NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Comprehensive sustainability assessment of marine NETPs

Horizon 2020, Grant Agreement no. 869192

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Executive Summary and policy relevant messages

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. The IPCC scenarios mainly focus on bioenergy with carbon capture and storage and afforestation/reforestation as Carbon Dioxide Removal (CDR) strategies. However, the conservation and restoration of marine ecosystems and other approaches such as ocean alkalinization can enhance the ocean's natural CO_2 sequestration potential.

Here we applied the Life Cycle Assessment methodology to derive a set of key performance indicators (KPIs) that allowed us to quantify the sustainability performance of the following scenarios:

- Kelp farming and sinking. Giant kelp is cultivated and sunk to the deep ocean, which enables the sequestration of the carbon captured during the photosynthesis process.
- Ocean liming. Calcium oxide particles are discharged in the open ocean and react with the CO_2 dissolved in the seawater to produce bicarbonate ions, which draws the transfer of atmospheric CO_2 to the seawater.
- Coastal enhanced weathering. Olivine particles are spread over coastal environments to promote the weathering reactions between CO_2 and silicate minerals.

For each scenario, we developed models based on both optimistic and pessimistic assumptions. We found that all the modeled scenarios can prevent net climate change impacts in the range of 836-980 kg CO_2-eq per tonne of sequestered CO_2. Our results indicate that coastal enhanced weathering is the best-performing marine NETP in terms of climate change impacts. Conversely, the ocean liming scenario based on the most pessimistic assumptions attains the highest climate change impacts – mainly driven by the high electricity consumption of the oxy-fuel limestone calcination process.

Overall, ocean liming led to the worst results across the studied NETPs in 5 of the 16 studied environmental KPIs due to its substantial energy consumption, whereas the coastal enhanced weathering scenario relying on optimistic conditions achieves the lowest impacts across all the environmental categories but three. Nevertheless, the performance of coastal enhanced weathering is highly variable and dependent on the value of the parameters selected to carry out the scenario analysis. A great share of the impacts of coastal enhanced weathering is associated with the olivine transportation; therefore, locating weathering sites close to the olivine mines is key to decreasing the impact of this NETP. On the other hand, the carcinogenic toxicity impacts of the coastal enhanced weathering scenarios – linked to the nickel and chromium content of olivine – are one order of magnitude greater than in the other scenarios.

Our results indicate that all the scenarios can prevent damage to human health and ecosystems due to the averted impacts of CO_2 emissions. Moreover, all the scenarios can prevent externalities, i.e., the externalities averted by CDR are only partially offset by the externalities associated with the impacts that occur throughout the NETPs' life cycle. The avoided externalities range between 36 and 103 € per tonne of CO_2 sequestered. They represent 27-78% of the ocean liming cost estimates, and they are up to 14 times greater than the coastal enhanced weathering costs, which could incentivize the implementation of these NETPs. However, the prevented externalities constitute <5% of the kelp selling price in the kelp farming and sinking scenarios; hence, it may difficult for kelp farming and sinking to economically compete with the other marine NETPs.

The current knowledge about marine NETPs is rather limited, since few demonstration projects have been conducted to date; thus our results are subject to the uncertainty linked to our data and modeling assumptions. Nevertheless, the NETPs' hotspots identified in this study could help guide future research.

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List of abbreviations

η_{CO_2}. CO_2 removal efficiency.

AL1. Optimistic kelp farming and sinking scenario.

AL2. Pessimistic kelp farming and sinking scenario.

CCS. Carbon capture and storage.

CDR. Carbon dioxide removal.

DALY. Disability-Adjusted Life Year.

d.w. Dry weight.

E_{CO_2}. Life-cycle CO_2 emissions.

EW1. Optimistic coastal enhanced weathering scenario.

EW2. Pessimistic coastal enhanced weathering scenario.

FU. Functional unit.

KPI. Key performance indicator.

LCA. Life cycle assessment.

NETPs. Negative emissions technologies and practices.

OL1. Optimistic ocean liming scenario.

OL2. Pessimistic ocean liming scenario.

S_{CO_2}. Sequestered CO_2 within a 100-year time frame.

1. Introduction

We define marine negative emissions technologies and practices (NETPs) as the carbon dioxide removal (CDR) strategies aiming to maximize the long-term storage of carbon in the ocean.

NETPs are needed to limit global warming to 1.5 °C,[1] as the latest IPCC report underscores.[2] The IPCC climate change mitigation pathways consider bioenergy with carbon capture and storage (BECCS) and afforestation/reforestation as the main CDR options. However, a portfolio of NETPs will probably be needed to meet the most ambitious CDR targets.[3] Hence the importance of investigating ocean-based NETPs.

The objective of this study is to assess the sustainability performance of marine NETPs. To that end, we quantified a set of key performance indicators (KPIs) for the following scenarios:

- 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.

1.1 Sustainability

The projected impacts of global warming on marine ecosystems are shown in Figure 1. 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.

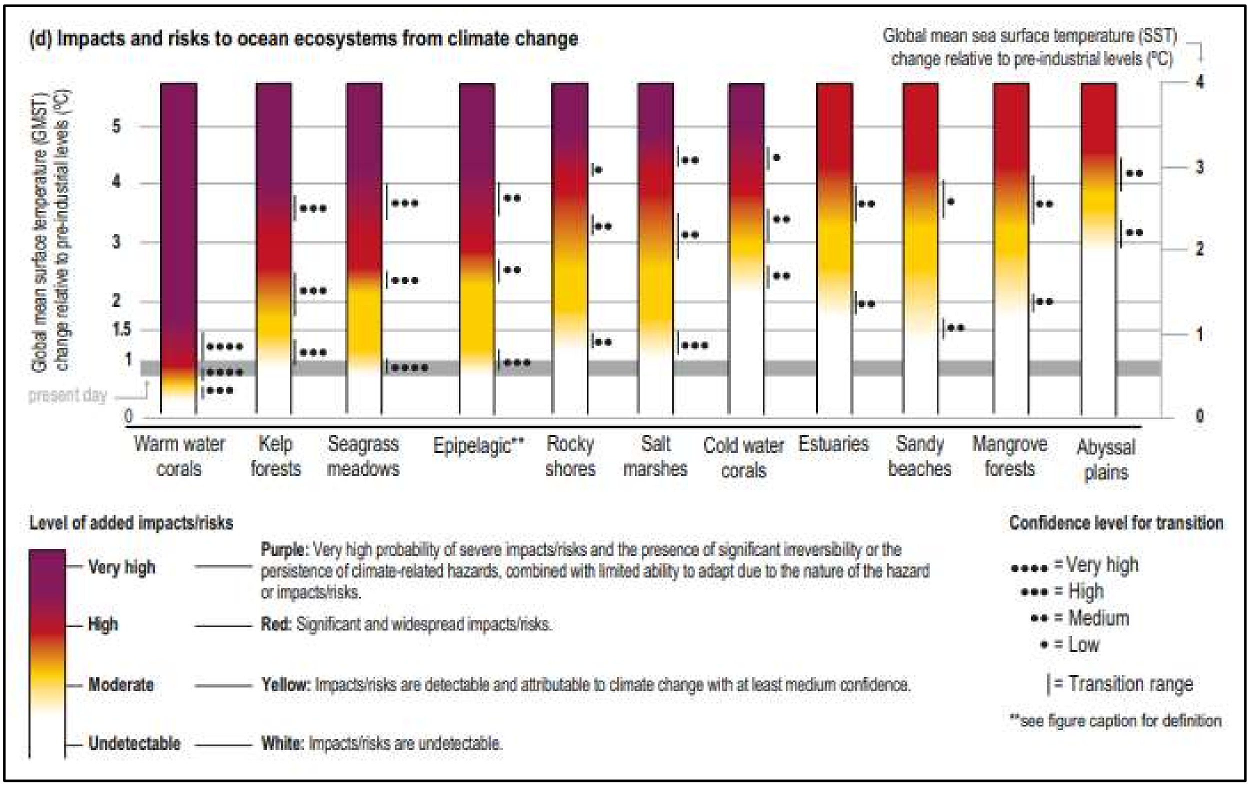

Figure 1. Assessment of risks for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. Impacts and risks are shown in relation to changes in Global Mean Surface Temperature (GMST) relative to pre-industrial level. From IPCC (2019): Technical Summary.[4]

1.2 The ocean's capacity to store CO_2

A large part of the CO_2 emitted by burning fossil fuels (present annual rate of about 9 Gtonne of C) will eventually be absorbed by the ocean through exchange with 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.[5] About 24% (166 Gtonne of C) of the total emissions since 1850 have ended up in the ocean.[6]

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.[7]

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).[8]

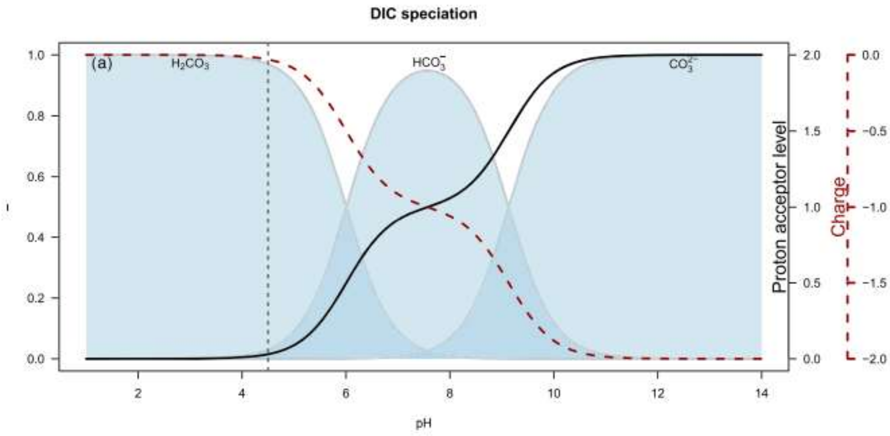

Figure 2. A Bjerrum diagram showing the distribution of carbonic acid, bicarbonate, and carbonate as a function of pH and the corresponding proton acceptor level (solid black line) and charge (red dashed line). From Middelburg et al. 2020.[5]

In the normal pH-range of seawater, most of the inorganic carbon is present as bicarbonate, as shown in Figure 2. When CO_2 is added, it will be transformed into bicarbonate and to a lesser extent, carbonate. This illustrates the 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.[9,10] This could be achieved by direct injection of pure CO_2 gas[11] 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.[12] Figure 3 shows how some ocean-based technologies fit into the CDR framework, and Table 1 compiles the main characteristics of alternative sequestration options.

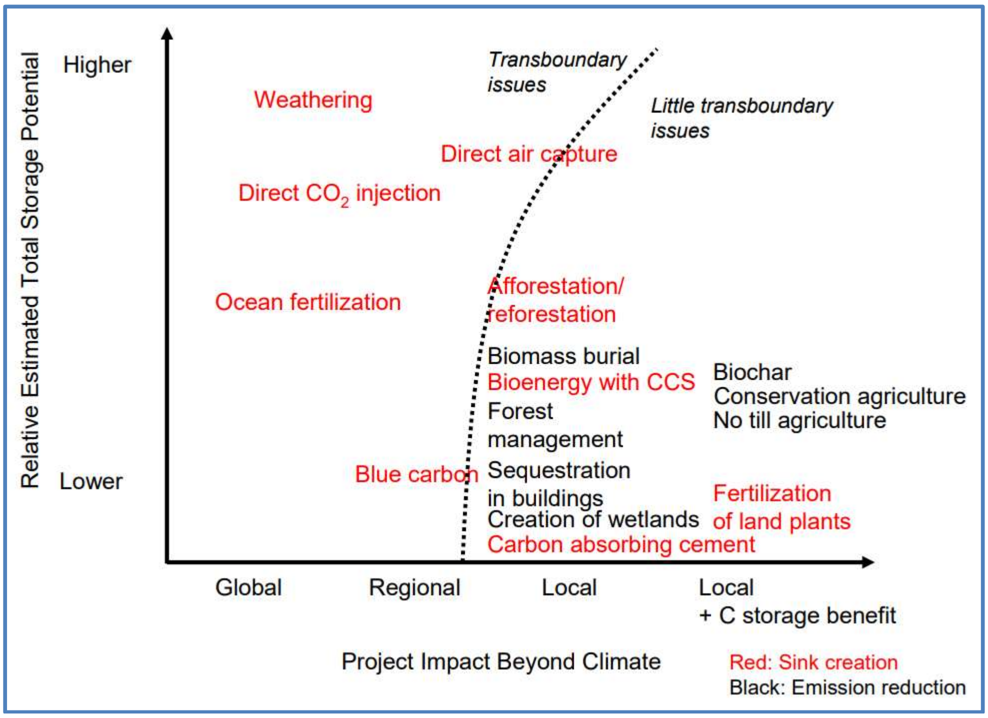

Figure 3. Relative estimated total storage potential for emission reduction and sink creation projects at different scales. From: IPCC Expert Meeting on Geoengineering.[13]

Table 1. Characteristics of CO_2 storage options for deep sea and/or seabed storage. From: Hoegh-Guldberg et al. (2019),[14] p. 71.

OPTION	CO_2 SOURCE	CO_2 STORAGE RESERVOIR	INITIAL CO_2 STORAGE FORM	TECHNICAL READINESS	COST PROFILE	PRINCIPAL ENVIRONMENTAL CONCERNS
CO_2 injection to seabed	Power plant	Geologic reservoirs beneath seafloor	Molecular CO_2	High to medium	High	Operational activities; leakage to ocean; impacts on deep sea ecosystems
CO_2 storage contained on top of the seafloor (CO_2 injection into CO_2 lakes or containment vessels)	Power plant	Reservoirs on seafloor separated from the ocean by physical or chemical barrier	Molecular CO_2	Low	High	Leakage to ocean; damage to seafloor; operational activities; impacts on deep sea ecosystems
CO_2 injection into deep ocean	Power plant	Deep ocean	Molecular CO_2	High	High	Ocean acidification; leakage to atmosphere; operational activities; impacts on deep-sea ecosystems
Carbonate dissolution (CO_2 release to the ocean, buffered by dissolved carbonate minerals)	Power plant	Ocean	Bicarbonate ions	Medium	High	Possible contaminants; local impacts on ecosystems
Alkalinity addition	Atmo-sphere	Ocean	Bicarbonate ions	Medium	High	Unintended ecosystem effects
Ocean fertilisation	Atmo-sphere	Ocean	Organic carbon	Low	Medium	Interference with marine ecosystems; ocean acidification; leakage to atmosphere

1.3 Marine geoengineering

NETPs are likely to have environmental impacts when deployed at large scale.[15] Some of the skepticism against such human interventions rests on the belief that it will be a form of “geoengineering” and thus a “manipulation” of the natural systems, which in the worst-case scenario may get out of balance.

The term geoengineering appeared in the 1960s when different interventions to control weather and climate such as aerosol seeding in the atmosphere were discussed. Climate geoengineering is a common term for large-scale intervention tools aiming to counteract anthropogenic climate change.[16]

The NETPs involving the addition of materials to the seawater are subject to the London Protocol,[17] which establishes a framework to regulate marine geoengineering activities.[18] The protocol currently allows the storage of CO_2 in sub-seabed geological formations[19] and prohibits ocean fertilization.[18]

1.4 Human perception of marine NETPs

The ocean is often perceived as a vulnerable environment that needs protection against human exploitation. Many people have little or no knowledge about the ocean and do not know about its vital role in regulating the Earth's climate.

As part of Task 8.1[3] of the NEGEM project, a brief survey on the public awareness of different NETPs was conducted among stakeholders representing research (51%), industry (28%), public sector (3%), Non-Governmental Organisation (8%) and others (10%). The results are shown in Figure 4. Ocean-based technologies appeared to be the least familiar option, followed by enhanced weathering and mineral carbonation.[4]

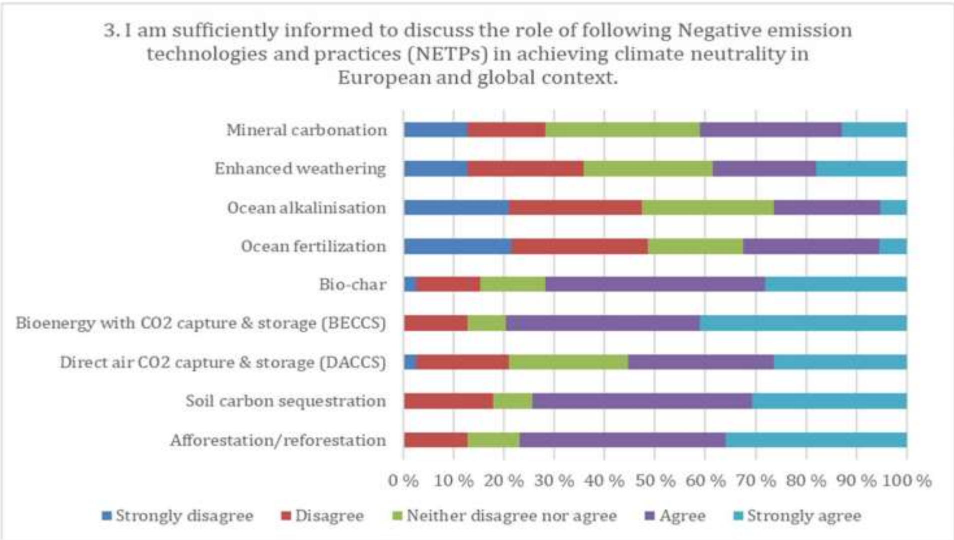

Figure 4. Distribution of answers to question on awareness of NETPs in NEGEM Task 8.1. From Koljonen et al., 2021.[4]

1.5 Marine CCS

Carbon capture and storage (CCS) is a vital component of several NETPs. CCS is itself still in the Demo phase, with a handful of on-going projects in the world. CO_2 can be sequestered in geological formations, underground or in the seabed.

The latter may be regarded as part of Marine NETPs. Seabed storage can be coupled with e.g., BECCS. Storage in the seabed has been demonstrated to work, e.g. at the Sleipner field in the North Sea where, since 1996, a million tonnes of CO_2 have been sequestered annually in the underlying saline aquifer formations.

1.6 The ocean's role in climate regulation

Marine NETPs use the ocean as a sink for the CO_2 that is either captured by technical devices from the atmosphere or driven into the ocean by stimulating certain natural fluxes. The ocean holds a much larger amount of CO_2 than the terrestrial biosphere and the atmosphere, and it has the potential to store much more CO_2. However, driving more CO_2 into the ocean will change the alkalinity balance and lower the pH, causing effects on marine organisms like corals and oysters.

Utilizing nature-based solutions, such as leveraging the ability of coastal and marine ecosystems to sequester carbon, also offer a sizable mitigation potential. The protection and restoration of these ecosystems provides valuable benefits by expanding sequestration and maintaining carbon stocks in soils and vegetation.

1.7 Sea-level rise and carbon

Sea-level rise should be accounted for when assessing the role of the NETPs deployed in coastal zones, as it may impact the capacity of coastal wetlands to store carbon. Coastal wetlands accumulate carbon 1 to 2 orders of magnitude faster than terrestrial systems. Salt marshes, mangroves, and seagrasses account for approximately 50% of the C buried in the ocean despite covering <2% of the ocean's surface.[20]

As new land is inundated by seawater and forests are replaced by salt marshes (marsh migration), the soils quickly accumulate carbon. However, coastal carbon stocks are in total reduced through the loss of woody aboveground biomass. This is illustrated in Figure 5 where the carbon stock is reduced during a transition period that may last several hundred years.[21]

The thermal expansion of warm ocean water is larger at low pressure than at depth. Enhanced downwelling of warm ocean surface water as a NETP could thus reduce some sea-level rise if this NETP was adopted on a large scale. It is an example of NETPs that can have positive side-effects, other than removing atmospheric CO_2.

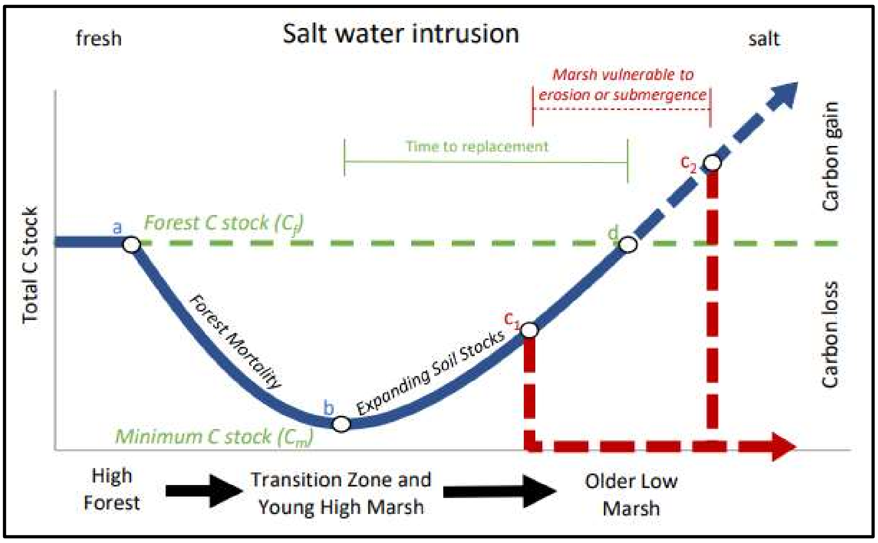

Figure 5. Conceptual diagram of the changing total C stock associated with the transition from forest to marsh. The total carbon stock in the forest (Cf) decreases through time following saltwater intrusion (a) in response to forest mortality. Carbon stocks reach a minimum (Cm) when forests are first replaced by marshes (b), but then increase through time as developing marsh soils accumulate carbon. For further details, see Smith and Kirwan (2021).[21]

1.8. Selected NETPs

Many technologies and practices can contribute to artificially sequestering CO_2 in the ocean. Figure 6 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.

Table 2 lists the marine NETPs reviewed in NEGEM Task 1.1. As discussed in Deliverable 1.1,[22] blue carbon and ocean alkalinization were selected for the present study.

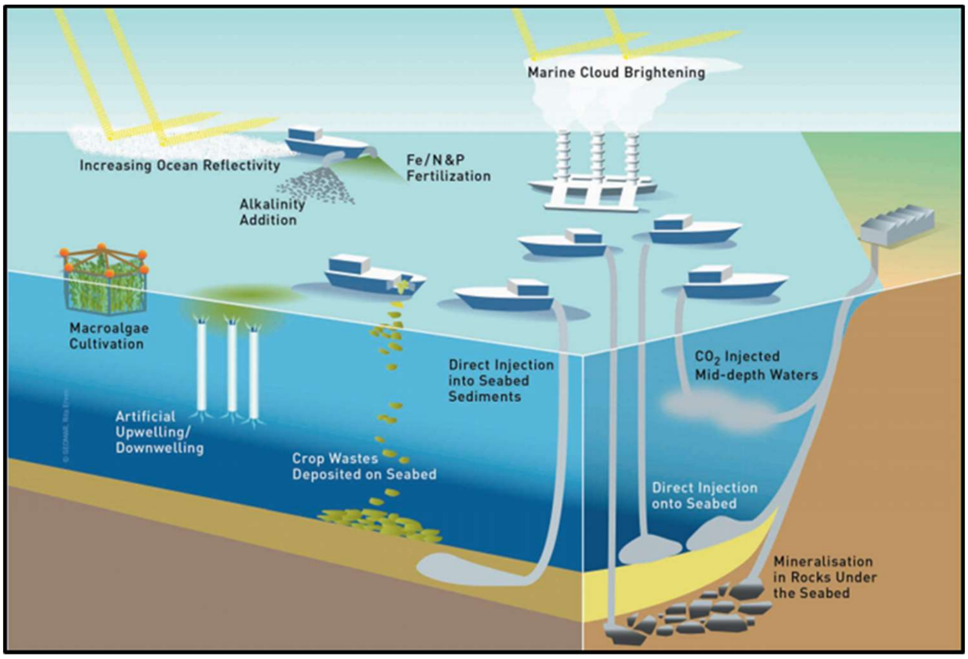

Figure 6. A sketch of some marine NETPs as envisaged by GESAMP (2019).[12]

Table 2. 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. [22]

	NETPs	TRL	Max CDR Gtonne/yr	Cost (2019€) €/tonne CO_2	Score [-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 $Mm^3 \cdot s^{-1}$ 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.

1.8.1 Blue carbon

Frigstad et al. (cited with permission)[23] 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%[24]) 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.[25-27] 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.[24,28-30] 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.[31,32] 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.[33,34]

There is also growing attention toward seaweed cultivation and its role in climate change. According to Duarte et al.,[35] 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.

1.8.2 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:[22]

- 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.

2. Methodology

We performed the life cycle assessment (LCA) – i.e., the evaluation of inputs, outputs and potential environmental impacts –[36] of the selected marine NETPs to derive a suite of technical, environmental and socioeconomic KPIs. Figure 7 provides an overview of the followed methodology. We applied an attributional modeling approach,[37] and defined the functional unit (FU) – the reference unit that quantifies the performance of the studied systems – as one tonne of CO_2 effectively sequestered within the timeframe of the analysis (100 years).

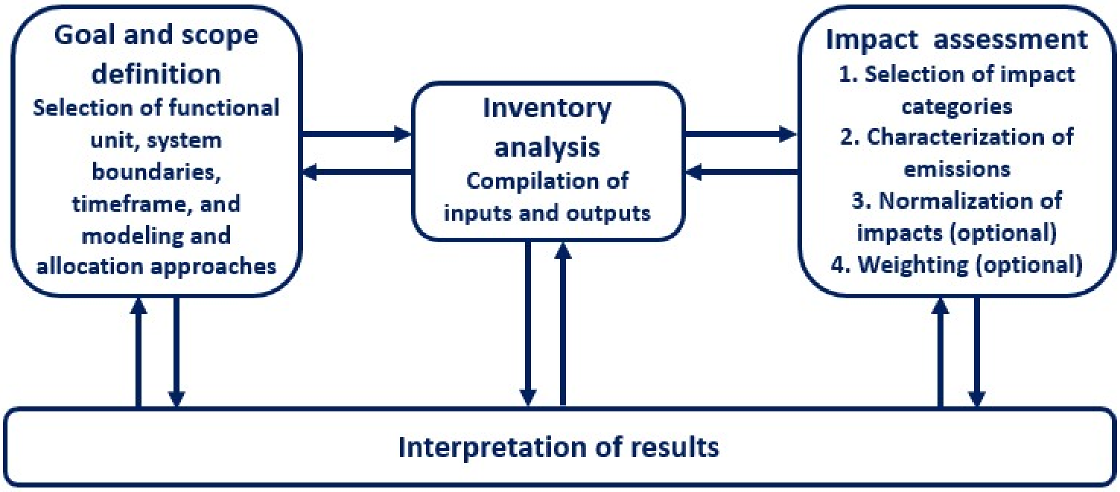

Figure 7. LCA phases (adapted from ISO 14040[31]).

Our life cycle models, implemented in SimaPro 9.1.0.8,[38] draw on data reported in the literature[39-44] and activities from the Ecoinvent 3.5 database.[45] We defined the CDR efficiency KPI (η_{CO_2}) as the ratio between the net amount of CO_2 that is removed from the atmosphere within the selected time horizon – computed as the sequestered CO_2 (S_{CO_2}, which corresponds to the FU) minus the overall life-cycle CO_2 emissions (E_{CO_2}) – and S_{CO_2} (equation e1). We estimated this KPI with the CO_2 elementary flows provided in the life cycle inventories.

$$\eta_{CO_2} = \frac{S_{CO_2} - E_{CO_2}}{S_{CO_2}} \qquad \text{(e1)}$$

We used the Environmental Footprint impact assessment method (EF 3.0)[46] to quantify the impacts of the assessed NETPs on the following environmental categories: climate change, ozone depletion, ionizing radiation, photochemical ozone formation, particulate matter, human toxicity (carcinogenic and non-carcinogenic), acidification, eutrophication (freshwater, marine and terrestrial), freshwater ecotoxicity, land use, water use, use of fossil resources and use of minerals and metals.

Furthermore, we applied the ReCiPe 2016 impact assessment method[47] (endpoint level, hierarchist perspective) to evaluate the damage to three areas of protection, namely human health, ecosystem quality and resource scarcity. Finally, we quantified the externalities – i.e., the monetized environmental impacts – applying the conversion factors proposed by Weidema[48] to the endpoint level impacts.

3. Scenario definition

Figure 8 provides an overview of the assessed scenarios and the life cycle stages they consider. The macroalgae farming and sinking scenarios are based on the long-line cultivation of *Macrocystis pyrifera* (giant kelp). The lines (nylon ropes) are inoculated with kelp spores, which are subsequently developed in a tank at the hatchery facilities. The lines are then transported to the offshore cultivation site, where they are anchored to the seafloor with concrete blocks and steel chains. After the 9-month culture period, the kelp (10% d.w.)[49] is harvested, transported to the open ocean – a distance of 200 nautical miles from the shore is assumed –[50] and sunk to ensure the permanent sequestration of the captured carbon. The hatchery, cultivation and harvesting inventories are taken from Aitken et al.[39] Optimistic and pessimistic scenarios (AL1 and AL2) were considered. They differ in the parameters compiled in Table 3.

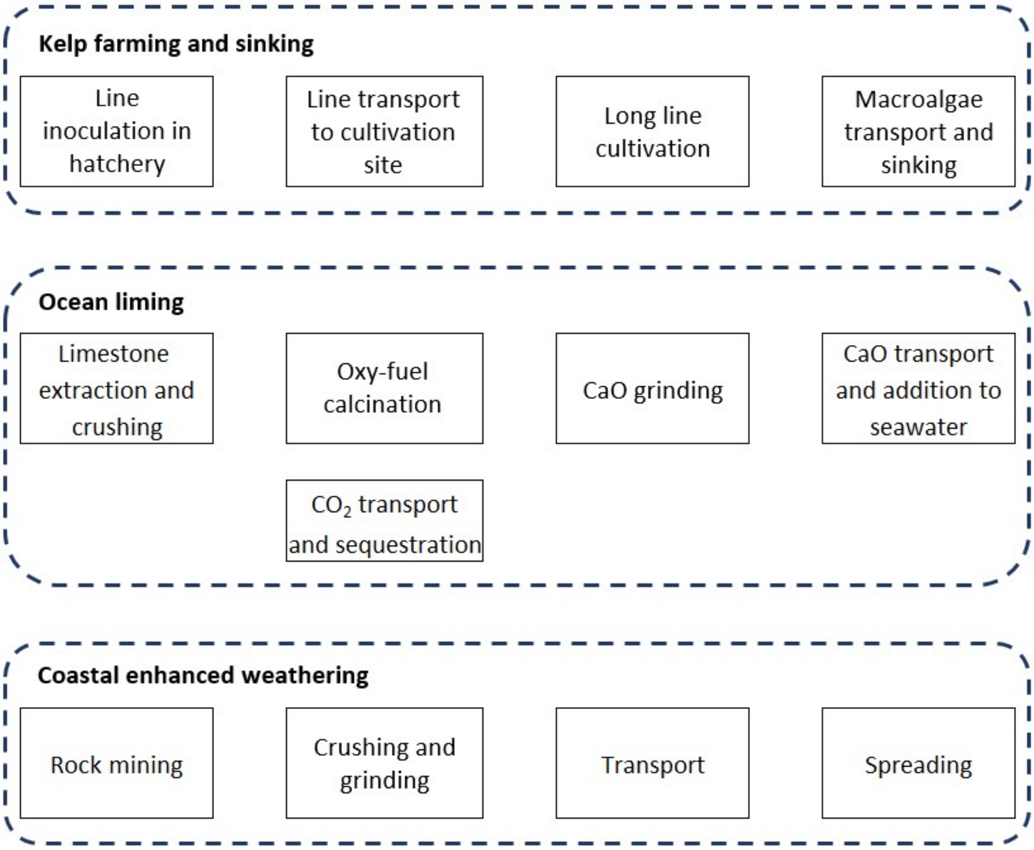

Figure 8. System boundaries and foreground activities considered in the LCA models of the assessed scenarios.

In the ocean liming scenarios, CaO particles are discharged in the open ocean. Renforth et al.[40] estimated that CaO particles of ≈80 µm completely dissolve before they reach the bottom of the ocean's surface mixed layer, triggering the drawdown of atmospheric CO_2 *via* reaction R4.

$$CaO + 2CO_2 + H_2O \rightleftarrows Ca^{2+} + 2HCO_3^- \quad \text{(R4)}$$

Theoretically, 2 moles of CO_2 react per mole of CaO. In reality, between 1.6 and 1.8 moles of CO_2 are absorbed in the seawater per mole of CaO, depending on the temperature and atmospheric CO_2 concentration.[40] The optimistic and pessimistic ocean liming scenarios (OL1 and OL2) are based on the extreme values of this range

(Table 3). Our life cycle model considers the production of CaO by means of the oxy-fuel calcination of limestone, according to Renforth et al.[40] (energy and water consumption in [51], natural gas emission factors taken from [52,53]). The CO_2 produced in the process – due to the oxy-combustion of natural gas and the decomposition of $CaCO_3$ – is compressed, transported a conservative distance of 400 km, and sequestered in a geological formation (life cycle inventory of the CO_2 transport and sequestration process derived from [54]). Grinding CaO requires 19.44 kWh/tonne.[40] The 2018 global electricity mix[55] is used to power the cryogenic air separation, CO_2 compression and CaO milling processes. The calcination plant is assumed to be located close to the shore, and therefore the produced CaO only requires transportation by ship to the open ocean discharge site.

Coastal enhanced weathering constitutes another type of ocean alkalinization NETP. We consider that olivine is mined, milled, and spread over the coastline. Given the washing effect of seawater on the beach, the olivine particles are transferred to the ocean, where they are dissolved and subsequently react with CO_2 according to reaction R5, shifting the equilibrium between the atmospheric and water CO_2 concentrations, and drawing the absorption of atmospheric CO_2 into the seawater.

$$(Mg,Fe)_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2(Mg,Fe)^{2+} + 4HCO_3^- + H_4SiO_4 \qquad \text{(R5)}$$

The dissolution of the olivine particles and therefore the CO_2 sequestration is not immediate. We estimated with Hangx and Spiers' model[41] that spreading 100 µm olivine particles over a beach at 25 and 15 ºC (scenarios EW1 and EW2) lead to the dissolution of 81 and 41% of the particles within a 100-year timeframe, respectively. Since the dissolution of the silicate minerals is the rate limiting step of the weathering reactions,[41] we assumed that the dissolved minerals can immediately react with CO_2.

In the pessimistic scenario (EW2), the marine chemistry conditions reduce by 20% the stoichiometric CO_2/olivine ratio given by reaction R5,[42] i.e., 0.96 tonne of CO_2 are sequestered per tonne of olivine. Conversely, in scenario EW1 we consider that 2.09 tonne of CO_2 are sequestered per tonne of olivine dissolved.[43] Only 57% of CDR is due to the increased alkalinity in EW1; the remaining CDR is due to the fertilization effect associated with the iron present in the olivine (37%) and the produced H_4SiO_4 (6%), which leads to the fixation of carbon by photosynthetic organisms.[43]

In both scenarios the nickel and chromium (Cr^{3+}) contents of olivine are 2.63 and 0.048 kg/tonne, respectively.[44] Crushing and grinding operations, assumed to be powered with the 2018 global electricity mix,[55] consume 13.4 kWh/tonne.[41]

Table 3. Parameters specific to the optimistic and pessimistic scenarios.

NETP	Parameter	Optimistic scenario (1)	Pessimistic scenario (2)	Unit
Kelp farming & sinking (AL)	Kelp productivity[35]	18.8	16.5	tonne per ha per 9 months (d.w.)
	Distance of cultivation site from shore	5	15	km
Ocean liming (OL)	Sequestered CO_2[36]	1.8	1.6	mol CO_2/mol CaO
	Limestone transport	50	100	km
Enhanced weathering (EW)	Dissolved olivine[37]	81.35	40.92	% (mass), 100 years
	Sequestered CO_2	0.96[38]	2.09[39]	tonne CO_2/tonne olivine
	Olivine transport	200	400	km

4. *Key findings*

Figure 9 displays the climate change impacts and the CDR efficiency of the six assessed scenarios. The averted climate change impacts vary between 836 and 980 kg CO_2-eq per tonne of CO_2 sequestered in the ocean, whereas the CDR efficiency lies in the range 0.87-0.98. EW1 is the best scenario in terms of both KPIs; the greenhouse gas emissions generated throughout the life cycle of this NETP – which are mainly associated with the olivine transportation – are substantially low compared to the other scenarios. Despite the considerably more pessimistic assumptions made in the EW2 scenario, it ranks second among the studied scenarios when they are ordered from lower to higher climate change impacts. Moreover, EW2 shows the third highest CDR efficiency, after OL1. Hence, we identify coastal enhanced weathering as a promising NETP for climate change mitigation.

The kelp farming and sinking scenarios can prevent 848-862 kg CO_2-eq per tonne of CO_2 sequestered, achieving CDR efficiencies of 0.87-0.88. Here the main source of greenhouse gases is the production of the nylon ropes, followed by the transport of the harvested algae. The performance of ocean liming is similar to that of AL1/2, but scenario OL2 attains the worst climate change and CDR efficiency KPIs, primarily because of the high electricity consumption of the oxy-fuel limestone calcination process.

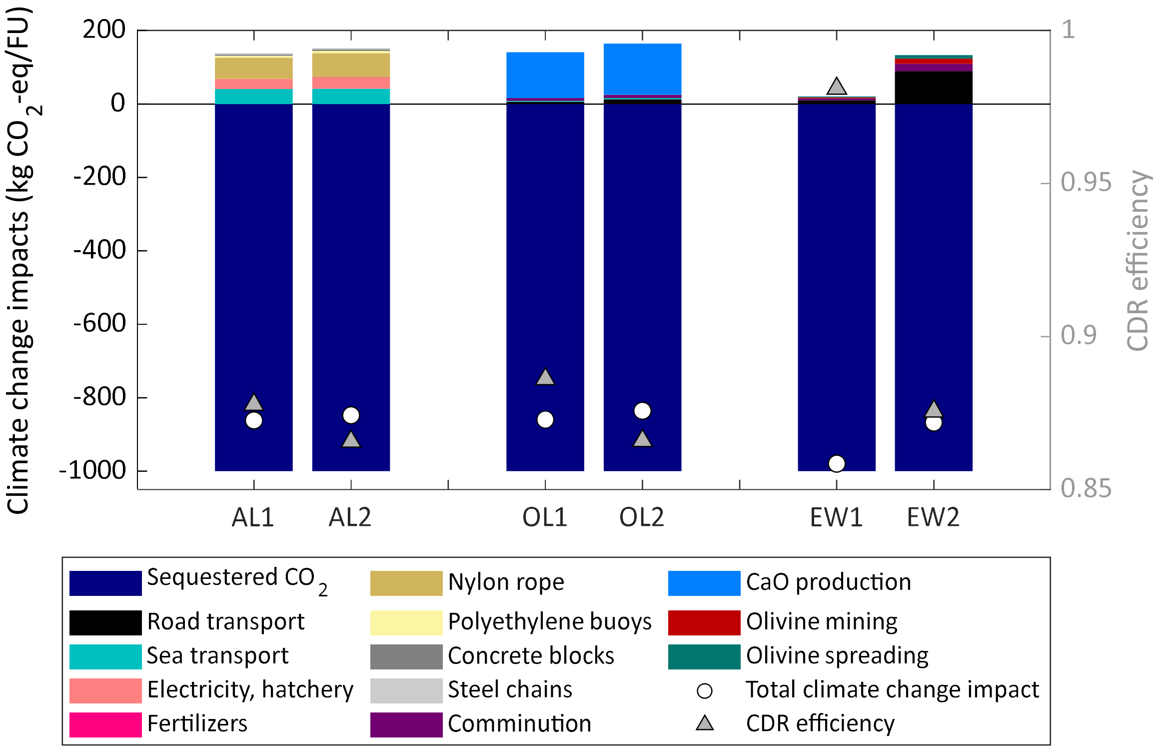

Figure 9. CDR efficiency and climate change impacts per tonne of sequestered CO_2 for the studied scenarios: kelp farming and sinking (AL1, AL2), ocean liming (OL1, OL2) and enhanced weathering (EW1, EW2).

Furthermore, the ocean liming scenarios show the highest impacts in five of the environmental categories depicted in Figure 10 – mainly because of the oxy-fuel limestone calcination process –, namely ionizing radiation, photochemical ozone formation and freshwater eutrophication (linked to the electricity consumption), water use (to cool the gas and remove the water in the CO_2 stream), and fossil resource use (mostly due to the natural gas consumption).

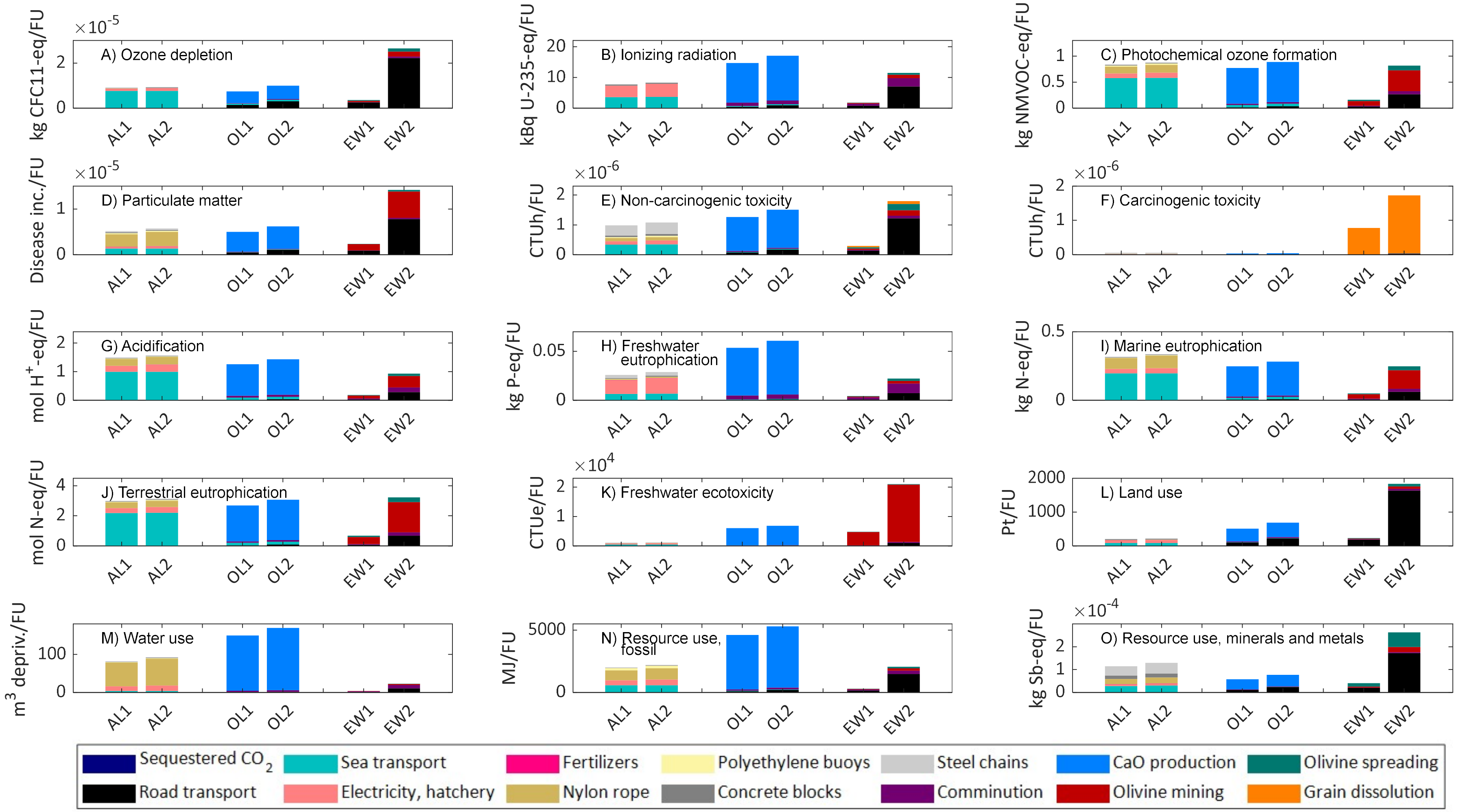

Figure 10. Environmental KPIs per tonne of sequestered CO_2: a) ozone depletion, b) Ionizing radiation, c) photochemical ozone formation, d) particulate matter, e) non-carcinogenic toxicity, f) carcinogenic toxicity, g) acidification, h) freshwater eutrophication, i) marine eutrophication, j) terrestrial eutrophication, k) freshwater ecotoxicity, l) land use, m) water use, n) resource use (fossil), o) resource use (minerals and metals) for the studied scenarios: kelp farming and sinking (AL1, AL2), ocean liming (OL1, OL2) and enhanced weathering (EW1, EW2).

Scenario EW1 attains the lowest impacts across all the environmental categories but three: carcinogenic human toxicity, freshwater ecotoxicity and land use (Figure 10). The carcinogenic toxicity impacts of coastal enhanced weathering – which are 13-51 times greater than those of the other scenarios – are due to the dissolution of the nickel and chromium present in the olivine grains, whereas freshwater ecotoxicity is associated with the emissions that occur in the blasting activities required in the olivine mining operations. Land use is linked to the olivine transportation. The carcinogenic toxicity, freshwater ecotoxicity and land-use impacts are amplified in scenario EW2, which also shows the highest values for the following environmental KPIs: ozone depletion, non-carcinogenic toxicity, mineral and metal use (all of which are mainly due to the olivine transportation), particulate matter (related to the olivine transportation and mining), and terrestrial eutrophication (principally because of the nitrogen emissions linked to the explosives used in the mining activities).

The kelp farming and sinking scenarios achieve the lowest impacts in the freshwater ecotoxicity and land-use categories. However, they lead to the highest acidification and marine eutrophication impacts due to the pollutants emitted during the transport of the harvested algae by ship, which also cause substantial terrestrial eutrophication and photochemical ozone formation impacts.

Figure 11 shows the damage inflicted by the assessed NETPs on human health, ecosystem quality and resource scarcity. The prevented harmful impacts of global warming on human health (Figure 11a) are only partially offset by the detrimental health effects produced throughout the NETPs' life cycle, chiefly linked to fine particulate matter formation. Hence, all the assessed scenarios can avert net human health impacts, ranging between $3.6 \cdot 10^{-4}$ and $8.1 \cdot 10^{-4}$ Disability-Adjusted Life Years (DALYs) per tonne of CO_2 sequestered in the ocean. The extreme values of this interval correspond to scenarios EW2 and EW1; the others present similar human health impacts, i.e., $4.9 \cdot 10^{-4}$-$5.5 \cdot 10^{-4}$ avoided DALYs/tonne of CO_2.

The modeled NETPs can also prevent net damage to ecosystems (Figure 11b). Terrestrial acidification is the main cause of ecosystem damage, but it is outweighed by the avoided climate change impacts on ecosystem quality. The averted ecosystem impacts span between $1.9 \cdot 10^{-6}$ and $2.6 \cdot 10^{-6}$ species·yr/tonne of sequestered CO_2 (one species·yr represents the loss of one species over one year). EW1 is the best-performing scenario in this impact category too, with the others – the most damaging of which is OL2 – avoiding comparable net impacts ($1.9 \cdot 10^{-6}$-$2.1 \cdot 10^{-6}$ species·yr/tonne).

The damage to resource availability (Figure 11c) varies between 2.5 and 38.8 USD/tonne of CO_2 in scenarios EW1 and OL2, respectively. The use of mineral resources is negligible compared to the consumption of fossil resources, which is particularly high in the ocean liming scenarios. The damage to resource scarcity is below 18.1 USD/tonne of CO_2 in the kelp farming and sinking and the enhanced weathering scenarios.

Finally, we expressed the impact of the analyzed marine NETPs on these areas of protection (human health, ecosystems and resource availability) in monetary units to estimate the associated externalities (Figure 12). The prevented impacts on human health and ecosystems result in net avoided externalities across the studied scenarios, with the averted human health impacts contributing to the largest share of the avoided externalities. The prevented externalities – which range between 36.2 and 103.0 €/tonne of CO_2 in the OL2 and EW1 scenarios – represent 27-78% of the cost estimates reported for ocean liming (Table 4). In the coastal enhanced weathering scenarios, the externalities are 5-14 times greater than the extimated costs, whereas they only represent 2-4% of the estimated costs of kelp farming and sinking, which exceed 1000 €/tonne of CO_2.

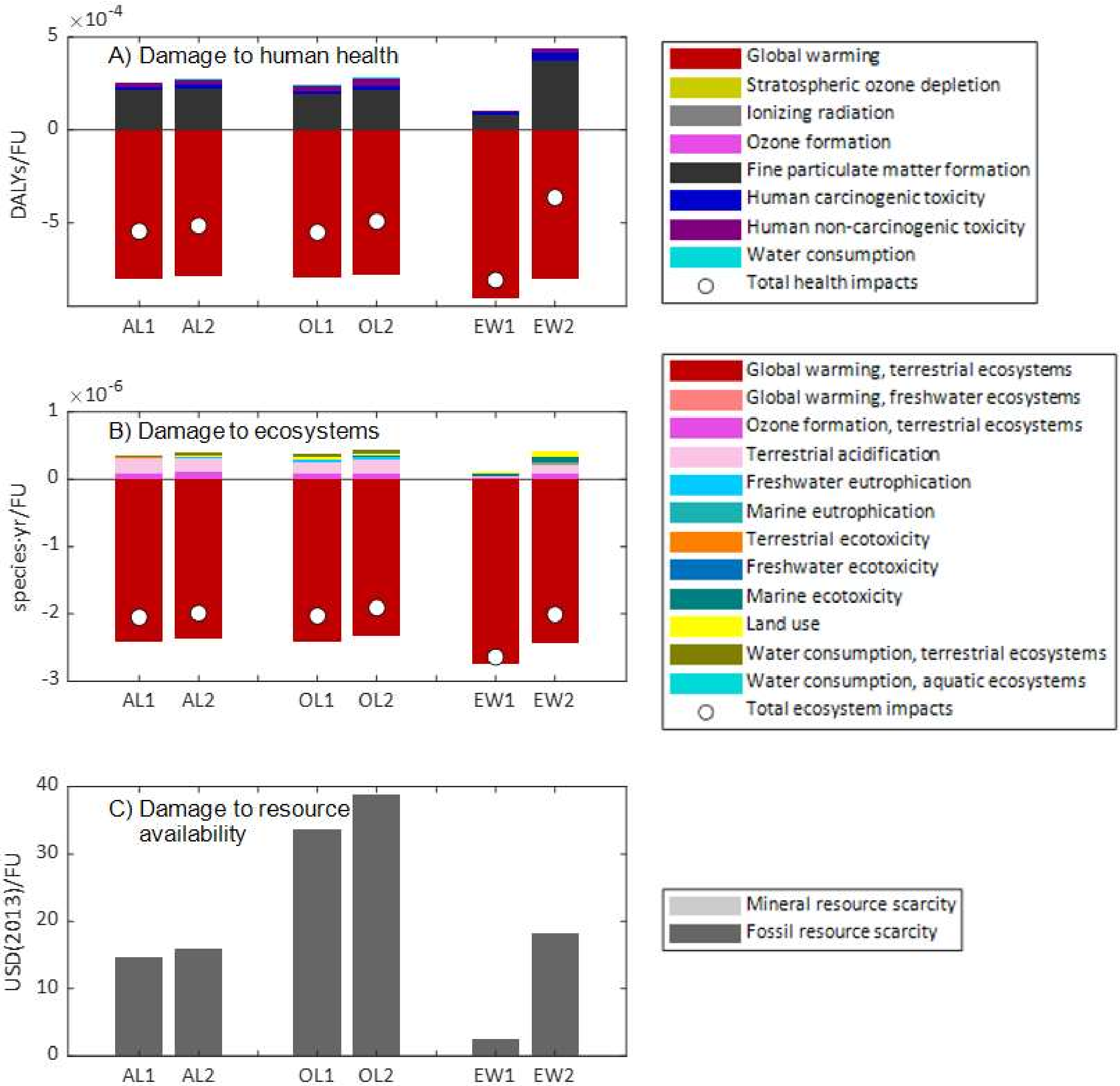

Figure 11. Endpoint KPIs per tonne of sequestered CO_2: a) damage to human health, b) damage to ecosystems, c) damage to resource scarcity for the studied scenarios: kelp farming and sinking (AL1, AL2), ocean liming (OL1, OL2) and enhanced weathering (EW1, EW2).

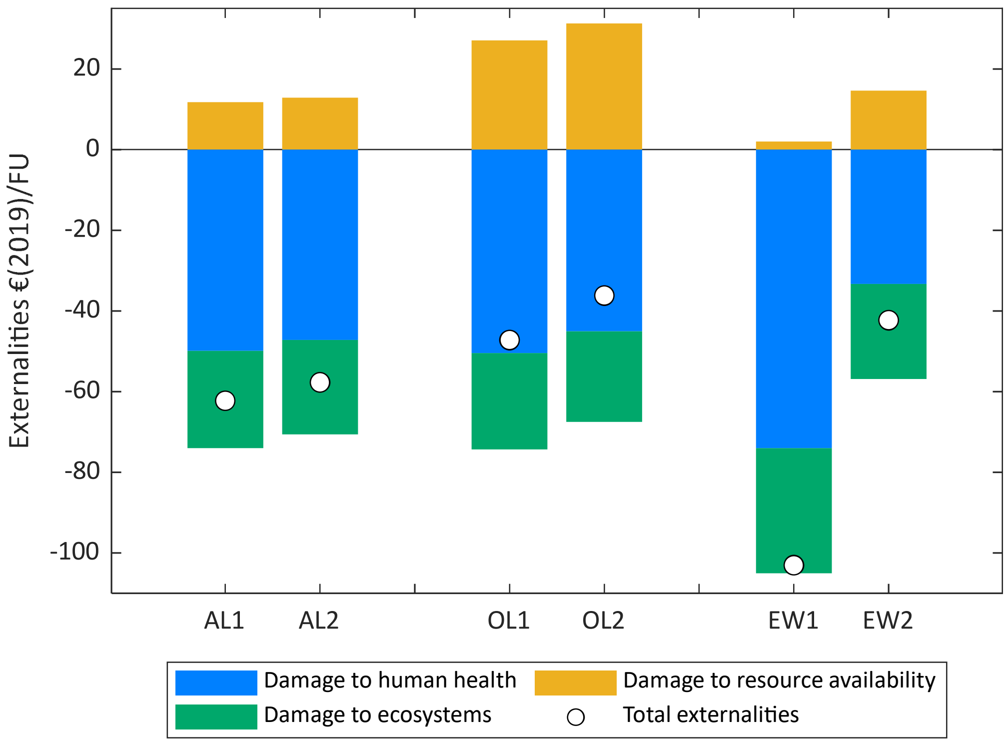

Figure 12. Externalities per tonne of sequestered CO_2 for the studied scenarios: kelp farming and sinking (AL1, AL2), ocean liming (OL1, OL2) and enhanced weathering (EW1, EW2).

Table 4. Estimated costs of marine NETPs.

	CO_2 sequestration costs[a] €(2019)/FU
Kelp farming and sinking[56,b]	1650-2654
Ocean liming[40]	60-133
Coastal enhanced weathering[57]	7-8

[a]Published estimates adjusted for inflation[58] and currency conversion.[59]
[b]No available estimates, kelp selling price taken as an approximation.

Figure 13 compiles the KPIs of the assessed scenarios, normalized with respect to the maximum KPI values of each category. The KPIs of the two coastal enhanced weathering scenarios significantly differ; under optimistic assumptions this NETP outperforms the others in most impact categories, but the impacts of the scenario based on pessimistic assumptions considerably exceed those of the other scenarios in several categories, namely ozone depletion, particulate matter formation, freshwater ecotoxicity and land use.

Overall, the performance of the ocean liming and the kelp farming and sinking scenarios varies with the selected KPIs. However, the ocean liming scenarios present substantially higher environmental impacts in the following categories: water use, resource scarcity, ionizing radiation, and freshwater eutrophication.

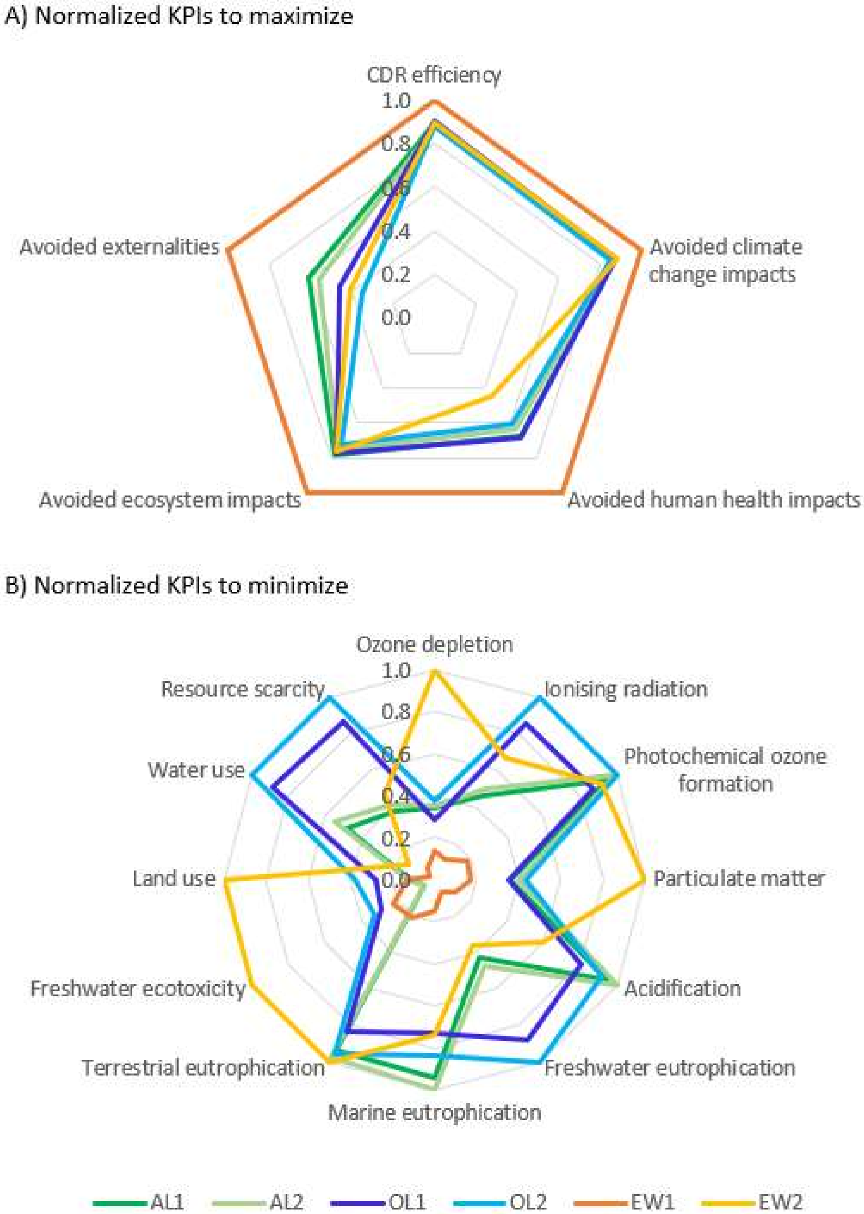

Figure 13. Normalized KPIs. A) KPIs to maximize, B) KPIs to minimize for the studied scenarios: kelp farming and sinking (AL1, AL2), ocean liming (OL1, OL2) and enhanced weathering (EW1, EW2).

5. Conclusions and further steps

Marine NETPs are still emerging CDR strategies. Only recently, initiatives such as Project Vesta[60] and Running Tide[61] have launched pilot projects to assess the feasibility of CDR *via* coastal enhanced weathering and kelp farming and sinking. Given the lack of a frame of reference, the results presented in this report are subject to the uncertainty inherent to our data and modeling assumptions, which we attempted to showcase by defining scenarios based on optimistic and pessimistic conditions. Therefore, experimental research is required to validate some of the assumptions made and uncover potential side-effects not accounted for here. At the same time, the insights gained from this work could help underpin future research activities.

This analysis enabled us to identify the main sources of impacts for the studied marine NETPs. Most of the impacts of the costal enhanced weathering scenarios stem from the olivine transportation. Hence, finding coastal environments close to the mine locations to spread the olivine particles could greatly reduce the impact of this NETP. On the other hand, the electricity consumption is the main contributor to the impacts of the ocean liming scenarios. Consequently, deploying cleaner electricity mixes would improve the performance of ocean liming. Likewise, coupling the calcination process with post-combustion capture technologies less reliant on electricity, such as monoethanolamine absorption, could decrease the detrimental impacts of this NETP. In the kelp farming and sinking scenarios, the deployed nylon ropes and the transport of the harvested algae to the open ocean sinking site account for a substantial share of the total impacts. Thus, using alternative materials to hang the algae and incorporating a drying process (e.g., a screw press) into the vessel to reduce the moisture content and hence the total biomass weight would improve the environmental performance of this NETP.

Coastal enhanced weathering is the most affordable of the assessed marine NETPs; its estimated cost is approximately 8 €/tonne of CO_2, one order of magnitude lower than the available cost estimates for ocean liming. Moreover, the externalities averted in the coastal enhanced weathering scenarios greatly exceed their estimated costs, whereas the externalities prevented with ocean liming represent a significant share of the costs, which could help advance the deployment of these NETPs. Although there are no available cost estimates for kelp farming and sinking, the high selling price of kelp leads us to believe that it might be difficult for this NETP to economically compete with the other NETPs assessed here.

These results highlight the importance of considering all the sustainability dimensions to guide future decisions. Further research should investigate other aspects neglected here, such as the implications of countering ocean acidification with the addition of alkaline materials to the seawater, the potential methane emissions associated with macroalgae cultivation – an increase in net primary productivity has been linked to the release of methane in the open ocean –,[62] or the possible rebound effects of iron fertilization (due to the iron present in the olivine) on the local biodiversity. The impacts of marine NETPs will be further analyzed in D3.5, whereas the sustainability performance of marine NETPs will be compared to that of the other NETPs in D3.8.

To prepare this report, the following deliverable has been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D1.1	Justification of NETPs chosen for the NEGEM project	ETH	Report	CO	6
D1.2	Comprehensive sustainability assessment of terrestrial biodiversity NETPs	ETH	Report	PU	12
D8.1	Stocktaking of scenarios with negative emission technologies and practices - Documentation of the vision making process and initial NEGEM vision	VTT	Report	PU	8

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