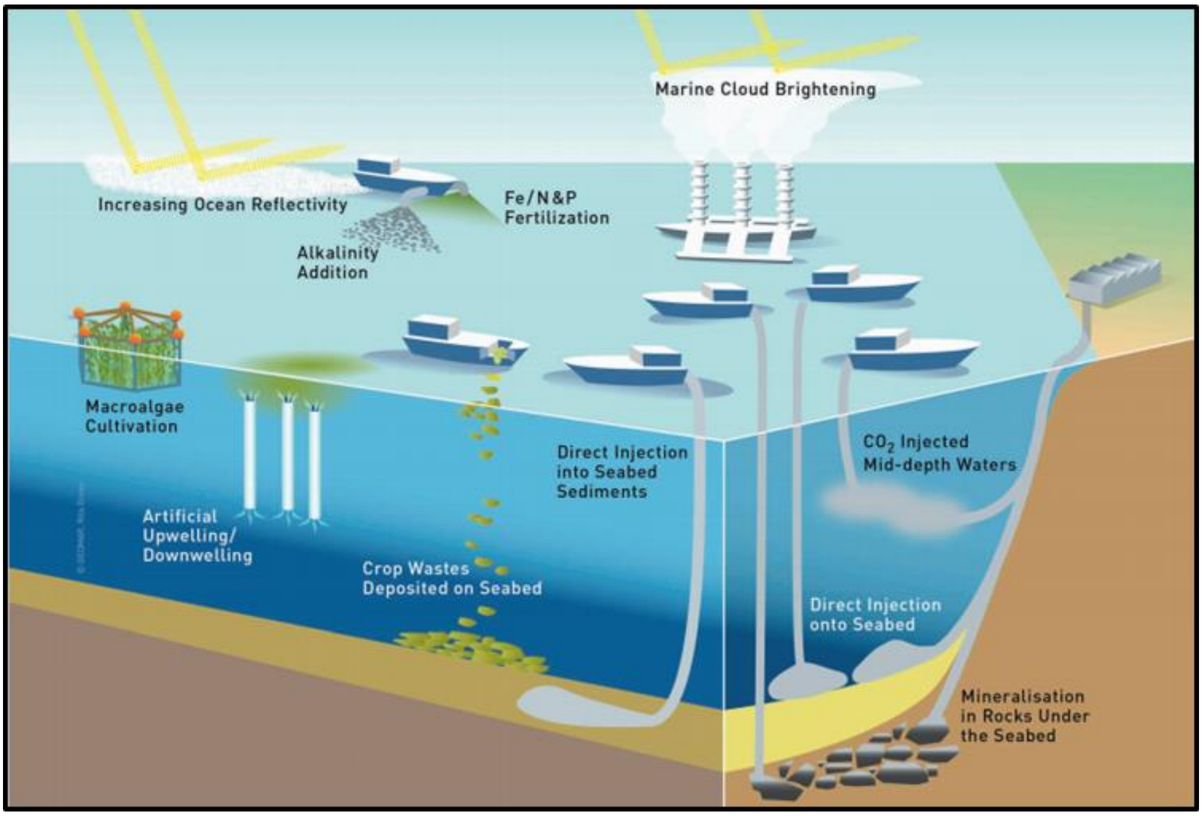


Figure 1. A sketch of some marine NETPs as envisaged by GESAMP (2019).

*Table 1. Overview of the marine NETPs considered in D1.1 according to their respective deployment potential score and the selected KPIs (high potential: green cells, intermediate potential: yellow cells). The NETPs in bold were chosen to be assessed in D1.*3 (Cobo et al. 2020).

	NETPs	TRL	Max CDR	Cost (2019€)	Score
			Gtonne/yr	€/tonne CO_2	[-3, 3]
MARINE	Downwelling	1-2[b]	0.035[a]	228-5142	-3
	Upwelling	1-3[b]	0.059[a]	n/a	-2
	Ocean fertilization (Fe)	1-4	3.6[8]	459	-2
	CO_2 extraction from seawater	2-3[b]	[c]	347-562	-1
	Ocean storage of terrestrial biomass	1-2[b]	6.75[d]	104	-1
	Ocean alkalinization	2-3[b]	8.43-12.15[e]	3-160	0
	Blue carbon	5-6	0.13-0.80[f]	9[f]	0
	Ocean fertilization (N and P)	2-3	5.5	21	1
	Direct injection[1*]	*1-2* [b]	*12.5*[g]	*14-19*	*1*
	Submarine storage in vessels[1*]	*1-2* [b]	[c]	*16*	*1*

[1*] Storage technology, integration with atmospheric CO_2 capture required to achieve negative emissions.

[2*] CO_2 capture technology, storage required to achieve negative emissions.

[a] 1 Mm^{3}·s^{-1} of seawater.

[b] Authors' assessment, based on the reviewed literature.

[c] Limited by resource use and scale-up rates.

[d] Crop residues.

[e] Assuming a constant CO_2 sequestration rate between 2020 and 2100.

[f] Wetland restoration.

[g] To limit the pH decrease to 0.1 units.

1.2.1 Blue carbon

Frigstad et al. (2020) describe how marine plants and algae take up inorganic carbon from the atmosphere and ocean through photosynthesis, and convert this carbon to biomass, thereby contributing to an oceanic carbon uptake from the atmosphere. The biological uptake of carbon in coastal vegetated systems (e.g., seagrass meadows, macroalgae forests, salt marshes, and mangroves) is referred to as coastal blue carbon.

How long this blue carbon remains in the oceans will vary; the carbon bound in marine biomass can have different fates after the organisms die. The carbon can be recycled in the water and a fraction can be released back to the atmosphere, while another fraction of the carbon may sediment on the seafloor (on coastal shelves or in the deep-sea sediments). A fraction of the carbon that settles on the seafloor (roughly estimated at 11%; Krause-Jensen and Duarte 2016) will escape the recycling process in the sediments and be sequestered (i.e., long-term storage of carbon) on climatically significant timescales (decades to centuries).

Ongoing research focuses on quantifying and understanding the capacity of coastal vegetated systems to act as permanent sinks of atmospheric carbon (McLeod et al. 2011, UNEP 2009, Fourqurean et al. 2012). Even small reductions in the global distribution of these habitats can have a negative impact on the natural sink capacity of these ecosystems.

Meanwhile, the potential regrowth or restoration of these habitats could increase their natural sink capacity, and thereby contribute to increasing the oceanic uptake of atmospheric carbon. Recognition of this ability has led to the development of strategies for climate change mitigation through the conservation and restoration of seagrass, saltmarsh, and mangrove habitats worldwide, termed coastal blue carbon strategies, and to the construction of blue carbon budgets for vegetated coastal habitats.

Recent research has demonstrated that kelp and macroalgae habitats can have significant carbon export (both particulate and dissolved organic carbon) to adjacent environments and that this organic material can be transported up to hundreds of kilometers where it eventually settles on the seafloor or is transported further to the deep sea. Here, a fraction is buried leading to blue carbon sequestration. (Krause-Jensen and Duarte 2016, Perrarrodona et al. 2018, Filbee-Dexter et al. 2019, Pedersen et al. 2019). However, scientific evidence is still lacking on how and to what extent macroalgae and other marine vegetated habitats contribute to carbon sequestration.

In addition to their role as natural carbon sinks, coastal vegetated habitats sustain biodiversity and provide a wide range of ecosystem services (Costanza et al. 2014, Spalding et al. 2014). Besides sustaining fisheries by providing nursery grounds for commercial fish, these habitats also have multiple benefits for humans through filtering water and pathogens, reducing eutrophication, and protecting against coastal erosion, thereby contributing to climate adaptation (Temmerman et al. 2013, Möller 2019).

There is also growing attention toward seaweed cultivation and its role in climate change. According to Duarte et al. (2017) seaweed aquaculture is the fastest-growing component of global food production and offers lots of opportunities to mitigate and adapt to climate change. Like natural blue carbon habitats, seaweed farms may act as CO_2 sinks, since they release carbon that may be buried in sediments or exported to the deep sea.

Blue carbon NETPs may also involve the conservation and restoration of coastal vegetated ecosystems, as they represent nature-based climate solutions with few costs and down-sides. For this reason, these methods are often mentioned as “no-regret solutions” beneficial to a range of sectors, such as fisheries, trade, environmental protection, and water management. However, life cycle analyses on these are still lacking.

1.2.2 Ocean alkalinization

Artificial ocean alkalinization aims to increase the pH of seawater to enhance the uptake of atmospheric CO_2 and transform it into other chemical compounds. The two most prominent alkalinization methods are (Cobo et al. 2020):

- Ocean liming or reactive mineral addition. Calcium oxide (CaO) particles, quick lime ($CA(OH)_2$) or reactive mineral particles like grinded olivine are added to the surface of the open ocean to react with CO_2 and form bicarbonate ions. Such mineral processes represent a massive acceleration of the natural chemical weathering processes.
- Coastal enhanced weathering. Olivine particles are spread over beach environments to promote the naturally occurring weathering reactions between CO_2 and silicate minerals.

Both methods rely on the addition of alkaline substances to the surface seawater, i.e., adding alkalinity, which will raise the pH in the seawater and increase the buffer capacity towards acidification. The pH of the ocean upper layer is already 0.1 units lower than that of the preindustrial level, due to the anthropogenic CO_2 emissions. Ocean alkalinization can help bring the pH level up or prevent it from getting lower.

The enhanced weathering reactions that occur as a result of adding a synthetic chemical, quick lime ($Ca(OH)_2$) and a mineral ($CaSiO_3$) to the ocean are:

$$Ca(OH)_2 + 2CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \quad (R1)$$

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2 \quad (R2)$$

The increase in alkalinity will lead to mineral carbonation reactions that produce solid carbonate minerals and release half of the previously captured CO_2:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \quad (R3)$$

The crushed minerals may contain some trace elements like iron and nutrients, which can lead to unintended algal blooms.

These approaches may need to capture annually on the order of Gtonne of atmospheric CO_2 to become significant climate mitigation strategies. This will entail handling mineral and Ca-streams on the same order of magnitude. Extracting, processing and transportation will come at a cost, both economically and environmentally.

1.2.3 Other NETPs with implications for the ocean

Besides the above mentioned NETPs, other technologies may have environmental implications as well. BECCS with capture and deep geological storage of CO_2 is one such technology.

Artificial upwelling seeks to stimulate primary production in marine environments by drawing nutrient-rich water from the deep water to near the surface. Accompanying enhanced phytoplankton production near-surface could lead to a drawdown of atmospheric CO_2 through the sinking of particulate organic carbon to the ocean floor, and sequestration for decades or centuries. In this respect, it resembles to some extent the kelp farming scenarios of Blue carbon.

Artificial upwelling might also produce co-benefits, including increases in fish production and cooling of coral reefs. Combining such upwelling (in large pipes) with OTEC, ocean thermal energy conversion, it can provide electricity from a renewable source and/or other commodities like potable water.

A large-scale deployment could optimistically yield benefits in terms of carbon uptake by the oceans, probably up to one gigaton annually (Oschlies et al. 2010). Due to the challenging engineering and environmental scale of this method, it was not selected for further study in NEGEM.

Direct air capture, DAC, also require long-term storage of the captured CO_2, likely as trapped in mineral form but may be also as gas stored in geological formations.

These may not be termed “ocean-based” NETPs in the usual context but may both involve ship- or seabed pipeline transport and sub-seabed storage of CO_2. We will also deal briefly with these aspects.

2 Climate change and the role of the ocean

The projected impacts of global warming on marine ecosystems are shown in Figure 2. Today's impacts on warm water corals are likely to be irreversible, while other systems, such as mangrove forests, show a higher degree of resilience.

It is important to assess whether the potential negative impacts of NETPs further reinforce the detrimental impacts of climate change on the marine environment. The environmental and social impacts of NETPs need to be assessed and minimized before they are deployed at large scale. Developing and implementing NETPs will require huge contributions from many STEM disciplines and society in general. Environmentally sustainable NETPs are those that will contribute to operating safely within the Earth's ecological limits.

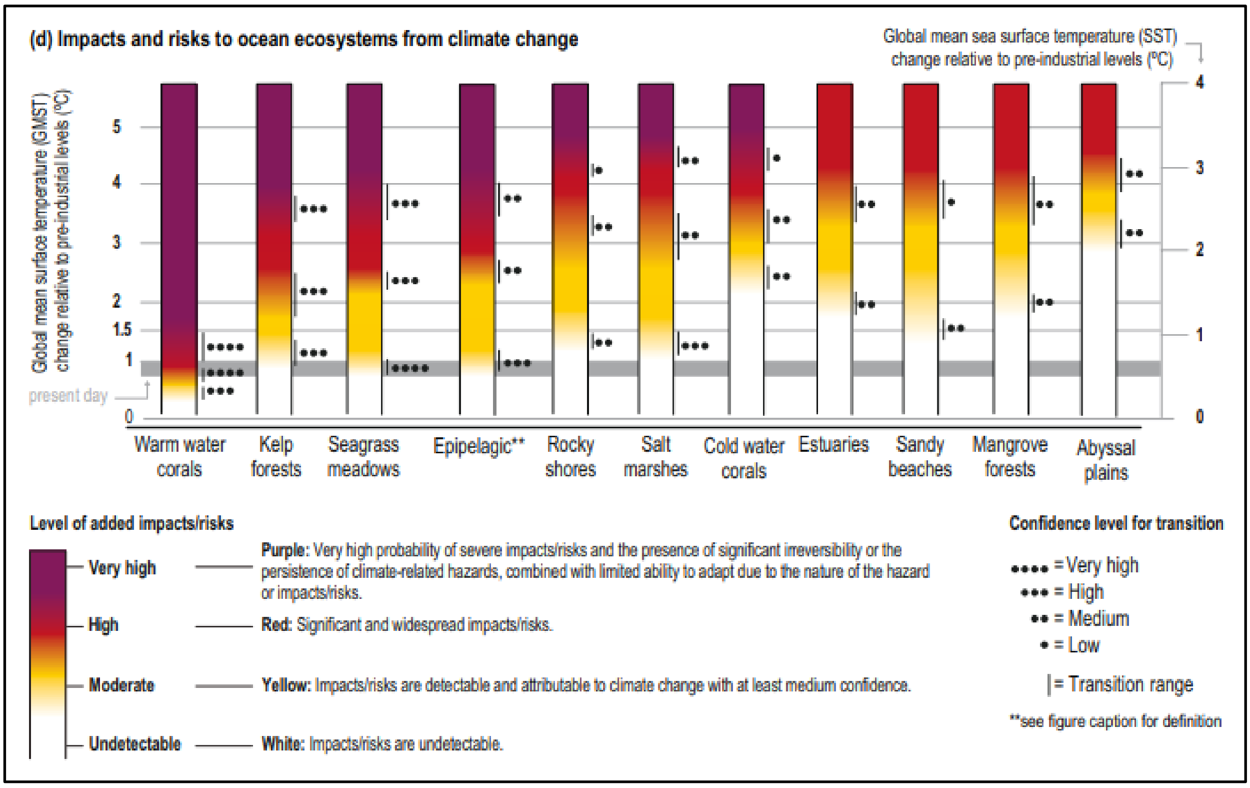


Figure 2. Assessment of risks for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. Impacts and risks are shown in relation to changes in Global Mean Surface Temperature (GMST) relative to pre-industrial level. From IPCC Technical Summary (2019).

1.2 The ocean's capacity to store CO_2

The ocean is the largest natural carbon sink and holds about 88% of the Earth's surface carbon. About ¼ of the global emissions (present annual rate is about 9 Gtonne of C) will eventually be absorbed by the ocean through exchange with the atmosphere. Mineral weathering plays an important role in the long-term cycling and trapping of CO_2, allowing for more to enter from the atmosphere.

Presently, the ocean uptake of anthropogenic carbon is around 2.5 Gtonne/year of C, or about 23% of the annual anthropogenic carbon emissions (Middelburg et al. 2020). About 24% (166 Gtonne of C) of the total emissions since 1850 have ended up in the ocean (Friedlingstein et al. 2019).

Since the transport of this carbon down the water column proceeds slowly, excess CO_2 may accumulate in the upper layers of the ocean, resulting in changes to seawater chemistry and impacts on the marine life that resides in this zone. The ocean already contains around 38,000 Gtonne of dissolved carbon (equivalent to 140,000 Gtonne of CO_2), which is much more than the atmospheric inventory of around 700 Gtonne of C.

Theoretically the ocean could absorb many times the present quantity before reaching chemical saturation (at which point environmental impacts would be devastating). If the capacity of sediments to store CO_2 as calcite was added, even more CO_2 could be absorbed, but this process is slow and would take several thousand years to become significant (Broecker and Peng 1982).

The total known fossil fuel reserves contain about 7,000 Gtonne of C (recoverable reserves contain about 4,000 Gtonne of C). About 2,000 Gtonne CO_2 from fossil fuels may be absorbed by or sequestered in the ocean without inducing significant changes in the chemical balance of seawater (pH change < 0.1; IPCC 2005).

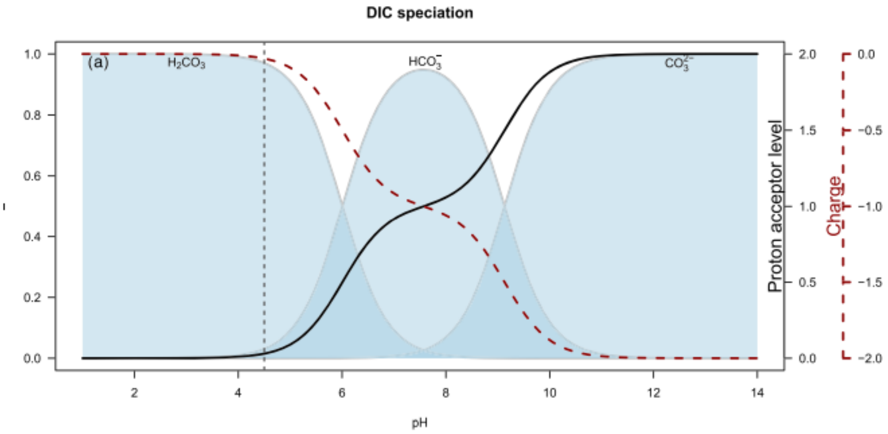


Figure 3. A Bjerrum diagram showing the distribution of carbonic acid, bicarbonate, and carbonate as a function of pH and the corresponding proton acceptor level (solid black line) and charge (red dashed line). From Middelburg et al. 2020.

In the normal pH-range of seawater, most of the inorganic carbon is present as bicarbonate, as shown in Figure 3. When CO_2 is added, it will be transformed into bicarbonate and to a lesser extent, carbonate. This illustrates the large buffer capacity of the ocean.

The large capacity of the ocean to sequester more CO_2 has led to many proposals to capture and subsequently sequester anthropogenic CO_2 in the deeper layers of the ocean as a means to reduce the greenhouse effect (Marchetti 1977, Rojelj et al. 2010). This could be achieved by direct injection of pure CO_2 gas (Reith et al. 2016) or indirectly by enhancing natural processes like the biological carbon pump to bring CO_2 to deeper layers, away from the atmosphere.

GESAMP (2019) lists 27 different approaches to marine sequestration. Figure 4 shows how ocean-based technologies fit into the CDR framework along with other CDR-technologies. Table 1 compiles the main characteristics of alternative sequestration options.

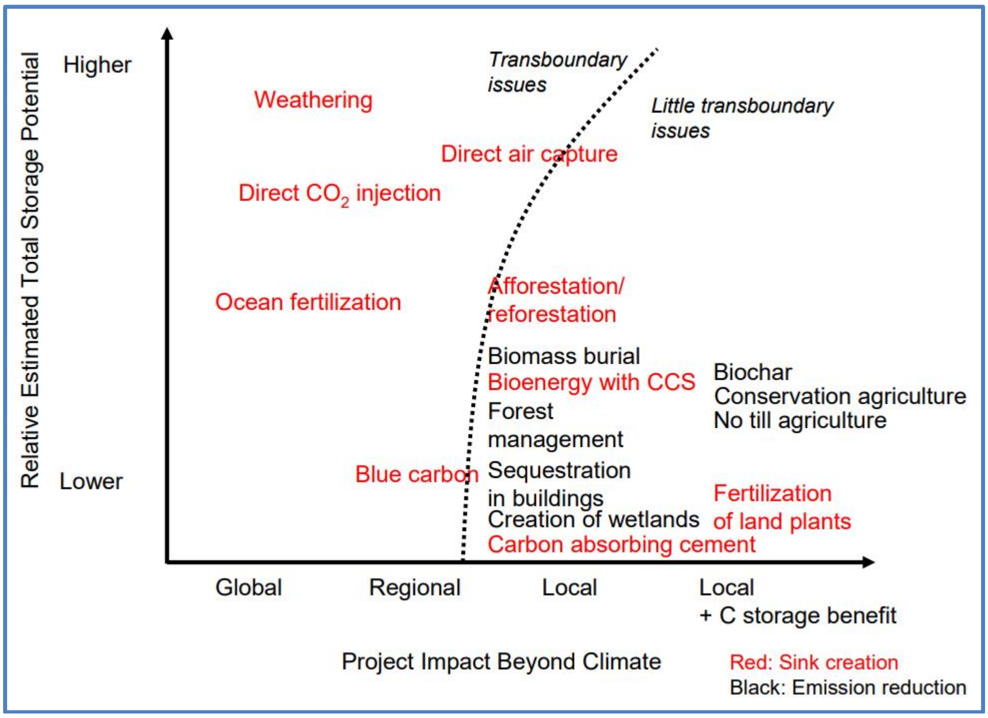


Figure 4. Relative estimated total storage potential for emission reduction and sink creation projects at different scales. From: IPCC Expert Meeting on Geoengineering, IPCC 2011).

3 Environmental impact reviews

This chapter contains a summary of key findings from literature regarding negative environmental impacts from each of the selected NETPs, with additional short comments on some alternative/emerging technologies and CCS. CDR technologies should in principle have a positive environmental impact, at least in total, as the positive ones outweigh any negative.

Removing CO_2 from the atmosphere and store it safely will help to ameliorate any on-gong og future negative impacts form climate change. However, introducing a technology with projected significant negative impact will be a hard sell, both regarding public acceptance and licensing and legislative permitting. Removing one negative impact by introducing another, looks for the moment like no viable scenario.

Predictions on environmental consequences naturally are predictions, or assumptions, as there is no experience from implementing industrial-scale CDR with carbon uptake in the ocean. None of the options studied here have moved beyond conceptual development and laboratory testing.

The present understanding is based on common scientific knowledge of geo-biochemical and physical processes in the Ocean, combined with results from a limited number of small-scale experiments and numerical modelling. Only a few experiments with iron fertilization in the ocean that may be termed medium/large-scale have been performed (GESAMP 2019).

Numerical modelling of impacts from ocean alkalinization can be derived from perturbation studies of coupled hydrodynamic and bio-geo-chemical models. Figure 5 shows an example of two modelled alkalinization scenarios with the accompanying scenarios for CO_2 emissions, reaching zero emissions in year 2350 CE and staying zero thereafter.

Simulation protocols have been established within the carbon dioxide removal model intercomparison project (CDRMIP), part of CMIP6 (Keller et al., 2018), with inter- model comparisons. These studies need to be accompanied by understanding of control simulations without alkalinization (Köhler, 2020). They primarily describe the broad mitigation effects on the CO_2 system and feedback on climate and not necessarily on any side-effects on certain parts of the ocean chemistry or ecosystem, such as nutrient cycling and microplankton.

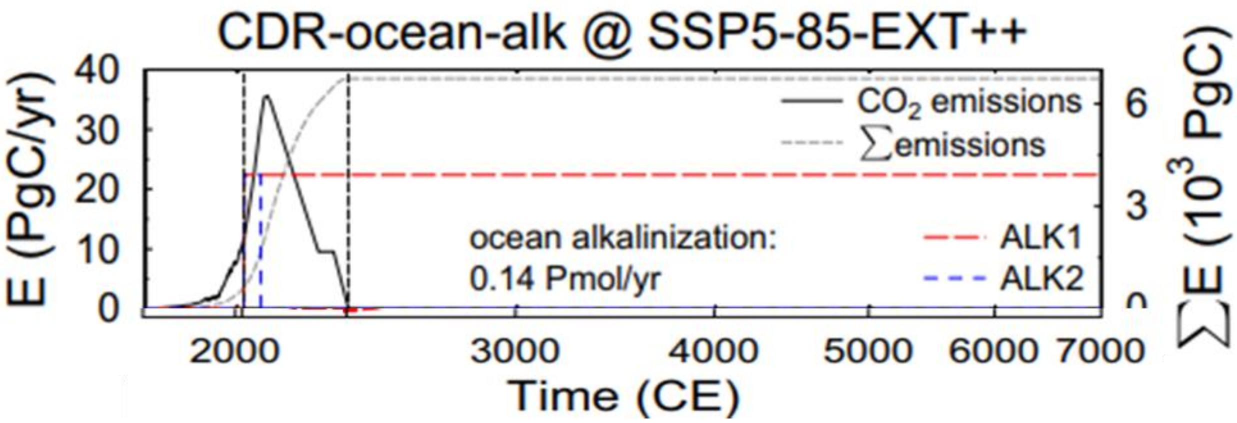


Figure 5. CO_2 emissions, (annual and cumulative emissions E, left and right y-axis. Timing of ocean alkalinization of 0.14 Pmol/yr in two scenarios ALK1 and ALK2 sketched in red and blues lines, respectively. Modified after Köhler, (2020). Time is in Common Era scale. The first vertical line (with ALK 1 starting) is at year 2020.

The literature seems to distinguish between “nature based” CDR methods, like Blue Carbon, and chemical methods, like iron fertilization and ocean alkalinization/enhanced weathering. The former does not necessarily imply any addition of chemicals or other material to the ocean, while the latter does.

3.1 Blue carbon habitats and farming

Blue Forests include coastal vegetated ecosystems such as mangroves, salt marshes, seagrass beds and kelp forests. These ecosystems are also called Blue Carbon Habitats because of their capacity to sequester and accumulate large stocks of carbon in their sediments at millenary time scales (Duarte et al. 2013).

Blue carbon habitats are suggested as a nature-based climate solution. Through ecosystem management and restoration of these habitats, carbon can be removed from the atmosphere and stored in their biomasses and sediments on the seafloor (Macreadie et al. 2021). Claes et al. (2022) consider three categories of blue-carbon solutions, classified by their scientific and economic maturity.

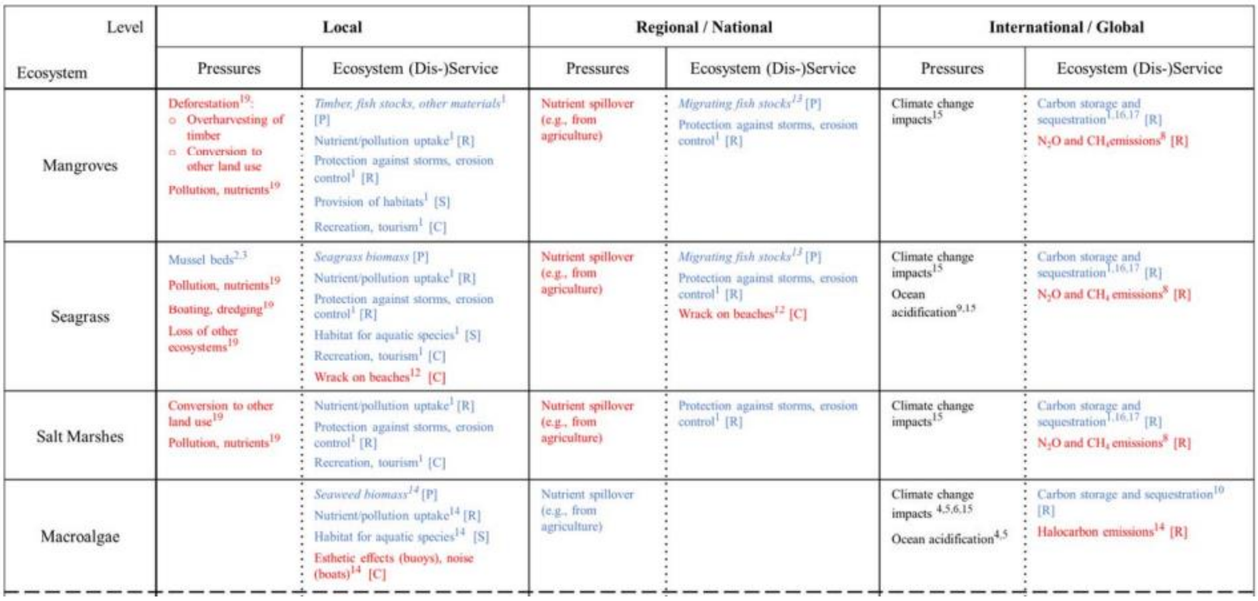
1) Established solutions of widely understood ecosystems, such as mangroves, salt marshes, and seagrass meadows,

2) Emerging solutions which includes the protection, restoration, and extension of seaweed forests (e.g., large-scale seaweed farming), and

3) Nascent solutions, potentially powerful solutions which focus on protecting and restoring marine fauna, from oysters to whales.

If fully implemented, the established solutions would abate 0.4 to 1.2 metric gigatons of carbon dioxide ($GtCO_2$) annually, which is 1-3 percent of total current annual CO_2 emissions. This increases to approximately 3 $GtCO_2$ of annual abatement (about 7 percent of total current annual CO_2 emissions) if the solutions in the emerging category were fully implemented. Nascent solutions that support rebuilding marine fauna might abate 1-2 $GtCO_2$ annually in the longer term, but these numbers are highly uncertain.

Table 2. Overview of services, disservices, and pressures for blue carbon ecosystems. From Merk et al. (2021).



Level Ecosystem	Local		Regional / National		International / Global	
	Pressures	Ecosystem (Dis-)Service	Pressures	Ecosystem (Dis-)Service	Pressures	Ecosystem (Dis-)Service
Mangroves	Deforestation[19]: ○ Overharvesting of timber ▫ Conversion to other land use Pollution, nutrients[19]	*Timber, fish stocks, other materials*[1] [P] Nutrient/pollution uptake[1] [R] Protection against storms, erosion control[1] [R] Provision of habitats[1] [S] Recreation, tourism[1] [C]	Nutrient spillover (e.g., from agriculture)	*Migrating fish stocks*[13] [P] Protection against storms, erosion control[1] [R]	Climate change impacts[15]	Carbon storage and sequestration[1,16,17] [R] N_2O and CH_4emissions[8] [R]
Seagrass	Mussel beds[2,3] Pollution, nutrients[19] Boating, dredging[19] Loss of other ecosystems[19]	*Seagrass biomass* [P] Nutrient/pollution uptake[1] [R] Protection against storms, erosion control[1] [R] Habitat for aquatic species[1] [S] Recreation, tourism[1] [C] Wrack on beaches[12] [C]	Nutrient spillover (e.g., from agriculture)	*Migrating fish stocks*[13] [P] Protection against storms, erosion control[1] [R] Wrack on beaches[12] [C]	Climate change impacts[15] Ocean acidification[9,15]	Carbon storage and sequestration[1,16,17] [R] N_2O and CH_4 emissions[8] [R]
Salt Marshes	Conversion to other land use[19] Pollution, nutrients[19]	Nutrient/pollution uptake[1] [R] Protection against storms, erosion control[1] [R] Recreation, tourism[1] [C]	Nutrient spillover (e.g., from agriculture)	Protection against storms, erosion control[1] [R]	Climate change impacts[15]	Carbon storage and sequestration[1,16,17] [R] N_2O and CH_4 emissions[8] [R]
Macroalgae		*Seaweed biomass*[14] [P] Nutrient/pollution uptake[14] [R] Habitat for aquatic species[14] [S] Esthetic effects (buoys), noise (boats)[14] [C]	Nutrient spillover (e.g., from agriculture)		Climate change impacts [4,5,6,15] Ocean acidification[4,5]	Carbon storage and sequestration[10] [R] Halocarbon emissions[14] [R]

Even if the carbon sequestration potential of blue carbon ecosystems is limited, they provide a multitude of other benefits on different geographical scales (Table 2).

They contribute to the important categories of ecosystem services established in the Millennium Ecosystem Assessment (2005):

1) supporting services by sediment formation, nutrient cycling, and as a habitat for aquatic species;

2) provisioning of food and materials, like timber or fish stocks;

3) regulating services, as BCEs purify the water through their absorption of pollutants and excess nutrients, reduce coastal erosion, offer protection against floods, and sequester significant amounts of carbon;

4) cultural services in the form of spiritual or recreational value to residents and tourists (Merk et al. 2021, Vegh et al., 2019).

Macreadie et al. (2022) points at a long range of multidisciplinary and interacting challenges towards operationalizing blue carbon as a natural climate solution but states that "*Implementing these actions and operationalizing blue carbon will achieve measurable changes to atmospheric greenhouse gas concentrations, provide multiple co-benefits, and address national obligations associated with international agreements."*

An important aspect of blue carbon habitat restoration is that, in contrast to other more technological NETPs, they also generate a long range of other ecosystem services, including those advancing United Nations Sustainable Development Goals (SDGs, Duarte et al. 2022). In addition to carbon capture and sequestration (Krause-Jensen & Duarte 2016), they provide increased biodiversity as well as nutrient removal, fisheries enhancement, coastal protection, and many other ecosystem services (Costanza et al. 2014, Gundersen et al. 2017, Teagle et al. 2017, Ortega et al. 2019, Feehan et al. 2021).

Therefore, *c*onservation and restoration of blue carbon habitats is often called "no-regret options" or "win-win solutions" for climate mitigation and adaptation strategies, which at the same time provide environmental, social, and economic benefit to a range of sectors, such as fisheries, trade, environmental protection, and water management (Frigstad et al. 2021). Still, among a few potentially negative effects of blue carbon nature-based solutions are the replacement of the original species society (e.g., soft-bottom invertebrate society) or in other ways disturbing/ unbalancing the existing system, e.g., when creating artificial reefs for macroalgae or corals (REF).

Seaweed (kelp) aquaculture is also suggested as a Blue Carbon option with large expectations. Large-scale farming of seaweed would incorporate dissolved CO_2 from the upper ocean into tissue that then can be sequestered at depth either by pumping biomass to depth or by its sinking through the water column (National Academies of Sciences, Engineering, and Medicine 2022). This is a fast-growing industry for food production (FAO 2021), but also offers opportunities to mitigate and adapt to climate change (Duarte et al. 2017).

Through the release and potential burial of carbon, seaweed (kelp) farms can act as a CO_2 sink. According to Duarte et al. (2017), the "*crop can also be used for biofuel production, with a potential CO_2 mitigation capacity, in terms of avoided emissions from fossil fuels, of about 1,500 tons CO_2 per km2 per year. Seaweed aquaculture can also help reduce the emissions from agriculture, by improving soil quality substituting synthetic fertilizer and when included in cattle fed, lowering methane emissions from cattle."*

Among the negative effects of seaweed cultivation, and limitations to expand the industry is, however, *"the availability and competition for suitable areas with other uses, engineering systems capable of coping with rough conditions offshore, and increasing market demand for seaweed products, among other factors. Despite* *these limitations, seaweed farming practices can be optimized to maximize climate benefits, which may, if economically compensated, improve the income of seaweed farmers” (*Duarte et al. 2017).

Despite the different usages of farmed seaweed biomass, large-scale kelp cultivation has also been proposed as a technology solely to remove carbon, by deliberately sinking the crop at great ocean depths (typically below 1000 m) without further utilizing the biomass. This technology has been theoretically assessed for its economic sustainability (NEGEM D1.3, National Academies of Sciences, Engineering, and Medicine 2022) and ethical considerations (Ricart et al. in prep.).

According to the National Academies of Sciences, Engineering, and Medicine (2022), the environmental impacts are *“potentially detrimental especially on local scales where seaweeds are farmed (i.e., nutrient removal due to farming will reduce NPP, C export, and trophic transfers) and in the deep ocean where the biomass is sequestered (leading to increases in acidification, hypoxia, eutrophication, and organic carbon inputs).”*

3.2 Ocean liming

There are several practical methods proposed to enhance the CO_2 uptake in the ocean by adding minerals that means adding alkalinity to the seawater. Higher alkalinity means larger capacity for the seawater to absorb CO_2 from the atmosphere.

Processing of waste from mining (mine tailings) can provide mineral substances for distributing in the ocean, in what is called ocean alkalinity enhancement, OAE. Increasing the sequestration capacity of the global surface ocean by one percent by adding alkalinity in this way means 11 percent reduction in the atmospheric burden (Siegel 2022).

Adding lime (in the form of calcium oxide, calcium hydroxide, or calcium carbonate), or silicate minerals such as olivine to the surface ocean can enhance the carbon pump, as artificial ocean alkalization (AOA), or “enhanced ocean alkalinity.” Oceanic dissolution of these minerals will increase total alkalinity and, in turn, result in chemical transformation of CO_2, and storage in the ocean in the form of bicarbonate and carbonate ions.

AOA would pose a host of potential risks to ocean ecosystems (Brent, 2019):

1. The process could potentially disadvantage marine organisms that are not able to concentrate carbon within their cells under conditions of increased alkalinity.

2. AOA could also cause spontaneous precipitation of calcium hydroxide. This might adversely impact coral reefs, because they are sensitive to high levels of turbidity.

3. The addition of non-carbon alkaline minerals to the oceans could alter primary and second production, thereby increasing contaminant accumulation in food chains via the release of minerals such as cadmium, nickel, chromium, iron and silicon.

A main environmental concern relates to the possible impacts of OAE on seasonal changes in biogeochemistry and plankton dynamics. The EU-project OceanNETs dealt with this issue in their Deliverable 5.3 (OceanNETs 2021b).

Depending on deployment scenarios, OAE should theoretically have variable effects on pH and seawater pCO_2, which might in turn affect:

a) plankton growth conditions and

b) the efficiency of carbon dioxide removal (CDR) via OAE.

The massive mining industry, transport and mineral distribution required for large-scale AOA, will have a number og environmental impacts, mainly terrestrial, onshore, and is not treated further in this study.

One way to find out about the effects, is via mesocosm experiments. The other, is via geo-biochemical models by careful parametrization of input to Earth System models. Work on this is in progress by OceanNETs and other projects.

Critical questions are related to how different magnitudes and temporal frequencies of OAE may affect seasonal response patterns of net primary productivity (NPP), ecosystem functioning and biogeochemical cycling. A meaningful response parameterization will have to resolve positive and negative anomalies that covary with temporal shifts (OceanNETs 2021b).

In the modelling studies by OceanNETs phytoplankton bloom patterns displayed pronounced temporal phase shifts and changes in their amplitude. Notably, simulations suggested that OAE can have a slightly stimulating effect on NPP, which is however variable, depending on the magnitude of OAE and the temporal mode of alkalinity addition. Furthermore, they found that increasing alkalinity perturbations can lead to a shift in phytoplankton community composition (towards coccolithophores), which even persists after OAE has stopped (OceanNEts 2021b).

Modelling of OAE over several years at an open ocean site is shown in Figure 6. Winter mixing distributes alkalinity vertically and remove short-term alkalinity peaks in the surface layer. Physical mixing determines the temporal and spatial scales, for which (potentially unfavourable) non-equilibrated conditions of the carbonate system may occur (OceanNETs 2021b).

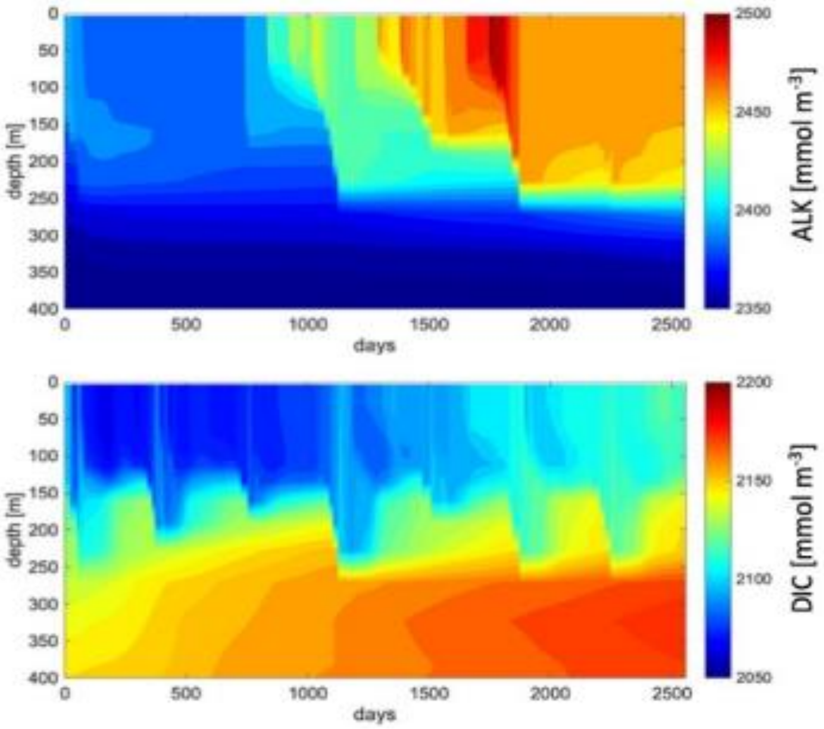


Figure 6. Vertical changes in open ocean alkalinity (top) and DIC (bottom) in response to seasonal alkalinity enhancement (OceanNETs 2021b).

3.3 Coastal enhanced weathering

This is an alternative to distribute fine-grained minerals on the open ocean surface. Olivine particles can be spread over beach environments to promote the naturally occurring weathering reactions between CO_2 and silicate minerals. This may be beneficial in terms of feasibility and lower economic cost. However, there are environmental issues, such as consequences for marine flora/fauna of altering the beach substrate and seawater chemistry in the littoral zone and near-shore.

3.4 CCS

Carbon capture and storage (CCS) is the method where CO_2 emissions typically from large point sources are captured then transported and deposited in a holding reservoir where the gas can be kept out of contact with the atmosphere permanently or for a long time.

CCS is part of the NETPs portfolio, e.g. in Bio-fuel-BECCS and direct air capture with storage- DACCS. A DACCS plant by Climeworks is in operation in Iceland, storing 4.000 tonnes of CO_2 annually in the underground (https://climeworks.com/news/climeworks-launches-orca).

CCS is also essential in eliminating the limestone calcination process emissions of CO_2 for making clinker in the cement industry (IPCC 2022).

CCS became a part of the portfolio of climate mitigation technologies in the 1990-ies and was promoted under the Kyoto summit meeting in 1997 as a Climate Technology Initiative (CTI). At that time, the deep ocean was considered as a viable holding reservoir for captured CO_2 (Ocean sequestration), while geological storage or sequestration was another option, among others. Several projects were initiated in the wake of the Kyoto summit and under the IEA to investigate on the feasibility of Ocean CO_2 sequestration.

Due to emerging concerns about the long-term ecological effects on the deep-sea fauna, further experiments and assessments where mostly put on hold after the turn of the century (Golmen, 2002).

The R&D focus was then turned to underground or sub-sea geological storage of CO_2 (IPCC 2005). Injecting CO_2 or other substances into oil or gas reservoirs was already a common practice in the oil industry, as enhanced oil recovery, EOR. The CO_2 gas used was usually stripped from the gas or oil stream, rather being captured from exhaust gas, so this practice was only a proxy to real CCS. Storing the CO_2 in geological formations will imply a solubility dissolution/trapping and finally stable mineral trapping of the CO_2 (Figure 7).

Over the past two decades many CCS projects were proposed, mostly associated with fossil fuel power plants. Only a few on industrial scale have materialized, while several are in the progress of being established, e.g. in the North Sea. Europe's expected share of stored CO_2 by 2050 amounts to 12 GT (IEA), corresponding to 400 MT annually on average.

For the moment areal plans and appraisal for ramp-up to GT storage at selected European sites are lacking, and no adequate methodology for assessment of GT storage is in place. A pan-European CO_2 transport and storage infrastructure for GT storage is missing. Limiting warming to 2°C or 1.5°C will imply a near elimination of coal use without CCS (IPCC 2022), underscoring the importance and capacity of this technology.

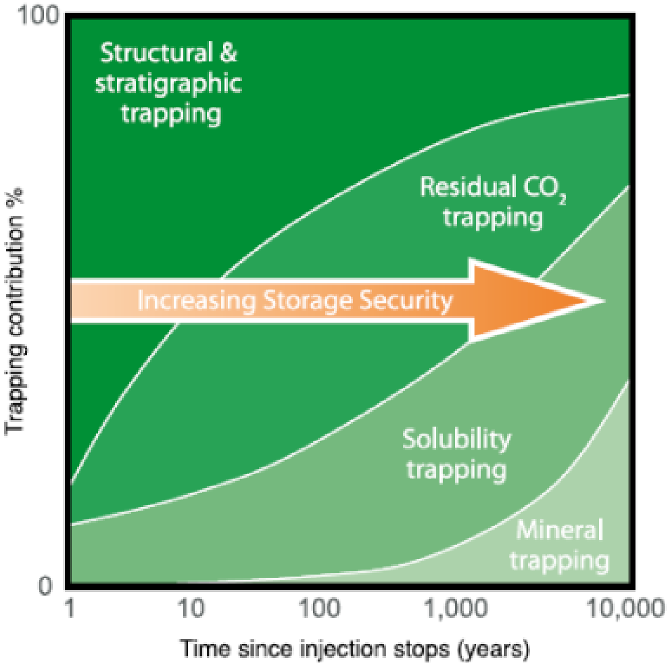


Figure 7. Geologically stored CO_2 may gradually go from physically trapped to residual/solubility trapping and finally to mineral trapping. From IPCC (2005).

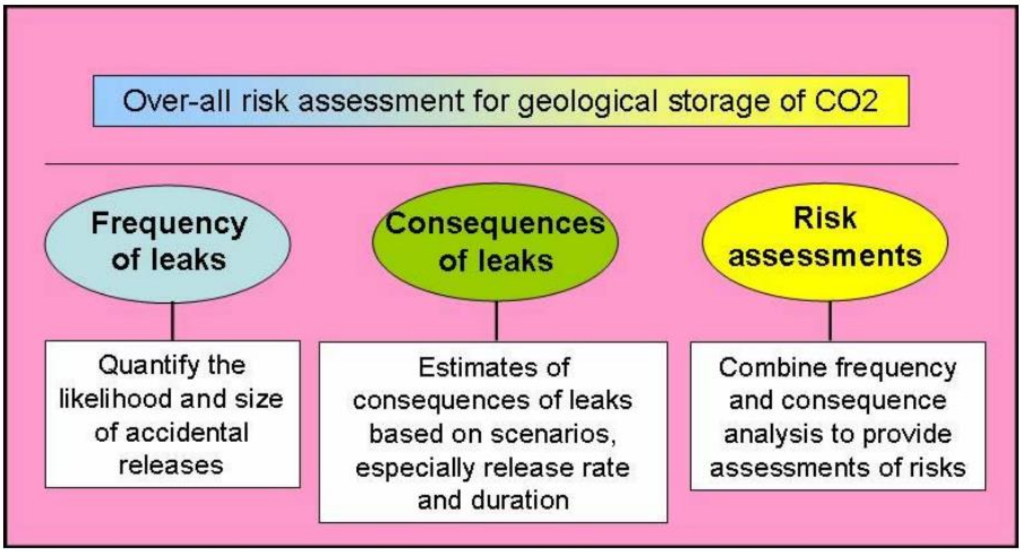


Figure 8. Elements of a total risk assessment for geological storage of CO_2.

The literature on aspects of CCS is exhaustive, counting thousands of journal articles and IEA-GHGT conference proceedings alone, in addition to books, white papers and reports. In short, the effects are related to (amine) capture of CO_2, transport to offshore storage sites (accidental leaks), and sub-sea storage (seeps and leaks to the ocean above).

Regarding environmental risk, CCS is commonly considered as an acceptable option, provided careful selection of the technologies involved and the storage reservoir. Each of the essential components Capture, Transport and Storage will have their association risk factors that needs to be addressed in the engineering and operational phase (Figure 8).

3.4.1 Capture of CO_2

The CO_2 in the exhaust form large emitters can be absorbed in an amine-based solution, which subsequently is processed and stripped free from the gas, for reuse as capture medium. The CO_2 gas is then collected and compressed/cooled at the site for pick-up by truck or ship or for pipeline transport to the storage site.

Some commonly used strategies to capture/separate gases include solvents for absorption and solid sorbents for adsorption/absorption, as well as membranes and cryogenic processes for separation. These various approaches for separating gases are used for all types of capture processes--pre-combustion, oxy-combustion, and post-combustion. For example, both solvents and membranes are used in both pre- and post-combustion.

Environmental consequences of CO_2 capture are mainly related to harmful compounds created during the capturing process. In particular, this is the case for the most mature way of capturing CO_2, using liquid amine solvents (Bui et al., 2018; Leung et al., 2014). This is currently the method of choice for large-scale industrial CO_2 capture operations (Stéphenne, 2014), existing pilot-scale BECCS (Holmes et al., 2021), and it has the potential for DAC (McQueen et al., 2021).

In brief, the CO_2 is extracted from the flue gas (or air) by a liquid amine solution. The rinsed flue gas is emitted to the atmosphere while the now CO_2-rich amine solution is heated to re-release the CO_2. A stream of pure CO_2 is obtained, suitable for long-term storage or reuse, while the amine solution is recycled in the capture process.

Despite being recycled, small yet significant amounts of amines are lost through various degradation processes. This causes environmental and human health concerns since two of the degradation products are carcinogens, namely nitrosamines and nitramines (Chen et al., 2018; Mazari et al., 2019; Reynolds et al., 2012; Yu et al., 2017).

Nitrosamines are established carcinogens associated with tobacco smoke, cured meats, etc., while the structurally similar nitramines have been less researched and thus its potency not fully understood. Formation can occur both inside the capture unit and in the atmosphere from amines escaping with the rinsed flue gas (Nielsen et al., 2012; Yu et al., 2017). The latter is of most concern since it is virtually impossible to eliminate atmospheric emission of volatile amines (Gouedard et al., 2012; Zhu et al., 2018), regardless of the type of amine solvent used (Mazari et al., 2015; Tan et al., 2021).

In the atmosphere, nitrosamines and nitramines will form within days if sunlight and NOx are present (Nielsen et al., 2012; Pitts et al., 1978). Because of their high water solubility, both compound groups will reside in the water phase after being deposited on ground, and thereby posing a threat to nearby drinking water sources. In Norway, a drinking water safety limit is set at 4 ng L^{-1} for the sum of nitrosamines and nitramines (Låg et al., 2011).

Corresponding low limits exist in other countries for the nitrosamines (Nawrocki and Andrzejewski, 2011). To evaluate the environmental and human health risk posed by amine-based CO_2 capture, a site-specific evaluation should be conducted.

Major influencing factors cover the presence of NOx (in the flue gas or other sources like vehicular traffic), proximity to populated areas and drinking water reservoirs. In Norway, such individual evaluations form the basis for regulatory amine emission permits. The permits are calculated using atmospheric dispersion and deposition modelling, back-calculating from the safety limit in nearby drinking water sources (Karl et al., 2014). The estimates are made conservatively to encompass the high uncertainty associated with certain of the processes involved (e.g. atmospheric dispersion, nitramine biodegradation rates, etc.). This likely causes unnecessary constraint on the operations as costly and energy intensive emission reduction measures (e.g. reheat) may be warranted (Norling et al., 2022).

Alternatively, the flue gas can be released to the ocean following purification and dissolution which is the plan for CO_2 capture plant at the cement factory in Brevik, Norway (Rannekleiv et al., 2019). By avoiding emission of amines to the atmosphere, formation of nitrosamines and nitramines is largely avoided.

Another promising CO_2 capture technology, ready for larger scale testing, is the use of solid sorbents (Bui et al., 2018). Materials equipped with amine(s) (Hamdy et al., 2021; McQueen et al., 2021) may be prone to nitrosamine and nitramine formation. However, the amount formed and released can be expected to be less compared to liquid amine solvents for which the volume is greater and the amines likely more volatile. This should be subject to further research.

3.4.2 Transport of CO_2

Transport of captured CO_2 will be via pipeline, ships or (onshore) trucks or train. Figure 9 shows and illustration of this for the Norwegian off-shore Northern Lights project, now commenced. The CO_2 will in this case be transported via pipeline from an onshore offloading terminal. Ships carrying CO_2 from distant capture sites will call at this terminal and transfer the CO_2 to temporary onshore storage, before pumping it offshore. In the future, other pipelines may be installed to carry larger amounts of CO_2 from Central Europe to the Northern Lights offshore storage facility, storing millions of tonnes of CO_2 annually. The supply can also come from NETP plants.

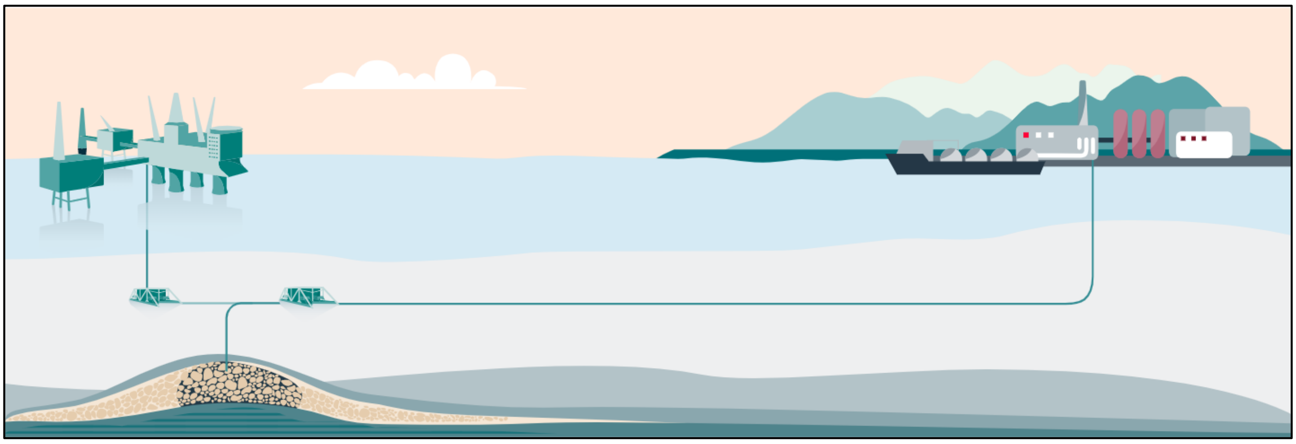


Figure 9. Schematic of the Northern Lights project to store captured CO_2 under the Norwegian part of the North Sea. The CO_2 will be derived from industrial sources but may also include CO_2 from NETP plants. Link: https://www.equinor.com/energy/northern-lights

Transport of the CO_2 may infer accidental leaks of the gas to the ambient. The actual scenarios will depend on the location, situation, amounts and the phase condition of the CO_2 under consideration. Whether the CO_2 is derived from conventional sources or NETPs should not make any difference regarding the environmental impacts and will resemble leak scenarios from storage. See the following paragraph for more discussion.

3.4.3 Storage of CO_2

The target sub-seabed reservoirs will be porous media such as sandstone incl. depleted oil/gas reservoirs and saline aquifers, overlain by non-permeable layers (overburden, cap-rock) to prevent leakage. At least for shallow aquifers, the overburden will commonly be either of carbonate minerals (limestones etc) or siliclastic minerals like quartz, feldspar etc forming sand/siltstones and shales.

Silicate minerals react slowly with dissolved CO_2 (carbonic acid) while carbonate rocks react faster. In the first case, the dissolved CO_2 will remain acidic and reactive for a long time. In the latter case, the CO_2 may cause rapid change of permeability, but simultaneously the brine will be buffered and have its pH increased (get less reactive). These two competing effects makes it challenging to assess which type of cap-rock is most prone to leakage (Wilson et al. 2007).

It is assumed that the CO_2 will be introduced deep enough (800+m) that it exists in liquid/supercritical form. The supercritical CO_2 will initially be buoyant in the subsurface, i.e. less dense than the surrounding brine or fluids. This means the gas may tend to rise through the porous media until it reaches the cap-rock above, where it can remain reactive to the minerals above for a long time.

Concerns have been raised on the risk of CO_2 escaping to the terrain or sea above though fractures in the bedrock, see e.g. Korre et al. (2012), Ishida et al. (2013). Many studies have been performed to assess this risk and the consequences if it should happen, an example is the recently completed EU-funded project STEMM-CCS: https://www.stemm-ccs.eu/.

Some pilots for geological CO_2 storage projects are running. There are no reports on serious leaks and environmental consequences. On the marine side, the Sleipner project in the Norwegian sector of the North Sea is commonly referred to. There, CO_2 stripped from the extracted natural gas is reinjected into saline formations sub-seabed. About 1 million tonnes of CO_2 have been injected annually, since 1996. The reservoir has been monitored with 3D seismic for many years, and while the CO_2 is seen to migrate inside the reservoir, no leaks to the sea above has been detected. Another marine site is the Tomakomai pilot CO_2 storage project, off the city of Tomakomai in Hokkaido, Japan. Monitoring of the seabed has not detected any leaks.

Environmental risks are linked to CO_2 escaping unintendedly from the storage reservoir, or from transport operations. While CO_2 is naturally occurring ion seawater, additional gas may lead to acidification of the water near the leak with lethal or sub-lethal effects on the marine fauna, depending on the sensitivity and the exposure. Fish will tend to escape from the impacted zone, while stationary animals near-by may be seriously affected.

Experiments by injecting CO_2 in-situ on or in the seabed have shown that bacterial communities as well as meiofauna are affected by the CO_2, with some sub-groups becoming dominant others under exposure (Ishida et al. 2013). The effects will be similar to those already occurring in the ocean due to increasing absorption of fossil fuels CO_2 from the atmosphere, however, with a stronger signal with localized impacts only.

CCS with geological storage is regarded as a method with large capacity to store conventional fossil fuel CO_2. From the NETPs perspective, applying BECCS and DAC as additional mitigation will likely rely on experiences gained through conventional storage, and thus benefit from risk-reducing measures and regulation imposed there.

4 Key findings and policy relevant messages

Marine NETPs holds a significant potential for capturing CO_2 directly or indirectly from the atmosphere and store it permanently in the deep ocean or on the seabed along the ocean rim. Some will be termed as “natural” (kelp farming etc.), while others will fall under the category of engineering/geoengineering. The latter tends to become subject of public opposition, partly due to many unknowns and as it is speculated that irreversible processes on the ocean may be initiated.

Still, for those NETPs chosen for further studies, there are environmental factors that need to be addressed. The many knowledge gaps have been regarded as an obstacle to assess the risks and full benefits of most ocean-based approaches (Keller et al. 2021, GESAMP 2019).

Seaweed cultivation is a growing industry world-wide, for the purpose of providing food or feed. When seaweed dies or is eroded away by waves, some I it will sink as debris to the seabed, for further decay and remineralization. In this respect, it is part of the natural CO_2-pump. Part of the sunk material may be permanently sequestered in the sediments in deep seabed throughs, and thus be kept out of the loop for re-entry of CO_2 into the atmosphere.

Large-scale kelp cultivation has thus been proposed as a method to remove CO_2 by deliberately sinking the crop at great ocean depths, thus enhancing the natural process and without further utilizing the biomass.

This method holds a significant potential to permanently store CO_2 and has been theoretically assessed for its economic sustainability. Still, it has not yet been proven to work on the large scale, and there are certain limitations to expand it as an industry, which for practical and economic reasons are best performed near-shore, at least in the near-term, even if plants offshore in the deep sea are anticipated to provide more efficient sequestration on the long-term.

Some studies indicate that environmental impacts of large-scale seaweed cultivation with seabed sequestration will potentially become detrimental especially at sites where seaweeds are farmed. This can be due to depriving the seawater of nutrients and thus reducing natural primary production in the surface waters. In the deep ocean the sunken biomass will be re-mineralized and become buried and sequestered. This may lead to increased seawater acidification, hypoxia near the seabed and in the pore water of sediments.

Along the shoreline there are many user interests and competition for ocean space. Increasing market demand for seaweed products as food and food ingredients can make traditional farming and harvesting more profitable than as a mere climate mitigation technology, NETP. Despite such limitations, according to the literature, seaweed farming practices can be optimized to maximize climate benefits, which may, if economically compensated, also improve the income of seaweed farmers.

Ocean alkalinization iv various forms have been proposed, to mimic and speed up natural mineral weathering that sequesters carbon. Common scientific knowledge of geo-biochemical and physical processes in the Ocean, combined with results from a limited number of small-scale experiments and numerical modelling. Only a few experiments with iron fertilization (not alkalinization) in the ocean that may be termed medium/large-scale have been performed. Numerical modelling of impacts from ocean alkalinization have been derived from perturbation studies of coupled hydrodynamic and bio-geo-chemical models, with little experience from large-scale experiments.

Ocean alkalinization can potentially disadvantage marine organisms that are not able to concentrate carbon within their cells under conditions of increased alkalinity. It can also cause spontaneous precipitation of calcium hydroxide that may negatively impact coral reefs, due to sensitivity to high levels of turbidity.

The addition of non-carbon alkaline minerals to the oceans can alter primary and second production, thereby increasing contaminant accumulation in food chains via the release of minerals such as cadmium, nickel, chromium, iron and silicon. Another main environmental concern relates to the possible impacts of OA on seasonal changes in biogeochemistry and plankton dynamics.

Besides the marine NETPs, some other technologies may infer environmental consequences for the ocean. For CCS with sub-seabed storage, consequences may be related to any sea transport of CO_2 and disposal thereof under the seabed. Consequences will be related to accidental leaks of CO_2 from transport or storage of CO_2 to the ambient, causing such as acidification effects and hypercapnia (CO_2-stress) for marine species.

Artificial upwelling can stimulate the biological pump in the ocean and bring down carbon for long-term sequestration in the deep ocean or on the seabed. As for other NETPs, this method needs considerable number of installations in order to bring down accountable amounts of CO_2.

The consequences of redistributing seawater and nutrients on a large scale by artificial upwelling may have unwanted environmental effects, leaving it as an option only, for the moment.

5 Conclusions and further steps

Proposed marine NETPs hold a potential to draw down large amounts of CO_2 from the atmosphere to the ocean in the context of CDR.

None of the key technologies like blue carbon and ocean alkalinization have been tested and proven to work on a large scale.

It is expected that marine NETPs will have some negative environmental consequences, even if they help to mitigate climate change. These may be minor or significant, depending on the type on NETP, and the location and scale.

Weighing the impact on reducing climate change by the NETPs against their negative environmental effects is not within the scope of NEGEM but may be pursued in follow-up studies.

Numerical modelling is the best tool available to assess the scale of the consequences under various scenarios. Experimental work in-situ like in mesocosms will help to improve parametrization of geo-biochemical processes. Both approaches should be focused on in follow-up studies, in order to improve the precision of predictions.

Other technologies like conventional CCS that are relevant for NETPs as well, are being heavily investigated already with several industry-scale pilot projects on-going, and more to come. In the framework of NETPs, these may therefore not require particular attention, as consequences are dealt with elsewhere like under the IEA-GHG programme.

For preparing this report, the following deliverable/s have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D 1.1	Justification of NETPs chosen for the NEGEM project	ETH	R	PU	6

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