NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Report on comparative life-cycle sustainability assessment of NETPs for impacts on human health, ecological functions and resources

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Executive Summary and policy relevant messages

Limiting global warming to 1.5 °C above pre-industrial levels will most likely require the large-scale deployment of Negative Emissions Technologies and Practices (NETPs).[1] However, a comparative sustainability assessment of multiple NETPs is still lacking in the literature. Here we conducted a life cycle assessment to investigate the damage caused by 24 NETPs systems to three areas of protection – human health, ecosystem quality and resource scarcity. The NETPs were classified as terrestrial (forestation, manufacturing of wood products, soil application of biochar), marine (kelp farming and sinking, ocean liming and coastal enhanced weathering), Bioenergy with Carbon Capture and Storage (BECCS systems comprising combustion, gasification and Fischer-Tropsch processes), and chemical (enhanced weathering on croplands and Direct Air Carbon Capture, DACCS).

While the global warming impacts averted by Carbon Dioxide Removal (CDR) lead to the prevention of harmful effects on health and ecosystems, the pollutants emitted and resources consumed throughout the NETPs life cycle can counteract these co-benefits and even generate net damage. We found trade-offs between the evaluated endpoint indicators; i.e., none of the assessed NETPs outperformed all the others in more than one area of protection. Nonetheless, coastal enhanced weathering and Low Temperature Solid Sorbent DACCS (LTSS-DACCS) attain good positions in all the scenario rankings, preventing net damage to human health ($5.8 \cdot 10^{-4}$-$8.6 \cdot 10^{-4}$ DALY – Disability-Adjusted Life Years – per tonne CO_2 sequestered) and ecosystems ($2.3 \cdot 10^{-6}$-$2.6 \cdot 10^{-6}$ species·yr/tonne CO_2), and generating minor damage to resource availability (2.2-8.2 \$/tonne CO_2). High Temperature Liquid Sorbent DACCS (HTLS-DACCS) can generate more benefits for human health and ecosystems than LTSS-DACCS; however, the strong dependance of HTLS-DACCS on natural gas makes it the most damaging NETP in terms of resource scarcity. Similarly, the ocean liming scenarios perform poorly in the resource scarcity impact category because of their high energy demand, despite the prevented health and ecosystems impacts.

Regarding the enhanced weathering configurations, their net health gains are reduced by 80-83% if dunite grains are spread on croplands instead of beach environments, because of the carcinogenic toxicity impacts that arise from the release of certain metals to the agricultural soil. Deploying basalt particles would generate substantial net harmful effects ($2.4 \cdot 10^{-3}$ DALY/tonne CO_2 sequestered) due to the non-carcinogenic toxicity impacts associated with the metals contained in basalt.

Our analysis reveals that the human health and ecosystems impacts prevented by kelp farming and sinking are low, mainly because the benefits of CDR are partially offset by the induced decline in the phytoplankton net primary productivity. This NETP is not appealing from the resource scarcity viewpoint either, due to the fossil resources consumed in the macroalgae cultivation and transport phases.

The NETPs deploying terrestrial biomass (classified as BECCS and terrestrial NETPs) are the most damaging to ecosystems, generating either net impacts ($1.8 \cdot 10^{-6}$-$2.7 \cdot 10^{-5}$ species·yr/tonne CO_2 sequestered) or, in the case of combustion-BECCS deploying *Miscanthus*, very low benefits ($6.5 \cdot 10^{-7}$ species·yr/tonne CO_2). The main reason for the ecosystems impacts of these NETPs is the substantial land use required in the biomass cultivation phase, although the crop water demand also has a harmful effect on ecosystems.

The impacts of the BECCS configurations on human health greatly depends on the selected biomass source. The configurations relying on poplar generate either net human health impacts (gasification and Fischer-Tropsch) or very low health benefits (combustion), because of the water used to irrigate the biomass, which may lead to a reduction in freshwater availability. By contrast, the BECCS scenarios deploying *Miscanthus*, which does not require irrigation, attain positions two to four in the human health ranking – preventing $8.8 \cdot 10^{-4}$-$1.3 \cdot 10^{-3}$ DALY/tonne CO_2 sequestered – due to the substitution of other energy vectors. Furthermore, the Fischer-Tropsch

BECCS scenarios can avert substantial damage to resource scarcity due to the replacement of the global 2030 electricity mix and fossil crude oil with the produced bioelectricity and syncrude.

Most terrestrial NETPs perform poorly in the human health impact category, mainly because of the water consumption in the wood and biochar scenarios, and the NO_X and fine particulate matter emissions that occur during fire events and the road construction and maintenance operations in the forestation scenarios. However, the production of glued laminated timber (glulam) attains the greatest health benefits across the studied scenarios due to the ability of glulam to replace steel as a construction material. Likewise, the biochar scenarios attain good positions in the resource scarcity ranking because the extra heat generated in the pyrolysis process avoids the extraction of natural gas.

Based on the findings presented in this report, we conclude that CDR strategies relying on chemical processes are more promising than those deploying biomass. Therefore, future research and policies should prioritize chemical NETPs. Nonetheless, given their current low deployment level and the urgency to scale them up, CDR pathways will likely integrate multiple NETPs. This analysis can help design optimal CDR pathways that exploit the synergies between NETPs and take advantage of the available local resources while minimizing detrimental impacts.

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List of abbreviations

AFF. Afforestation.

AL. Macroalgae farming and sinking.

APS. Announced Pledges Scenario.

BAS. Basalt.

BC. Soil application of biochar.

BECCS. Bioenergy with Carbon Capture and Storage.

CCS. Carbon Capture and Storage.

CEW. Coastal Enhanced Weathering.

CDR. Carbon Dioxide Removal.

COMB. Combustion-BECCS (electricity production).

DACCS. Direct Air Carbon Capture and Storage.

DALY. Disability-Adjusted Life Year.

DUN. Dunite.

EW. Enhanced Weathering.

FT. Fischer-Tropsch BECCS (syncrude production).

FU. Functional Unit.

GAS. Gasification-BECCS (hydrogen production).

GEO. Geothermal energy.

GLU. Glulam production.

Glulam. Glued laminated timber.

HTLS. High Temperature Liquid Sorbent.

LCA. Life Cycle Assessment.

LCI. Life Cycle Inventory.

LTSS. Low Temperature Solid Sorbent.

MISC. *Miscanthus.*

NETPs. Negative Emissions Technologies and Practices.

NG. Natural Gas.

OL. Ocean liming.

PNPP. Phytoplankton Net Primary Productivity.

POP. Poplar.

OSB. Oriented Strand Board production.

REF. Reforestation.

1. Introduction

To stand a 67% chance of limiting global warming to 1.5 °C above pre-industrial levels, the cumulative net anthropogenic CO_2 emitted since the beginning of 2020 should not surpass 400 Gtonne.[2] Nonetheless, if the current emissions levels are maintained, we will exceed the remaining carbon budget within this decade.[2] To avoid this, most climate change mitigation pathways projected by the IPCC rely on Carbon Dioxide Removal (CDR) in addition to stringent emissions reductions, with some of them removing up to 1000 Gtonne CO_2 from the atmosphere by 2100 (median estimate for scenarios with low or limited temperature overshoot: 584 Gtonne CO_2).[1]

Here we define Negative Emission Technologies and Practices (NETPs) as those capable of removing CO_2 and other greenhouse gases from the atmosphere and either effectively sequestering them in a sink that is not subject to foreseeable perturbations, or permanently transforming them into other compounds with lower global warming potentials. A system can only attain negative emissions if the global warming impacts caused by the greenhouse gases emitted throughout its entire life cycle do not exceed the global warming impacts prevented by the greenhouse gas removal.

Many negative emissions systems have been proposed in the literature;[3] greenhouse gases can be removed from the atmosphere by enhancing the natural carbon capture capacity of terrestrial and marine sinks, or by deploying technologies to transform or capture and sequester greenhouse gases. We differentiate between two types of technologies: bioenergy technologies that generate waste streams with a high content in biogenic carbon, and chemical technologies, which exploit the ability of greenhouse gases to react with specific compounds.

A few studies have previously investigated the sustainability implications of certain NETPs,[4–9] but a comprehensive assessment comparing multiple NETPs is still lacking. Here we aim to fill this gap by evaluating the potential damage caused by 12 NETPs to three areas of protection – human health, ecosystems quality and resource scarcity – at the global scale. We defined two scenarios for each main NETP configuration in order to assess how the results change under different assumptions. The selected NETPs – which were preliminary identified in WP1 as promising in terms of their Technology Readiness Level, CDR potential, costs and side-effects are the following:

- Terrestrial NETPs, which sequester carbon in the soil and land-based biological stocks. They comprise afforestation, reforestation, the production of oriented strand board and glued laminated timber, and the soil application of biochar (considering a pyrolysis process with and without capture and storage of the generated CO_2).
- Marine NETPs. They store carbon in the ocean and consist of kelp farming and sinking, ocean liming and coastal enhanced weathering.
- Bioenergy with Carbon Capture and Storage (BECCS). These NETPs transform biomass into various energy vectors and sequester the produced biogenic CO_2. We modeled combustion-BECCS to generate electricity, gasification-BECCS to produce hydrogen and BECCS based on the Fischer-Tropsch process to produce syncrude. Two types of biomass feedstock were considered for each BECCS scenario: *Miscanthus* and poplar.
- Chemical NETPs, which rely on chemical reactions to remove greenhouse gases from the atmosphere. These include Low Temperature Solid Sorbent Direct Air Carbon Capture and Storage (LTSS-DACCS) powered by wind and geothermal energy, High Temperature Liquid Sorbent DACCS (HTLS-DACCS) deploying natural gas and wind, and enhanced weathering based on the spreading of basalt and dunite rocks on croplands.

2. Methodology

We conducted an attributional Life Cycle Assessment (LCA)[10] of the selected NETPs following the LCA phases summarized in Figure 1. We 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). We assume that the secondary functions of the assessed NETPs – i.e., the products and services they provide in addition to CDR – substitute equivalent functions provided by other systems, and therefore we applied the system boundary expansion method.[10]

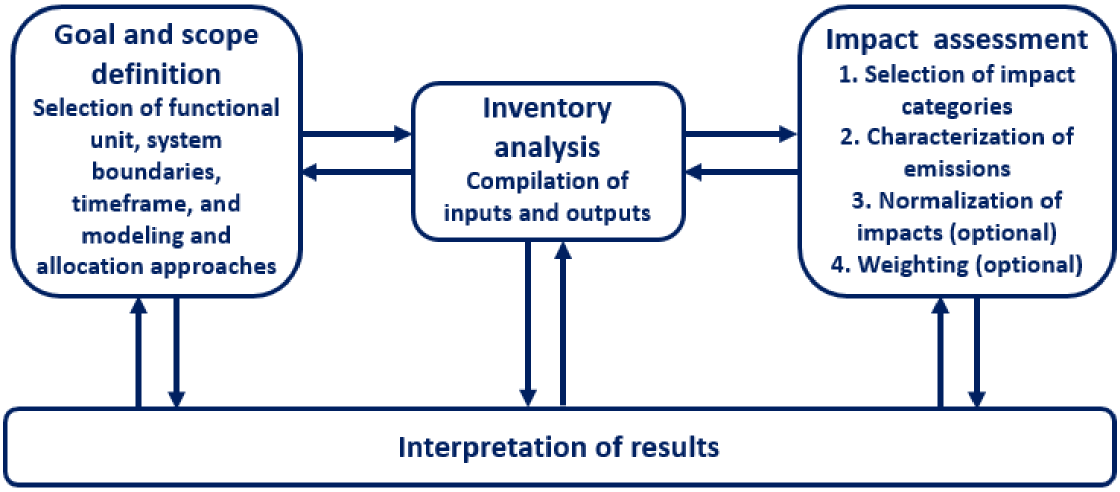

Figure 1. LCA phases. Adapted from ISO 14040[11].

We used the ReCiPe 2016 impact assessment method[12] (hierarchist perspective), which translates the midpoint impacts associated with emissions and resource consumption into damage to three areas of protection, namely human health, ecosystem quality and resource scarcity, as Figure 2 shows. This method quantifies the damage to human health in DALYs (Disability-Adjusted Life Years), which represent the years of healthy life lost. The damage to ecosystems is expressed in species·yr, i.e., the local species loss integrated over time. The damage to resource scarcity represents the extra costs (in $\$_{2013}$) associated with the extraction of future fossil and mineral resources.

The damage to area of protection *a* caused by NETP *n* ($D_{a,n}$) is estimated with equation e1, where $EF_{s,n}$ represents the elementary flows of NETP *n* for the set *S* of stressors – which comprises the substances emitted and the resources consumed by NETPs – , and $CF_{s,a}$, the characterization factor provided by the ReCiPe method, which quantifies the impact of stressor *s* on area of protection *a*. Note that CDR is modeled as a negative CO_2 elementary flow, leading to negative damage, which we refer to as *prevented impact*.

$$D_{a,n} = \sum_{s \in S} EF_{s,n} \cdot CF_{s,a} \quad \forall\, a, n \qquad \text{(e1)}$$

The developed life cycle models were implemented in SimaPro 9.1.0.8,[13] and are based on data reported in the scientific literature and activities from the Ecoinvent 3.5 database (cut-off by classification allocation method).[14] Neither our data nor the applied characterization factors are geographically differentiated, i.e., our results represent global averages and cannot be ascribed to any specific world region.

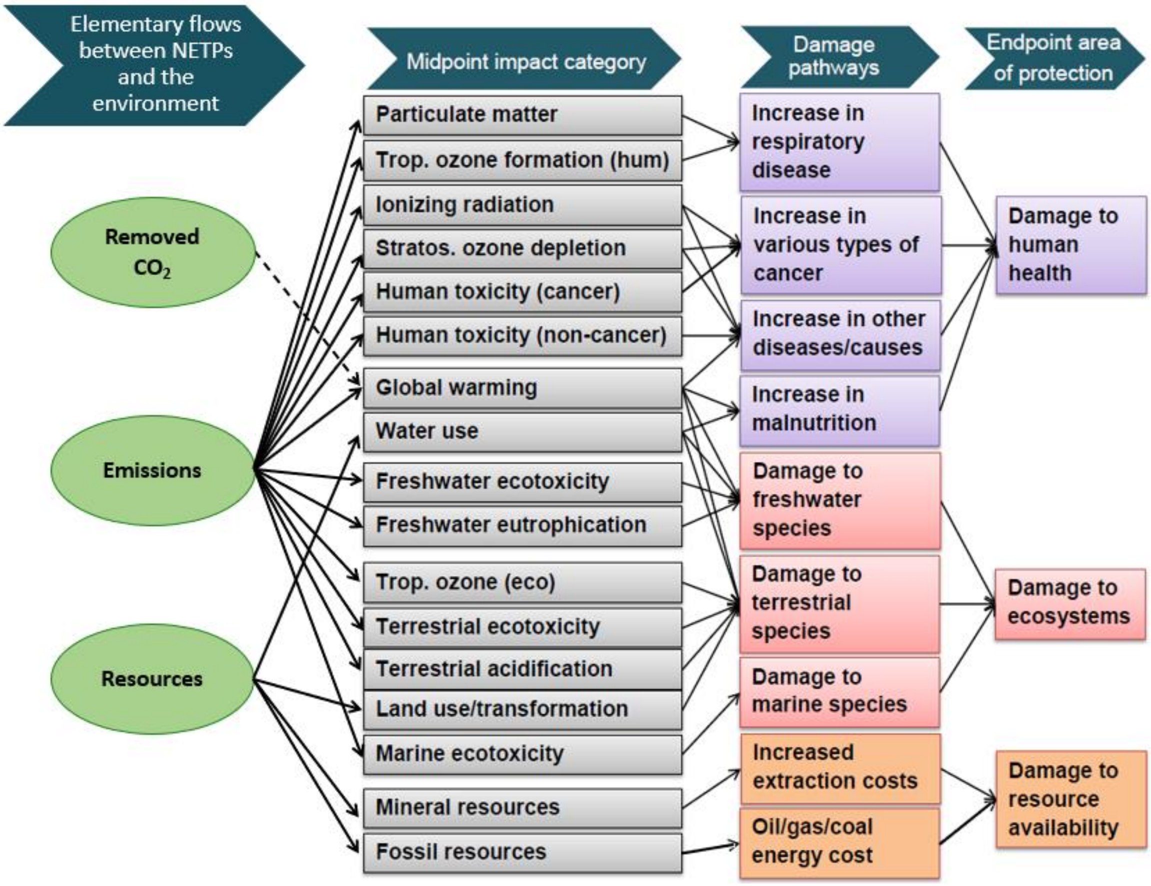

Figure 2. Links between NETPs and the damage caused to the three assessed areas of protection. The dashed arrow indicates the beginning of a cause-and-effect chain leading to prevented damage. Adapted from Huijbregts et al.[12]

3. Scenario definition

This report builds on the LCA models described in Deliverables 1.2-1.5.[15–18] We have updated and improved the Life Cycle Inventories (LCIs) used in the WP1 Deliverables in order to harmonize the data and assumptions made across all the scenarios.

The foreground activities of our models deploy the 2030 global electricity mix projected by the IEA in the Announced Pledges Scenario (APS), which assumes that all the climate commitments made by governments around the world will be met on time.[19] Furthermore, the scenarios that generate a pure stream of CO_2 demand additional electricity (132 kWh/tonne) in order to compress the CO_2 to 150 bar prior to injecting it in a geological reservoir. We consider that the captured CO_2 is transported through onshore pipelines over a distance of 400 km, with an intermediate recompression stage.[20]

Here we provide a brief overview of the 24 studied NETPs configurations – classified as terrestrial, marine, BECCS or chemical NETPs –, and the changes with respect to previous Deliverables. For a complete description of the assessed scenarios and data sources, refer to Deliverables 1.2-1.5.[15–18]

3.1. Terrestrial NETPs

The studied terrestrial NETPs include forestation – afforestation and reforestation –, the production of engineered wood – oriented strand board and glued laminated timber (glulam) –, and the application of biochar to the soil – considering scenarios with and without the Carbon Capture and Storage (CCS) of the CO_2 produced in the pyrolysis process.

Forestation practices in boreal regions can induce a decrease in the surface albedo that might lead to a net warming effect, whereas the net climate forcing of temperate forests is extremely uncertain and location-dependent.[21,22] Therefore, here we focus on tropical forests, which can generate net cooling.[21,22] We consider afforestation (tropical dry forest) and reforestation (tropical rainforest) scenarios. We have incorporated into our previous forestation models the carbon leakage rate due to natural disturbances such as fires and pests – 1.6%/year, assuming a 2%/year disturbance rate and 80% mortality rate.[23] The leaked carbon is released as CO_2, CO and CH_4, and N_2O and NO_X are emitted as well, in accordance with the emission factors provided by the IPCC.[24]

In Deliverable 1.2[15] we showed the poor performance of medium density fiberboard in most impact categories. Hence, here we have replaced that scenario with the manufacturing of another engineered wood product, i.e., oriented strand board. Both oriented strand board and glulam are produced with poplar wood. In the glulam scenarios, the non-marketable wood is used to produce oriented strand board. We consider that glulam replaces steel as a construction material, whereas oriented strand board is used as a substitute for gypsum plasterboard. Given the good mechanical properties of oriented strand board and glulam, and their application as structural materials, we assume that they remain functional within the 100-year time horizon of our analysis.

In the biochar scenarios, poplar wood chips are subjected to a slow pyrolysis process at 450 ^{o}C that allows the sequestration of 50% of the biomass carbon in the biochar. The excess heat generated by burning the gas and tars generated in the pyrolysis process is assumed to replace heat produced in the combustion of natural gas. In one of the two studied biochar scenarios, the CO_2 generated as the pyrolysis byproducts are burnt is captured via chemical absorption in a monoethanolamine solution and injected into a geological reservoir. Consistent with other works,[25] we considered an average decomposition time of biochar in the soil of 1000 years and a linear decomposition rate, i.e., 10% of the sequestered carbon is released as CO_2 within the selected 100-year time horizon. Nonetheless, the decomposition rate is highly variable, and dependent on the soil temperature.[26]

We assume that the cultivation of poplar in the wood and biochar scenarios results in the sequestration of 0.16 kg of soil organic carbon per m^2, the soil carbon sequestration rate estimated for this species in the tropical shrubland of Western Africa.[15]

3.2. Marine NETPs

We assessed the following marine NETPs: kelp farming and sinking, ocean liming and coastal enhanced weathering. We defined scenarios based on optimistic and pessimistic assumptions, as we described in Deliverable 1.3.[17]

A novel Earth system modeling study found that macroalgae farming and sinking leads to a reduction in the phytoplankton net primary productivity – due to the canopy shading effect of macroalgae and the competition for nutrients –, which offsets approximately 37% of the CDR.[27] We now include this rebound effect into our kelp farming and sinking model.

The ocean liming scenarios are based on the addition of calcium oxide particles to the ocean surface for their subsequent reaction with the dissolved CO_2 to form bicarbonate ions, which shifts the equilibrium between the CO_2 concentrations in the air and seawater, drawing the transfer of atmospheric CO_2 to the ocean. Calcium oxide is produced through the oxy-calcination of calcium carbonate, generating CO_2 that is stored in a geological reservoir.

In the coastal enhanced weathering scenarios, dunite rock – rich in olivine – is mined, milled, and spread over beach environments. When the olivine particles are transferred to the ocean, they dissolve and react with the dissolved CO_2 to produce bicarbonate ions, which triggers the absorption of atmospheric CO_2 into the seawater. We assume that the weathering process occurs at 25 °C and a particle size of 44 µm, i.e., the maximum size that would allow the rock to completely dissolve within 100 years, according to the model developed by Hangx et al.[28] By applying the correlation between the energy demand and particle size proposed by Strefler et al.,[29] we estimate that the grinding operations would require 22.6 kWh/tonne rock. Furthermore, our model now describes the emission of all the metals that compose the dunite rock – taken from Amann et al.[30] – to the seawater as the rock dissolves.

3.3. BECCS NETPs

We evaluate the BECCS configuration described in Deliverable 1.4,[16] which is based on the Fischer-Tropsch process to produce syncrude. In this report we also include hydrogen production through biomass gasification coupled with CCS, and combustion-BECCS for electricity generation.

For each BECCS configuration, we considered two types of biomass: *Miscanthus* (typically found in Africa, Asia, America and Europe)[31] and poplar (widely distributed throughout the Northern Hemisphere).[32] We assumed that the land where the crops are planted was originally grassland. According to Qin et al.,[33] the median Soil Carbon Sequestration rate associated with planting *Miscanthus* and poplar in natural grasslands ($\mathrm{SCS_b}$) is 0.033 and -0.062 kg/m²/year within 0-100 cm of soil depth. We estimated the change in Soil Organic Carbon $\Delta\mathrm{SOC_b}$ associated with the production of 1 kg of biomass *b* with equation e2.

$$\Delta SOC_b = \frac{SCS_b \cdot LO_b \cdot MW_{CO_2}}{MW_C} \quad \forall\, b \qquad \text{(e2)}$$

$\mathrm{LO_b}$ represents the land occupation of *Miscanthus* and poplar (0.3750 and 0.3704 m²·year/kg wet biomass, respectively), and MW_{CO_2} and MW_C denote the molecular weights of CO_2 and carbon. We calculated that 0.0453 kg CO_2 are sequestered per kg *Miscanthus*, and 0.0841 kg CO_2 are emitted per kg poplar (on a wet basis) due to the land transformation. The LCIs of *Miscanthus* and poplar were derived from [34] and [35], respectively. Table 1 shows the main characteristics of the biomass. In all the BECCS scenarios we consider a conservative distance of 100 km (by road) from the biomass cultivation site to the power plant. Since all the BECCS scenarios assume that biomass is grown on previously undisturbed land, our LCIs also include the construction and maintenance of roads (7.5 m per ha of plantation).[36]

Table 1. Biomass data.

	Miscanthus	**Poplar**
Biomass	Chopped grass	Wood chips
Moisture content (%)	42[37]	50
Carbon content (%, wet basis)	27.84	25.16
LHV (GJ/tonne, wet basis)	9.41[37]	7.32
Rotation period (years)	19.21	15
Land transformation (m^2/kg, wet basis)	$1.95 \cdot 10^{-2}$	$2.47 \cdot 10^{-2}$

The combustion-BECCS technology is modeled based on the data provided by the IEA,[38] complemented with the biomass emission factors reported in [39]. The key differences between the combustion technologies considered in the two modeled combustion-BECCS scenarios (COMB-POP and COMB-MISC, the first deploying poplar and the second *Miscanthus*) are displayed in Table 2.

Table 2. Boiler characteristics.

	COMB-MISC	**COMB-POP**
Boiler	Circulating fluidized bed	Bubbling fluidized bed
Nominal capacity (MW_e)	250	75
Gross energy efficiency (%, LHV)	34.3	32.4

In both combustion-BECCS scenarios, part of the low-pressure steam generated in the biomass combustion process is diverted from the turbine to supply the heat required to desorb the CO_2 generated in the biomass combustion from the monoethanolamine (MEA) solution. The parameters used to model the CO_2 capture process are compiled in Table 3.

We assume that the electricity generated in the combustion-BECCS scenarios (742.3 and 527.3 kWh/tonne CO_2 sequestered in COMB-MISC and COMB-POP, respectively) replaces the same amount of electricity generated with the 2030 global grid mix, the composition of which is taken from the APS projected by the IEA.

Our gasification-BECCS model is based on the LCI provided by Susmozas et al,[7] who studied an indirect gasification process with two fluidized bed reactors; one where biomass reacts with steam to produce syngas and char, and another reactor where the char is burned to supply the heat required in the gasification process. The hydrogen concentration in the syngas is increased through the water-gas-shift reaction, and it is subsequently separated from the other gas compounds in a pressure swing adsorption unit. The off-gas is burned to generate steam and electricity, and 70% of the generated CO_2 is separated from the exhaust gas with a membrane system. The composition of the polymeric membrane is derived from [40,41]. This BECCS configuration enables the sequestration of 50% of the atmospheric carbon captured by the biomass. Given the projected increase in the market penetration of hydrogen electrolyzers in the APS,[19] we assume that the hydrogen generated in the gasification-BECCS scenario replaces hydrogen produced in a PEM electrolysis cell powered by solar photovoltaics and wind energy (50/50%). The LCI of the PEM electrolyzer is taken from Bareiβ et al.[42]

Table 3. Parameters describing the CO_2 capture from the flue gas stream.

Efficiency	CO_2 capture (%)	90
Energy input	Electricity for CO_2 capture (kWh/tonne CO_2 captured)[38]	28.7
	Desorption heat (GJ/tonne CO_2 captured)[38]	3.26
Material consumption	MEA make-up (kg/tonne CO_2 captured)[38]	2.5
	Water[a] (kg/tonne CO_2 captured)	5.84
	NaOH[b] (kg/tonne CO_2 captured)[43,44]	0.13
	Activated carbon[c] (kg/tonne CO_2 captured)[20]	0.075
Air emissions	NH_3 (kg/tonne CO_2 captured)[20]	0.35
	MEA (kg/tonne CO_2 captured)[45]	0.031
Waste	Solvent mixture to hazardous waste incineration (kg/tonne CO_2 captured)[44]	4.12

[a]30% weight MEA solution.[38]
[b]To recover MEA.
[c]To dry CO_2.

The Fischer-Tropsch BECCS configuration also relies on an indirect gasification process.[16] The CO_2 in the syngas stream is captured in an absorption process based on methanol; this process sequesters 54% of the carbon initially captured by biomass. We assume that the produced syncrude – a mixture of hydrocarbons with five or more carbon atoms that requires further refining to be used as a drop-in transportation fuel – avoids the extraction of an equivalent amount of fossil crude oil.

3.4. Chemical NETPs

The studied NETPs within this category are HTLS-DACCS powered by natural gas and wind, LTSS-DACCS deploying geothermal and wind energy, and enhanced weathering based on basalt and dunite. The coastal enhanced weathering and ocean liming scenarios described in the marine NETPs section also belong to this category.

In the HTLS-DACCS scenarios, atmospheric CO_2 is absorbed into a basic solution, which is regenerated with high-temperature heat. Natural gas supplies the high-temperature heat, and the electricity demand is met with either wind or natural gas. The CO_2 derived from the combustion of natural gas is captured and sequestered.

In the LTSS-DACCS scenarios, CO_2 is adsorbed onto a solid sorbent that is subsequently regenerated with low-temperature heat. We studied two LTSS-DACCS configurations. The first one consumes geothermal electricity, and the excess geothermal heat generated in the electricity production process is sufficient to supply the low temperature heat. The second LTSS-DACCS configuration deploys a heat pump and relies on wind energy to provide both heat and electricity. We did not consider DACCS powered by the grid mix due to the poor results obtained for these scenarios in Deliverable 1.5.[18] We assumed that the DACCS plants are located next to the sequestration site in all the scenarios.

The enhanced weathering systems comprise the mining, crushing and grinding of dunite and basalt rocks. The rock grains are subsequently spread over cropland areas so that the silicate minerals can react with atmospheric CO_2, sequestering it as bicarbonate ions. We assume that the release of K_2O and P_2O_5 as the rock grains dissolve avoids the application of industrial fertilizers. Further details are available in Deliverable 1.5.[18]

4. Key findings

Here we describe the environmental performance of the 24 assessed scenarios. Prior to evaluating the damage caused to the three areas of protection, we focus on the global warming impacts of NETPs, which affect both human health and ecosystems. Figure 3A depicts how the unit processes and flows that integrate the studied systems contribute to the total global warming impacts, whereas Figure 3b shows the ranking of the scenarios from lower to higher global warming impacts.

All the studied NETPs avert net global warming impacts, but these differ widely across scenarios. The global warming impacts prevented by CDR are partially offset by the greenhouse gases emitted throughout the NETPs life cycle in all the scenarios. Furthermore, the NETPs displacing other products and services in the market avoid the global impacts associated with them.

The first three scenarios in the ranking – soil application of biochar, combustion-BECCS deploying *Miscanthus* and glulam production – can avert over 1000 (1047-1139) kg CO_2-eq per tonne CO_2 sequestered due to their ability to avoid the production of additional heat, electricity and steel, respectively. However, seven of the twelve NETPs dependent on terrestrial biomass (i.e., terrestrial NETPs and BECCS) are located in the second half of the ranking. Coupling the pyrolysis process with CCS decreases the prevented impacts of the biochar scenario by 20%, relegating it to position number nine in the ranking. The reason is that, even though less biomass is required to sequester the same amount of carbon – and therefore less harmful impacts are generated –, the credits associated with the produced heat are lower because part of it is used in the CO_2 capture process. On the other hand, the afforestation and reforestation scenarios prevent 628-830 kg CO_2-eq/tonne CO_2 sequestered. The CO_2 removed through forestation is mainly offset by the direct emissions associated with natural disturbances. The oriented strand board scenario shows a similar performance, preventing 755 kg CO_2-eq/tonne CO_2.

The selected biomass source determines the global warming impacts of BECCS, with the scenarios deploying *Miscanthus* – which leads to soil carbon sequestration – outperforming those relying on poplar – which generate land-use change CO_2 emissions. Switching from *Miscanthu*s to poplar in the combustion-BECCS scenarios would reduce the prevented impacts by 22%. Similarly, the BECCS scenarios generating hydrogen and syncrude avert 875-876 kg CO_2-eq/tonne CO_2 if *Miscanthus* is used and only 534-543 kg CO_2-eq/tonne CO_2 in the BECCS scenarios deploying poplar.

Overall, the NETPs relying on chemical processes attain good positions in the ranking; seven of the twelve NETPs in the first half of the ranking are classified as chemical NETPs or marine NETPs dependent on chemical reactions. These NETPs do not generate any products or services in addition to CDR, but their life cycle CO_2-eq emissions are low, and therefore the removed CO_2 is minimally offset. The enhanced weathering scenarios deploying dunite rock (on both coasts and croplands) can avoid 941-981 kg CO_2-eq/tonne CO_2 sequestered, although the use of basalt on croplands significantly reduces the prevented impacts (821 kg CO_2-eq/tonne CO_2) due to the larger amounts of rock and smaller grain sizes needed relative to the dunite scenarios. On the other hand, HTLS- and LTSS-DACCS consuming wind electricity can prevent 944 and 924 kg CO_2-eq/tonne CO_2, respectively. Nonetheless, using energy sources with higher carbon footprints can reduce the avoided impacts of DACCS by up to 8%.

The global warming impacts avoided by the ocean liming scenarios are near the median (873-888 kg CO_2-eq/tonne CO_2). In these scenarios, CDR is mainly counterbalanced by the greenhouse gases associated with the oxy-calcination process used to produce the calcium oxide particles, which demands a considerable amount of electricity. Finally, the kelp farming and sinking scenarios attain the last positions in the ranking; they can only prevent 481-495 kg CO_2-eq per tonne CO_2 sequestered by the macroalgae because of the decline in the phytoplankton net primary productivity.

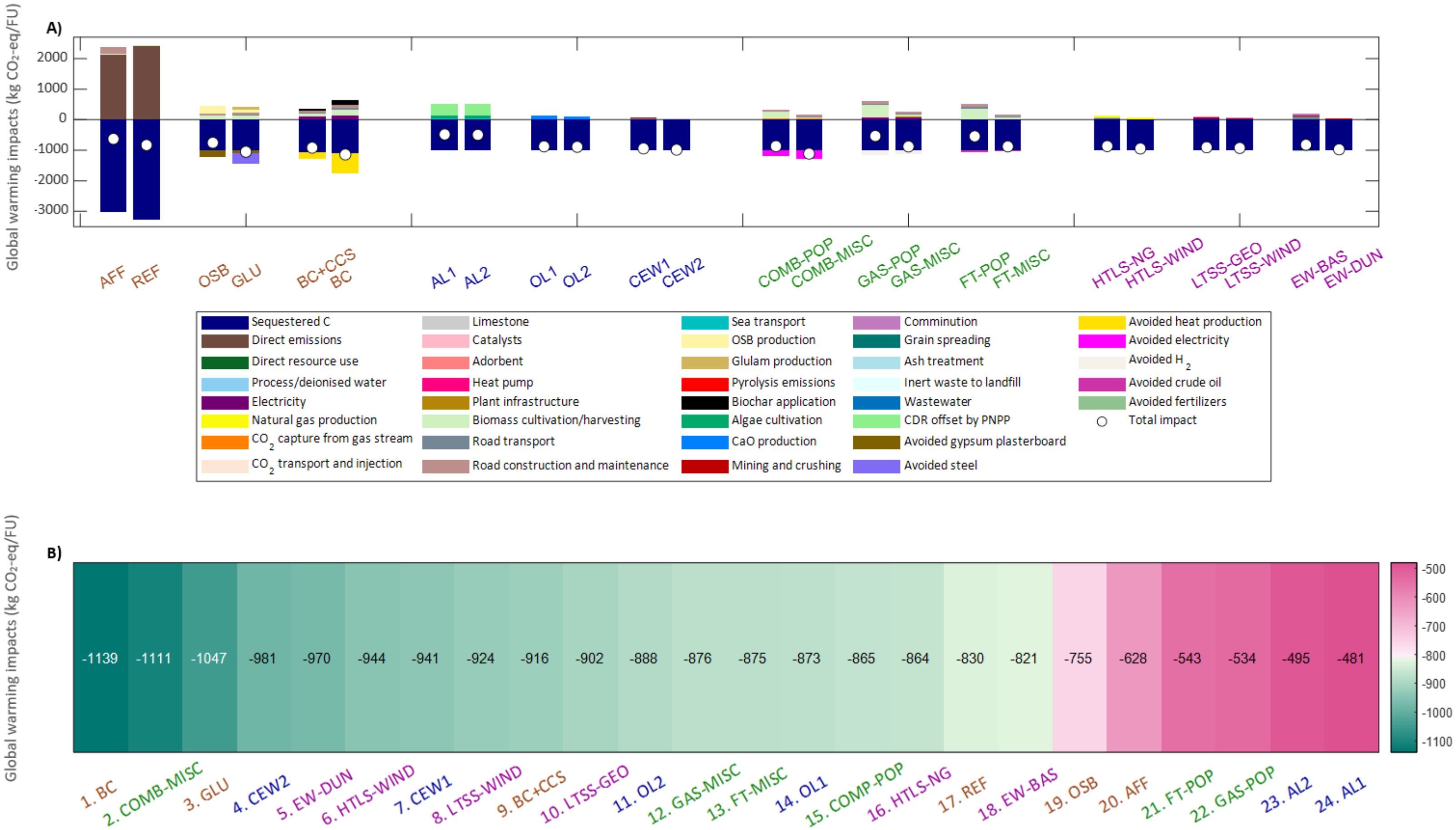

Figure 3. Global warming impacts per tonne CO_2 sequestered within the 100-year time horizon (i.e., per functional unit, FU). A) Specific contributions to the total global warming impacts. B) Ranking of scenarios according to their global warming impacts. We assessed terrestrial NETPs (brown): afforestation (AFF), reforestation (REF), oriented strand board production (OSB), glulam production (GLU), soil application of biochar (BC), and soil application of biochar with carbon capture and storage (BC+CCS); marine NETPs (blue) under pessimistic (1) and optimistic (2) assumptions: macroalgae farming and sinking (AL), ocean liming (OL), coastal enhanced weathering (CEW); BECCS (green) based on poplar or Miscanthus (POP or MISC): combustion-BECCS (electricity production, COMB), gasification-BECCS (hydrogen production, GAS), or Fischer-Tropsch BECCS (syncrude production, FT); chemical NETPs (purple): High Temperature Liquid Sorbent DACCS powered by natural gas or wind (HTLS-NG or HTLS-WIND), Low Temperature Solid Sorbent using geothermal or wind energy (LTSS-GEO or LTSS-WIND), and enhanced weathering using basalt or dunite rock (EW-BAS or EW-DUN).

The health impacts of the assessed scenarios are shown in Figure 4. Figure 4A illustrates the contributions of the unit processes and elementary flows to the total health impacts, whereas Figure 4B shows the disaggregated contribution of the midpoint impacts to the total health effects.

We found that 18 of the assessed scenarios can prevent net damage to human health due to the decrease in the risk of floods and certain diseases – malnutrition, malaria and diarrhea – associated with climate change. Note that these health benefits are distributed unevenly among world regions.[9] In the remaining seven scenarios, the water consumption and pollutants emitted throughout the NETPs life cycle counteract the health gains attributed to CDR.

Enhanced weathering based on basalt rock is the most detrimental NETP in terms of human health impacts; the emission of the metals contained in basalt – principally lead, zinc, cadmium and arsenic – to the agricultural soil as the rock dissolves causes non-carcinogenic toxicity health effects. The net health impacts of this NETP equal $2.5\cdot10^{-3}$ DALY/tonne CO_2 sequestered, 3.5 times higher than the second most damaging NETP for human health, i.e., Fischer-Tropsch BECCS deploying poplar.

The other scenarios generating net health damage are either terrestrial NETPs or BECCS. Gasification- and Fischer-Tropsch BECCS (both based on poplar), biochar and oriented strand board production generate health impacts ranging between $2.4\cdot10^{-4}$ and $7.0\cdot10^{-4}$ DALY/tonne CO_2. These impacts are mainly attributed to the large water demand of poplar in the biomass irrigation phase, which translates into potential water shortages that could lead to malnutrition, damaging human health. It is imperative to interpret these results with caution, since the plants water demand is site-specific. Afforestation also leads to net health impacts, but their extent is one order of magnitude lower than in the aforementioned scenarios. These health effects are mainly due to the formation of fine particulate matter associated with the road construction and maintenance operations, which are not required in the reforestation scenarios.

On the other side of the health impacts spectrum, glulam production is the scenario that achieves the largest health benefits – $1.9\cdot10^{-3}$ DALY/tonne CO_2. Although the life cycle health effects of this NETP are substantial, they are offset by the toxicity impacts prevented by displacing the production of steel. The BECCS scenarios deploying *Miscanthus* are ranked second to fourth – net health benefits between $8.8\cdot10^{-4}$ and $1.3\cdot10^{-3}$ DALY/tonne CO_2 in the Fischer-Tropsch and combustion-BECCS scenarios, respectively – principally because of the credits associated with the generated energy vectors.

The coastal enhanced weathering scenarios also show a good performance (preventing $7.5\cdot10^{-4}$-$8.6\cdot10^{-4}$ DALY/tonne CO_2), followed by HTLS-DACCS (which avoids $6.6\cdot10^{-4}$-$7.6\cdot10^{-4}$ DALY/tonne CO_2), and LTSS-DACCS (heath gains between $5.8\cdot10^{-4}$ and $6.5\cdot10^{-4}$ DALY/tonne CO_2). In the latter, the harmful health impacts are not only driven by the energy consumption, but also by the adsorbent and heat pump. The performance of the ocean liming scenarios – where the harmful health effects mainly stem from the generation of the electricity used in the oxy-calcination process – is rather similar, i.e., $5.9\cdot10^{-4}$-$6.3\cdot10^{-4}$ DALY averted per tonne CO_2.

The remaining scenarios capable of preventing net health impacts are in the second half of the human health ranking. Reforestation avoids $5.4\cdot10^{-4}$ DALY/tonne CO_2; in this scenario the main stressor counteracting the health benefits of CDR is the NO_X emitted during fire events, which leads to the formation of fine particulate matter. Combustion-BECCS based on poplar, macroalgae farming and sinking, enhanced weathering with dunite and biochar coupled with CCS prevent between $1.5\cdot10^{-4}$ and $2.1\cdot10^{-4}$ DALY/tonne CO_2. Notably, the carcinogenic toxicity impacts of the enhanced weathering scenario based on dunite are five times higher than those of enhanced weathering deploying basalt because of the greater nickel content of dunite. However, the non-carcinogenic toxicity impacts of dunite are 10 times lower with respect to the scenario deploying basalt. It is worth remarking that the release of the same compounds to the seawater in the coastal enhanced weathering scenarios does not lead to significant health effects.

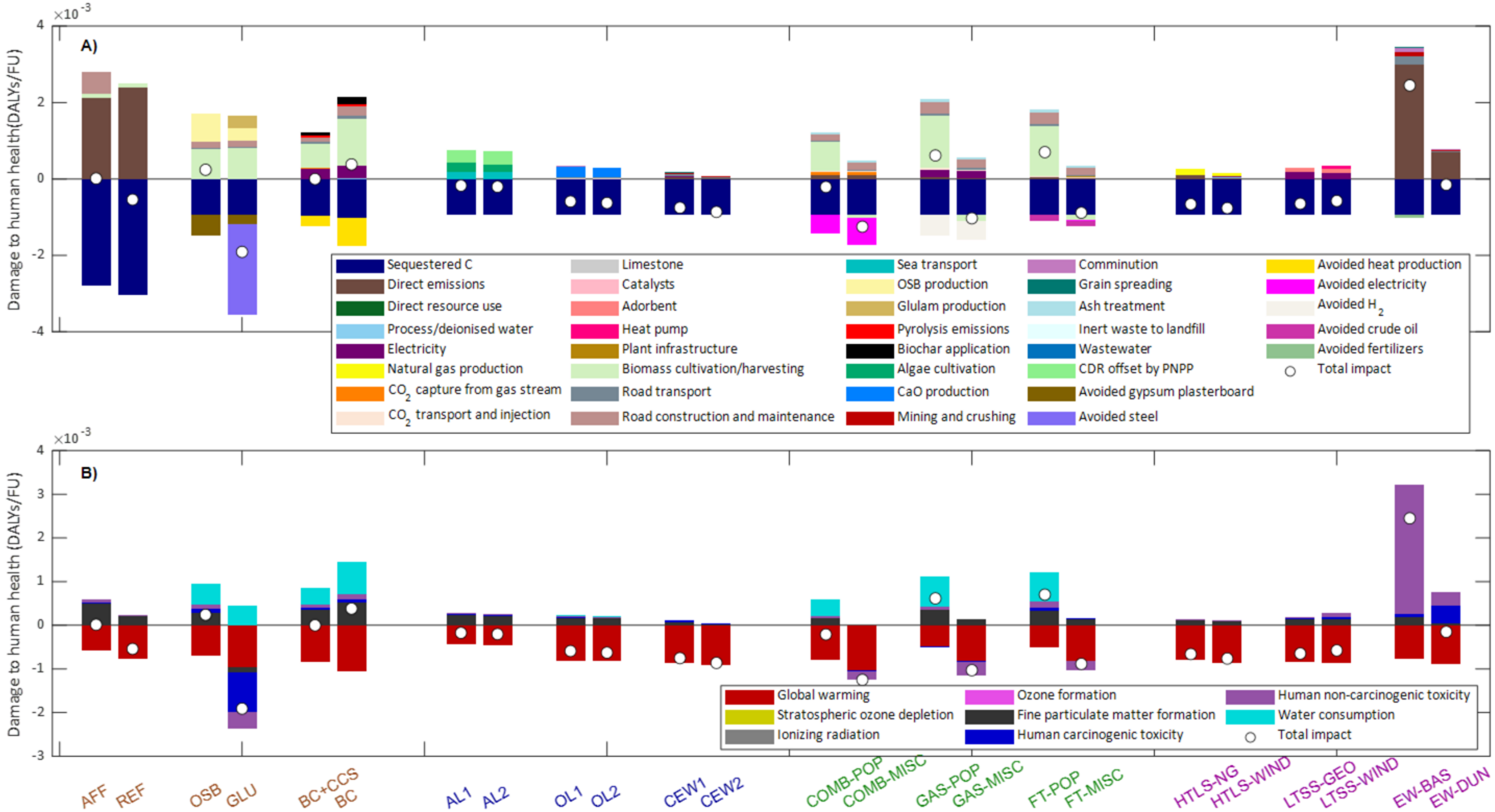

Figure 4. Human health impacts per tonne CO_2 sequestered within the 100-year time horizon (i.e., per functional unit, FU). A) Specific contributions to the total health impacts. B) Health impacts disaggregated by cause. We assessed terrestrial NETPs (brown): afforestation (AFF), reforestation (REF), oriented strand board production (OSB), glulam production (GLU), soil application of biochar (BC), and soil application of biochar with carbon capture and storage (BC+CCS); marine NETPs (blue) under pessimistic (1) and optimistic (2) assumptions: macroalgae farming and sinking (AL), ocean liming (OL), coastal enhanced weathering (CEW); BECCS (green) based on poplar or Miscanthus (POP or MISC): combustion-BECCS, (electricity production, COMB), gasification-BECCS (hydrogen production, GAS), or Fischer-Tropsch BECCS (syncrude production, FT); chemical NETPs (purple): High Temperature Liquid Sorbent DACCS powered by natural gas or wind (HTLS-NG or HTLS-WIND), Low Temperature Solid Sorbent using geothermal or wind energy (LTSS-GEO or LTSS-WIND), and enhanced weathering using basalt or dunite rock (EW-BAS or EW-DUN).

Figure 5 depicts the ecosystems impacts of the studied NETPs. The increase in global temperatures leads to species loss; therefore, CDR has a favorable effect on ecosystems. Nonetheless, the prevented ecosystems damage can be offset by the resource consumption and pollutants emitted throughout the NETPs life cycle. Notably, the applied methodology does not account for the potential benefits associated with habitat creation, which might be considerable in the forestation and macroalgae farming and sinking scenarios.

With the exception of combustion-BECCS deploying *Miscanthus*, all the scenarios reliant on terrestrial biomass (i.e., terrestrial NETPs and BECCS) generate net ecosystems damage. These detrimental impacts are mainly driven by the use of land in the biomass cultivation phase, although the impacts related to the consumption of water for irrigation are also significant in the scenarios based on poplar.

Afforestation presents the highest ecosystems impacts because of its substantial land use ($2.7 \cdot 10^{-5}$ species·yr/tonne CO_2 sequestered), followed by reforestation, and gasification- and Fischer-Tropsch BECCS deploying poplar, all leading to the loss of $1.0 \cdot 10^{-5}$ species·yr/tonne CO_2. The impacts of the gasification- and Fischer-Tropsch BECCS configurations using *Miscanthus* are one order of magnitude lower, $1.8 \cdot 10^{-6}$-$1.9 \cdot 10^{-6}$ species·yr/tonne CO_2.

Given the higher CDR efficiency of combustion-BECCS, its ecosystems impacts are low compared to the other BECCS configurations using the same biomass. Whereas the impact of combustion-BECCS based on poplar is $4.3 \cdot 10^{-6}$ species·yr/tonne CO_2, deploying *Miscanthus* in the combustion process could prevent ecosystems damage equivalent to $6.5 \cdot 10^{-7}$ species·yr/tonne CO_2; this is the BECCS scenario generating the least gross ecosystems damage and preventing the most impacts associated with the substitution of the generated energy. The ecosystems impacts of the wood and biochar NETPs are within the same range as the BECCS systems, between $3.0 \cdot 10^{-6}$ species·yr/tonne CO_2 (glulam production) and $7.6 \cdot 10^{-6}$ species·yr/tonne CO_2 (soil application of biochar).

The kelp farming and sinking scenarios generate net ecosystems benefits ($8.7 \cdot 10^{-7}$-$9.4 \cdot 10^{-7}$ species·yr/tonne CO_2), but these are low relative to the other marine NETPs, mainly because of the reduction in the phytoplankton net primary productivity, which offsets the averted climate impacts and therefore, the ecosystems benefits.

The enhanced weathering scenario based on basalt attains the lowest ecosystems benefits among the chemical NETPs, averting $1.8 \cdot 10^{-6}$ species·yr/tonne CO_2. Here, the land use associated with the road transport and mining operations is the main source of ecosystem impacts. The extent of the ecosystems impacts prevented by the other NETPs classified as chemical and the marine NETPs dependent on chemical processes are quite similar, ranging between $2.1 \cdot 10^{-6}$ species·yr/tonne CO_2 (ocean liming and HTLS-DACCS powered by natura gas) and $2.6 \cdot 10^{-6}$ species·yr/tonne CO_2 (enhanced weathering deploying dunite, on both croplands and coasts). Notably, the metals released in the enhanced weathering scenarios do not pose a significant threat for ecosystems.

The damage caused by the assessed NETPs to resource scarcity is shown in Figure 6. The impacts on resource availability are predominantly caused by the extraction of fossil resources. The extraction of mineral resources only plays an important role in the glulam production scenario, due to the credits linked to the avoided steel production.

Five scenarios can avert impacts to resource availability. The prevented extraction of crude oil in the Fischer-Tropsch BECCS scenarios positions this NETP as the best-performing in this category; the avoided impacts are quantified as 63.5-70.0 $\$_{2013}$/tonne CO_2. The generated heat in the biochar scenarios averts natural gas extraction costs of 35.0 $\$_{2013}$/tonne CO_2 (scenario without CCS) and 0.3 $\$_{2013}$/tonne CO_2 (scenario with CCS). Finally, the avoided extraction of fossil resources used to power the 2030 electricty mix would avert impacts equivalent to 2.1 $\$_{2013}$/tonne CO_2 in the combustion-BECCS scenario deploying *Miscanthus*.

The rest of the scenarios generate net damage to resource scarcity. The low demand for fossil and mineral resources in the reforestation, LTSS-DACCS and dunite-based enhanced weathering scenarios also makes these NETPs appealing in terms of damage to resource availability, with impacts ranging between 2.2 $\$_{2013}$/tonne CO_2 (coastal enhanced weathering) and 8.2 $\$_{2013}$/tonne CO_2 (LTSS-DACCS powered by wind).

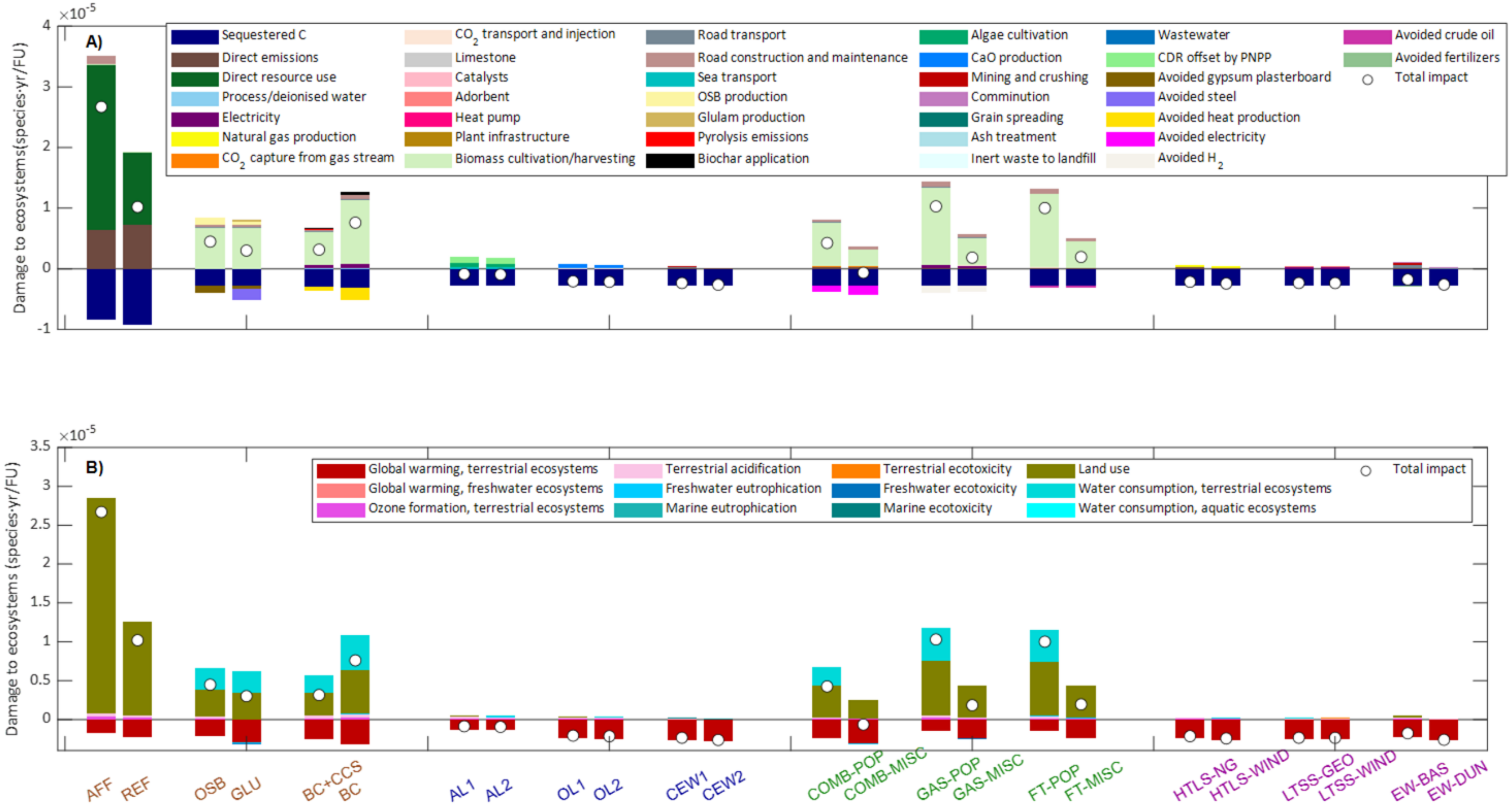

Figure 5. Ecosystems impacts per tonne CO_2 sequestered within the 100-year time horizon (i.e., per functional unit, FU). A) Specific contributions to the total ecosystems impacts. B) Ecosystems impacts disaggregated by cause. We assessed terrestrial NETPs (brown): afforestation (AFF), reforestation (REF), oriented strand board production (OSB), glulam production (GLU), soil application of biochar (BC), and soil application of biochar with carbon capture and storage (BC+CCS); marine NETPs (blue) under pessimistic (1) and optimistic (2) assumptions: macroalgae farming and sinking (AL), ocean liming (OL), coastal enhanced weathering (CEW); BECCS (green) based on poplar or Miscanthus (POP or MISC): combustion-BECCS (electricity production, COMB), gasification-BECCS (hydrogen production, GAS), or Fischer-Tropsch BECCS (syncrude production, FT); chemical NETPs (purple): High Temperature Liquid Sorbent DACCS powered by natural gas or wind (HTLS-NG or HTLS-WIND), Low Temperature Solid Sorbent using geothermal or wind energy (LTSS-GEO or LTSS-WIND), and enhanced weathering using basalt or dunite rock (EW-BAS or EW-DUN).

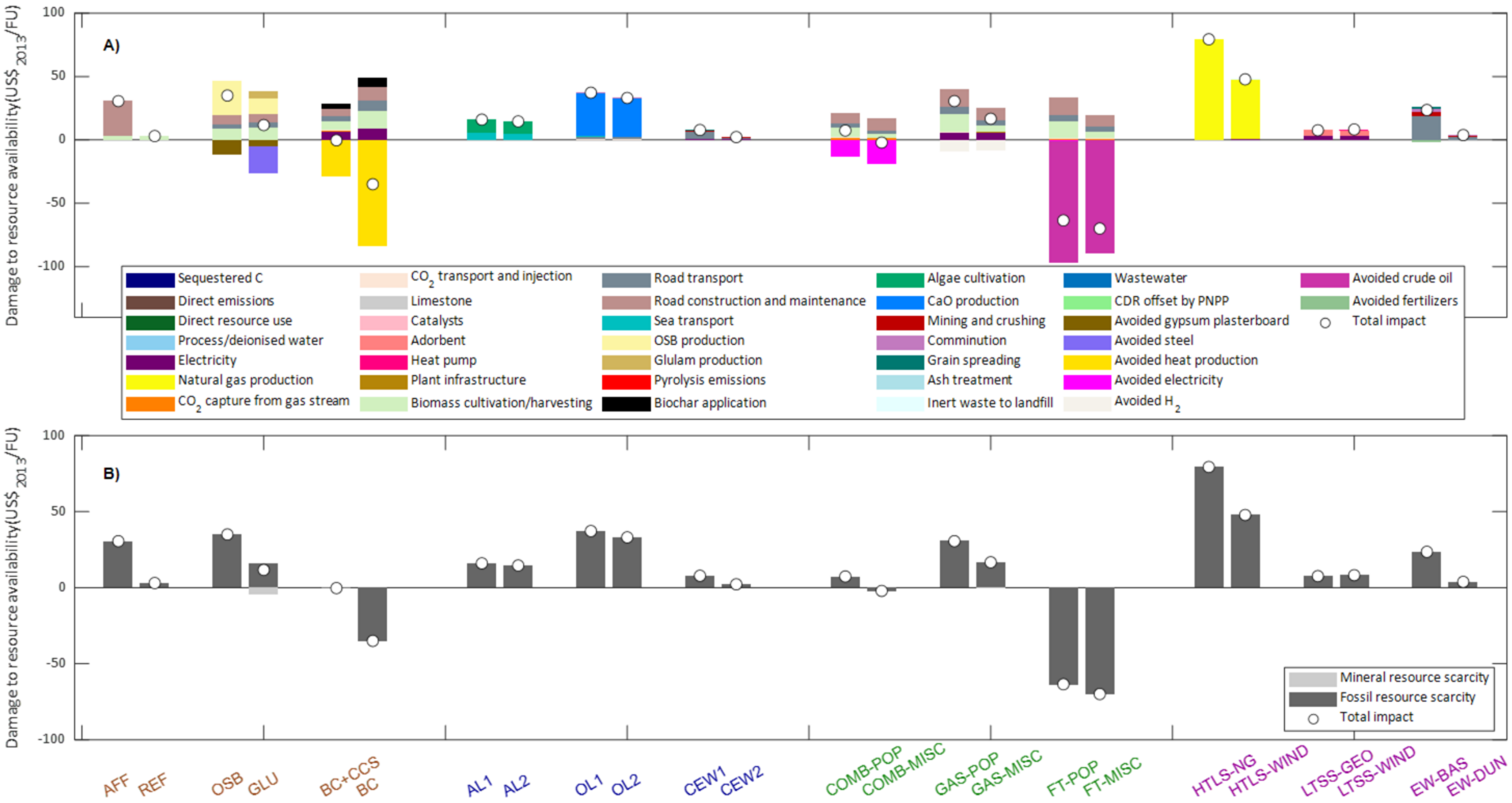

Figure 6. Impacts on resource availability per tonne CO_2 sequestered within the 100-year time horizon (i.e., per functional unit, FU). A) Specific contributions to the total impacts on resources. B) Resources impacts disaggregated by cause. We assessed terrestrial NETPs (brown): afforestation (AFF), reforestation (REF), oriented strand board production (OSB), glulam production (GLU), soil application of biochar (BC), and soil application of biochar with carbon capture and storage (BC+CCS); marine NETPs (blue) under pessimistic (1) and optimistic (2) assumptions: macroalgae farming and sinking (AL), ocean liming (OL), coastal enhanced weathering (CEW); BECCS (green) based on poplar or Miscanthus (POP or MISC): combustion-BECCS (electricity production, COMB), gasification-BECCS (hydrogen production, GAS), or Fischer-Tropsch BECCS (syncrudel production, FT); chemical NETPs (purple): High Temperature Liquid Sorbent DACCS powered by natural gas or wind (HTLS-NG or HTLS-WIND), Low Temperature Solid Sorbent using geothermal or wind energy (LTSS-GEO or LTSS-WIND), and enhanced weathering using basalt or dunite rock (EW-BAS or EW-DUN).

The HTLS-DACCS scenarios, reliant on natural gas, are the most detrimental to resource scarcity, with impacts between 47.8 and 79.4 $\$_{2013}$/tonne CO_2. The ocean liming scenarios, with a high electricity consumption, perform slightly better (33.1-37.2 $\$_{2013}$/tonne CO_2), while the production of oriented strand board, an energy intensive process, shows a similar performance (35.0 $\$_{2013}$/tonne CO_2).

Surprisingly, the construction and maintenance of roads in the forestation scenario accounts for 90% of the impacts of this NETP on resource availability, which amount to 30.6 $\$_{2013}$/tonne CO_2. The impacts associated with the construction and maintenance of roads also represent the greatest share of the damage to resource scarcity in the BECCS scenarios.

Figure 7 summarizes the ranking of the scenarios according to their impacts on the three areas of protection, from lowest to highest. Only four NETPs scenarios attain positions within the first half of the three rankings: the coastal enhanced weathering and LTSS-DACCS systems. The HTLS-DACCS and ocean liming scenarios also perform well in the human health and ecosystems categories, but their impact on resource availability is substantial. Dunite-based enhanced weathering on croplands shows a good performance in terms of damage to ecosystems and resource availability, but its human health impacts are considerable. If basalt is deployed instead, the performance of this NETP across the three areas of protection significantly worsens.

All the BECCS and terrestrial NETPs are located in the second half of the ecosystems impacts ranking. Excluding combustion-BECCS based on *Miscanthus*, all these NETPs generate net harmful effects on ecosystems. Overall, the impacts of the BECCS scenarios greatly depend on the selected biomass and the credits linked to the produced energy vector. On the other hand, the health benefits of terrestrial NETPs are low, and some of them even generate net health impacts. The exception is the production of glulam, which attains the first position in the health ranking due the avoided credits. Regarding the impact of the scenarios reliant on terrestrial biomass on resource availability, this is only substantial in the oriented strand board production, afforestation and gasification scenarios.

Unlike most of the scenarios deploying terrestrial biomass, the macroalgae farming and sinking scenarios prevent net ecosystems impacts. However, their net health and ecosystems benefits are low, and the damage caused to resource availability is not negligible.

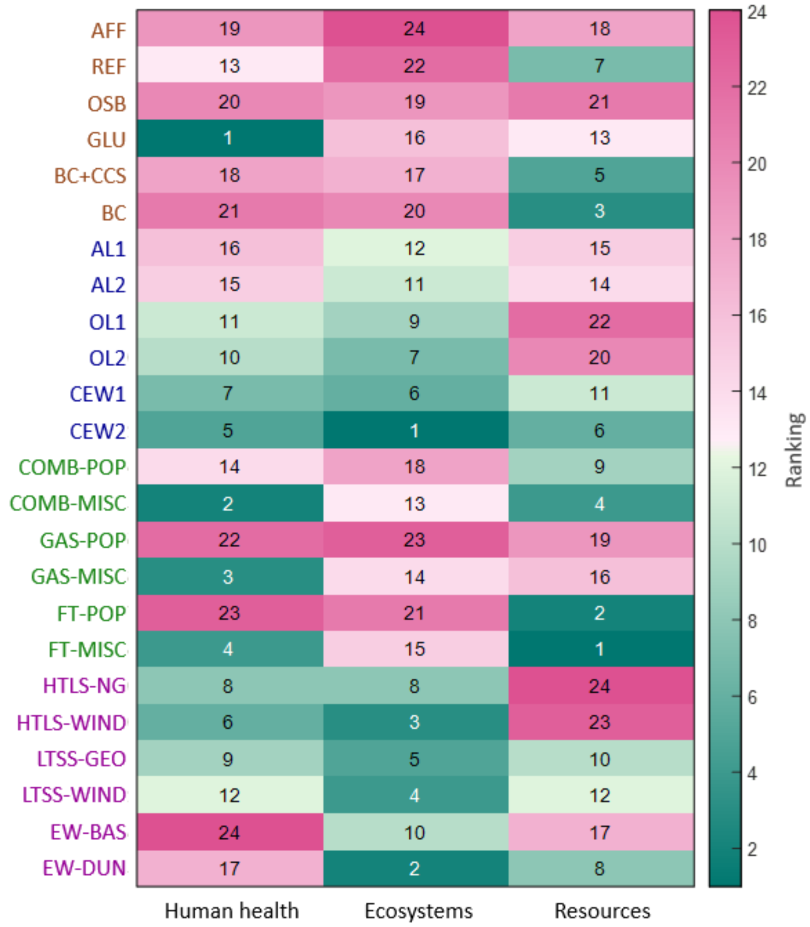

Figure 7. Ranking of NETPs according to their impacts on human health, ecosystems and resource availability. We assessed terrestrial NETPs (brown): afforestation (AFF), reforestation (REF), oriented strand board production (OSB), glulam production (GLU), soil application of biochar (BC), and soil application of biochar with carbon capture and storage (BC+CCS); marine NETPs (blue) under pessimistic (1) and optimistic (2) assumptions: macroalgae farming and sinking (AL), ocean liming (OL), coastal enhanced weathering (CEW); BECCS (green) based on poplar or Miscanthus (POP or MISC): combustion-BECCS (COMB), gasification-BECCS (GAS), or Fischer-Tropsch BECCS (FT); chemical NETPs (purple): High Temperature Liquid Sorbent DACCS powered by natural gas or wind (HTLS-NG or HTLS-WIND), Low Temperature Solid Sorbent using geothermal or wind energy (LTSS-GEO or LTSS-WIND), and enhanced weathering using basalt or dunite rock (EW-BAS or EW-DUN).

5. Conclusions and further steps

In this report we compared the sustainability performance of the NETPs studied in WP1. We assessed the damage caused to human health, ecosystems and resource scarcity by 24 NETPs configurations. While CDR leads to health and ecosystems benefits due to the averted climate change impacts, the resources consumed and pollutants emitted throughout the life cycle of the studied NETPs can counteract these co-benefits and even generate net harmful impacts.

We found that none of the assessed NETPs performs better than all the others in the three assessed areas of protection concurrently. However, we identified coastal enhanced weathering and LTSS-DACCS as the most promising NETPs, generating net health and ecosystems co-benefits, and low damage to resource availability.

Spreading dunite particles on croplands instead of coastal areas would substantially reduce the health co-benefits of enhanced weathering, whereas deploying basalt rock would lead to the worst health effects across all the scenarios, due to the toxicity impacts associated with the metals released to the agricultural soil.

Even though the health and ecosystems co-benefits of HTLS-DACCS are greater than those of LTSS-DACCS, HTLS-DACCS is the most damaging NETP from the resource scarcity viewpoint due to its heavy reliance on natural gas. Hence, future analyses should consider the use of electric furnaces to supply the high temperature heat to the HTLS-DACCS systems. Likewise, the ocean liming scenarios attain health and ecosystems co-benefits, but perform poorly in the resource scarcity impact category because of their high energy demand. Deploying less energy-intensive methods to capture the CO_2 generated in the calcination process could mitigate the damage caused to resource scarcity by this NETP.

We conclude that kelp farming and sinking is not a particularly appealing NETP, given the low extent of the health and ecosystems benefits – mainly due to the induced decline in the phytoplankton net primary productivity –, and its below-the-average performance in terms or resource scarcity.

The scenarios relying on terrestrial biomass (BECCS and terrestrial NETPs) generate net detrimental ecosystems impacts, mainly because of their substantial land use requirements. Hence, the use of forest and agricultural residues could release some of the pressure exerted by BECCS on the land system. The exception to the harmful effects of BECCS on ecosystems is combustion-BECCS based on *Miscanthus*, which prevents ecosystems impacts – to a low extent compared to other scenarios – due to the avoided electricity credits. Given the substantial land requirement of the afforestation scenario, our analysis depicts it as the most damaging NETP for ecosystems. However, if the planted forests were based on native species, this NETP could have positive effects on biodiversity.[46]

The health and resource impacts of BECCS and terrestrial NETPs are highly variable, dependent on the biomass source (the cultivation of *Miscanthus* generates less impact than poplar) and the products and energy services displaced by the NETPs. The impacts avoided by replacing other products and services allow the glulam scenario to attain the first position in the health ranking, and the biochar and Fischer-Tropsch scenarios to prevent significant net damage to resource availability.

The main limitation of the applied methodology is that it only accounts for the impacts associated with resource consumption and pollutants emissions. Therefore, we did not quantify potential ecosystems benefits that might arise from the creation of new habitats, which could be relevant in the forestation and macroalgae scenarios. Moreover, our models are based on global data; i.e., the results could differ for specific regions. Nonetheless, our conclusions might help guide future policy development.

Based on these results, we recommend focusing future R&D and financial efforts on NETPs dependent on chemical processes. Although our analysis portrays coastal enhanced weathering and DACCS as the most attractive NETPs in terms of co-benefits and trade-offs, few experimental studies have been carried out to date on coastal enhanced weathering. These are essential to ensure the effectiveness of this NETP and confirm that it does not pose additional risks. On the other hand, only a few DACCS facilities are currently operating; substantial investments in this technology – and the renewable energies required to power it – must be made to facilitate the rapid scale-up needed to reach the gigatonne scale at a pace consistent with climate change mitigation scenarios limiting warming to 1.5 °C.

A portfolio of NETPs will most likely be needed to overcome the deployment constraints of individual NETPs while exploiting co-benefits and minimizing local risks. This analysis can help design optimal CDR pathways compliant with sustainability criteria.

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
D1.3	Comprehensive sustainability assessment of marine NETPs	NIVA	Report	PU	16
D1.4	Comprehensive sustainability assessment of Bio-CCS NETPs	VTT	Report	PU	12
D1.5	Comprehensive sustainability assessment of geoengineering and other NETPs	ICL	Report	PU	24

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