NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Comprehensive sustainability assessment of geoengineering and other NETPs

Horizon 2020, Grant Agreement no. 869192

Number of the Deliverable	Due date	Actual submission date
1.5	**31.05.2022**	**31.05.2022**

Work Package (WP): 1 – In-depth technology assessment

Task: 1.5 – Sustainability assessment of geoengineering and other NETPs

Lead beneficiary for this deliverable: ICL

Editors/Authors: Selene Cobo, Gonzalo Guillén-Gosálbez, Nixon Sunny, Solene Chiquier, Niall Mac Dowell

Dissemination level: Public

Call identifier: H2020-LC-CLA-02-2019 - Negative emissions and land-use based mitigation assessment

Document history

V	Date	Beneficiary	Author/ Reviewer
1.0	17.05.2022	ICL	Selene Cobo (ETH), Gonzalo Guillén-Gosálbez (ETH), Nixon Sunny (ICL), Solene Chiquier (ICL), Niall Mac Dowell (ICL)/ Conor Hickey (UOXF)
1.1	31.05.2022	ICL	Selene Cobo, Gonzalo Guillén-Gosálbez, Nixon Sunny, Solene Chiquier, Niall Mac Dowell

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 869192

Partners

VTT – VTT Technical Research Centre of Finland Ltd, Finland
PIK - Potsdam Institute for Climate Impact Research, Germany
ICL - Imperial College of Science Technology and Medicine, United Kingdom
UCAM - University of Cambridge, United Kingdom
ETH - Eidgenössische Technische Hochschule Zürich, Switzerland
BELLONA - Bellona Europa, Belgium
ETA - ETA Energia, Trasporti, Agricoltura, Italy
NIVA - Norwegian Institute for Water Research, Norway
RUG - University of Groningen, Netherlands
INSA - Institut National des Sciences Appliquées de Toulouse, France
CMW - Carbon Market Watch, Belgium
UOXF - University of Oxford, United Kingdom
SE - Stockholm Exergi, Sweden
St1 - St1 Oy, Finland
DRAX - Drax Power Limited, United Kingdom
SAPPI - Sappi Netherlands Services, The Netherlands

Executive Summary and policy relevant messages

This deliverable studied the environmental performance of direct air CO_2 capture and storage (DACCS), and enhanced weathering (EW) with minerals on agricultural land. These technologies were assessed using the same methodological approach followed for the assessment of terrestrial, marine, and bio-CCS negative emission technologies and practices (NETPs). Thus, the reported life cycle assessment framework used in deliverables 1.2, 1.3, and 1.4, is used here to ensure consistency across the different deliverables within work package 1.

The following set of Key Performance Indicators (KPIs) were used to evaluate DACCS and EW: ozone depletion, ionizing radiation, photochemical ozone formation, particulate matter, non-carcinogenic toxicity, carcinogenic toxicity, acidification, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, freshwater ecotoxicity, land use, water use, both fossil and mineral resource use, and damage to human health, ecosystem quality, and finite resources.

Whilst there are several sustainability assessments of DACCS available in the literature, there are few studies available on EW which covered KPIs other than CO_2 sequestration potential. In line with the literature, we found that the climate change impacts associated with DACCS can largely be minimised by using cleaner electricity sources and adsorbents, whereas minimising road transport emissions improve the Carbon Dioxide Removal (CDR) efficiency of EW. However, previous studies of EW focussed on basic rocks, and excluded ultrabasic rocks in CDR assessments on account of their toxic effects, owing to the release of nickel and chromium into the soil. We found that this approach overlooks the non-carcinogenic toxicity effects of EW using basic rocks, especially given that they are significantly higher than that of ultrabasic rocks.

Overall, the CDR efficiencies of EW applications generally range between 84% and 96%, whereas a much wider range is observed for DACCS (11 – 93%), owing to the effect of the electricity mix used to meet the demand. The highest CDR efficiencies are generally achieved when wind electricity is coupled with the DACCS processes. However, future work needs to assess the economic viability of this system configuration to minimise the cost of CDR. The high-temperature liquid sorbent (HTLS)-DACCS processes generally outperform the low-temperature solid sorbent (LTSS)-DACCS processes across a wide range of environmental KPIs, except for water use. These impacts are higher for LTSS-DACCS compared to HTLS-DACCS across all scenarios for the following indicators – ozone depletion potential, particulate matter formation, acidification, freshwater eutrophication, land use, metals use, etc. Nonetheless, they are driven by the supply of electricity, and they are expected to decline with increasing decarbonisation of the electricity grid.

Most importantly, the capacity for CDR deployment to damage human health was explored through endpoint assessments in this study. This revealed that EW using basic rocks such as basalt may have damaging long-term consequences on human health due to the non-carcinogenic toxicity effects. Thus, warranting additional research before supportive policy measures are introduced to scale-up EW technology. Similarly, HTLS-DACCS processes using natural gas could create an infrastructure lock-in if solely utilised for DACCS.

A key limitation of this work is that the regional variations in the weathering rates for the EW processes were not accounted. Future research should explore this parameter to tailor the results to the specific regions of use. Similarly, the economic performance of the system archetypes was not considered in this analysis, and it should be evaluated to compute the cost of CDR, accounting for the externality costs associated with each CDR technology. This will be further expanded upon in work packages 4, 7, and 8 of the NEGEM project.

NEGEM

Table of contents

Executive Summary and policy relevant messages 3
List of figures 5
List of tables 5
List of abbreviations 6
1. Introduction 7
2. The sustainability of DACCS processes 9
3. The sustainability of EW processes 10
4. Methodology 11
5. Scenario definition 12
6. Key findings 14
7. Conclusions and further steps 23
References 25

List of figures

Figure 1. Process schematic for DAC via temperature–vacuum swing adsorption process.

Figure 2. System boundary covering the operations across the EW supply chain. Rocks are excavated and transported to the grinding facility where they are crushed. The ground rock is transported to the area of application and spread on soil.

Figure 3. Phases involved in the life cycle assessment of different technologies (adapted from ISO 14040).

Figure 4. CDR efficiency and climate change impacts per tonne of sequestered CO_2 for the studied scenarios.

Figure 5. Environmental KPIs per tonne of sequestered CO_2.

Figure 6. Endpoint KPIs per tonne of sequestered CO_2.

Figure 7. Externalities per tonne of sequestered CO_2 for the studied scenarios.

Figure 8. Normalised KPIs covering the different scenarios.

List of tables

Table 1. Parameters of the enhanced weathering scenarios.

Table 2. Energy consumption of direct air capture.

Table 3. Available cost estimates.

List of abbreviations

η_{CO_2}	CO_2 removal efficiency
BAS	Basalt
CDR	Carbon Dioxide Removal
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DALY	Disability-Adjusted Life Year
DUN	Dunite
EW	Enhanced Weathering
E_{CO_2}	Life-cycle CO_2 emissions
FU	Functional Unit
GEO	Geothermal energy
HTLS	High Temperature Liquid sorbent
KPI	Key Performance Indicator
LCA	Lifecycle Assessment
LTSS	Low Temperature Solid Sorbent
NETPs	Negative Emissions Technologies and Practices
NG	Natural Gas
PV	Solar photovoltaics
S_{CO_2}	Sequestered CO_2 within a 100-year time frame

1. Introduction

Limiting the global average warming to well below 1.5°C reduces the potential for runaway warming and its consequences. However, this is difficult to achieve, especially without large-scale deployment of NETPs, as global greenhouse gas (GHG) emissions are still rising[1]. Yet, the overall environmental implications of deploying NETPs have not been studied thoroughly in the academic literature. Technologies such as direct air carbon capture and storage (DACCS) and enhanced weathering (EW) are often appraised mainly on their ability to remove CO_2, owing to the urgent need to stabilise its atmospheric concentrations[2]. But there is less attention on their impacts on the environment and finite resources. This is a research gap which needs to be addressed to avoid environmental burden shifting, and it is being investigated in recent articles such as Madhu et al.[3], and Deutz and Bardow[4].

Madhu et al. compared direct air capture (DAC) by temperature swing adsorption (TSA)[1] with high-temperature aqueous solution (HT-Aq), and found that they can permanently remove 86% and 73% of the CO_2 captured, respectively[3]. Nonetheless, DAC processes were found to use significantly greater quantities of steel, concrete, copper, and aluminium, compared to a strategy which avoids an equivalent amount of CO_2 by shifting from gasoline to electric vehicles[3]. Deutz and Bardow note that using DAC to remove 1% of the annual CO_2 emissions is not constrained by material and energy availability, but rather the ability to scale up amine production as the key adsorbent[4] in established processes.

There is a critical gap in life cycle assessment[2] of EW in literature. The first publicly available life cycle assessment (LCA) on terrestrial EW was published in 2019, and it highlights potential impacts of EW on acidification, ecotoxicity, human toxicity, etc[5]. Edwards et al.[6] note some of the pitfalls of this technology, such as the impact of mining operations on deforestation, erosion of silicates into rivers with associated increases in sedimentation, pH, and turbidity. More research needs to be undertaken to establish the environmental risks and potential co-benefits associated with upscaling this technology[7].

Expanding on recent literature, the primary objective of this report is to assess the sustainability of two Negative Emissions Technologies and Practices (NETPs) relying on chemical mechanisms to capture atmospheric CO_2 - EW and DACCS. We quantify a selection of key performance indicators (KPIs) for the following scenarios:

- EW based on either dunite or basalt rock, with grid electricity supplying the energy required to crush the rock.
- Low Temperature Solid Sorbent DACCS (LTSS-DACCS). The system configurations deploy either excess geothermal heat, or heat pumps powered by three different energy sources.
- High temperature Liquid Sorbent DACCS (HTLS-DACCS). Here, the combustion of natural gas is coupled with carbon capture and storage (CCS) to supply the high-temperature heat. We assess four HTLS-DACCS configurations deploying alternative energy sources to meet the electricity demand.

[1] Temperature swing adsorption is a technology by which CO_2 is captured using a sorbent at a given temperature and desorbed in a more concentrated form at a different desorption temperature.

[2] Life cycle assessments are generally used to evaluate the environmental impacts of a process or a product value chain. It considers system boundaries starting from the extraction of the raw materials through to disposal at the end of life (i.e., cradle-to-grave). Alternatively, it is also common to use a cradle-to-gate methodology where the analysis considers the value chain leading up to its production at the plant battery limits. Note that the term “sustainability assessment” may also consider economic and social implications in addition to the environmental impacts.

We selected these NETPs based on the literature review conducted in Deliverable 1.1.[8] We analyse enhanced weathering instead of mineral carbonation (as proposed in Deliverable 1.1) as the latter is a sequestration method and can only be considered a NETP if it is coupled with a Carbon Dioxide Removal (CDR) technology; hence enhanced weathering is better aligned with the goals of the NEGEM consortium.

The remainder of this document is structured as follows – section 2 presents a high-level overview of the sustainability of DACCS processes identifying key findings and research gaps, section 3 provides an overview of the potential benefits and risks of EW, whilst identifying gaps in research, section 4 introduces the methodology used for LCA, section 5 summarises the scenarios investigated, section 6 and 7 synthesise the key findings of the study and concludes with recommendations.

2. The sustainability of DACCS processes

DACCS is a crucial technology for reducing the mitigation costs associated with large-scale CDR. It involves the capture of CO_2 from ambient air, followed by its subsequent transport, and injection into a permanent geological storage reservoir (see Figure 1). Realmonte et al. performed an inter-model comparison of the role of DACCS in scenarios which limit the global average temperature rise to 1.5°C and 2°C [9]. They found that DACCS complements other NETs such as BECCS. And, concurrent with other studies, they identify scale-up constraints as the a key challenge to overcome in the near-term[10]. They presented scenarios with an average DACCS deployment rate of 1.5 $GtCO_2$/yr, requiring considerable sorbent production and up to 300 EJ/yr of energy input by 2100. They stressed the importance of deploying DACCS alongside other NETs rather than assuming that it is available at scale to avoid the risks of a temperature overshoot by 0.8°C.

Given the urgent need to scale-up DACCS, there is an imperative to understand the wider environmental and social consequences of its deployment at scale. In their study, Deutz and Bardow note that "the potential climate benefits of DAC are partly offset by indirect environmental impacts due to the supply of energy and materials."[4] They presented technology-specific data on plant construction and adsorbent, thereby addressing gaps in research where previous researchers had relied on proxy data.

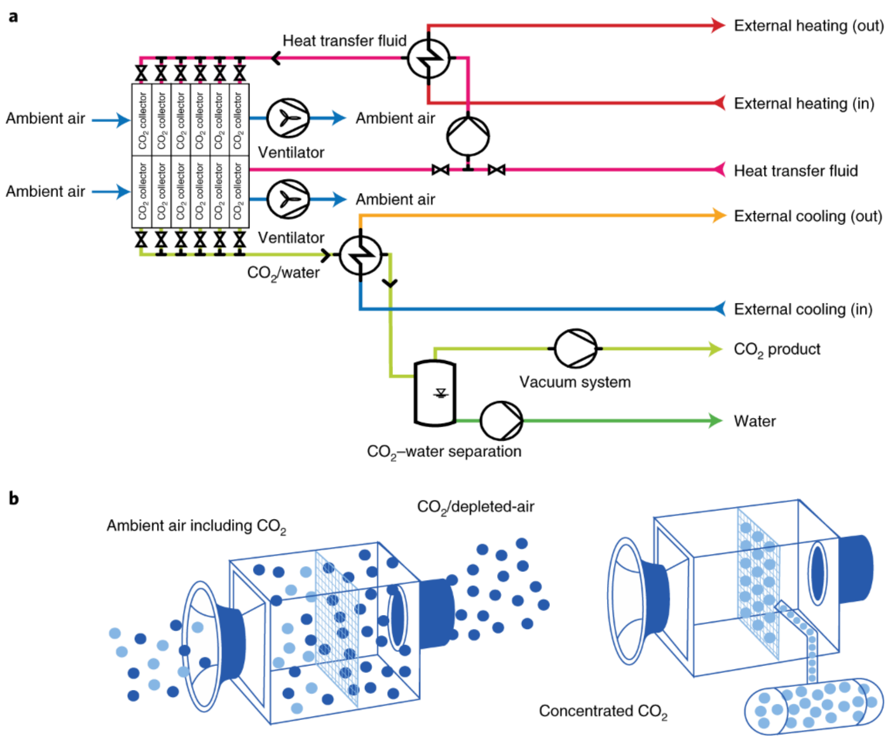

Figure 1: Process schematic for DAC via temperature–vacuum swing adsorption process[4].

They studied the environmental impacts of the captured CO_2 from cradle-to-grave; six different adsorbents; construction of the DAC plant; and capturing 1% of the global annual CO_2 emissions using this process. They considered options such as the conversion of the captured CO_2 to methane, and geological storage.

They found that the carbon footprint of the DAC process depends linearly on the carbon footprint of the electricity supply. The CO_2 capture efficiency is the ratio of avoided CO_2 emissions from cradle-to-gate to CO_2 captured and reaches 95.1 – 96.4% depending on the heat source. They note that the CO_2 capture efficiency does not reach 100%, even if assuming surplus power generation. The construction of the DAC plant and the adsorbent production reduce the CO_2 capture efficiency by 0.6% and 2.4%, respectively.

Deutz and Bardow normalised the environmental KPIs and showed that the largest impacts are on human toxicity, resource depletion, and minerals and metal requirement, with the energy supply and adsorbents being key determinants of their performance[4]. Recently, Leonzio et al.[11] performed an LCA on the different sorbents used for DAC and found that cellulose-based amine sorbents outperform physisorbents and chemisorbents.

Erans et al.[10] note that there may be competing trade-offs between the use of DACCS for climate change mitigation and other objectives such as energy security and the sustainable development goals by the United Nations. Overall, the relative importance of indirect environmental impacts of DACCS are unclear and more work needs to establish any limitations to ensure that policy adequately addresses all aspects of environmental stewardship.

3. The sustainability of EW processes

EW is the process by which CO_2 is sequestered from the atmosphere through the dissolution of silicate minerals on the land surface. In this process, basic rocks are crushed and ground to small particles, and spread onto croplands or agricultural lands for permanent CDR (see Figure 2). Natural rock weathering is a slow process to compensate for changes in the atmospheric composition, but grinding the rock to small particle sizes increases its surface area and promotes the dissolution of the material and consequently, the CDR rate[12,13]. The technical potential of EW in each region is a function of the application area, the rate of application, the type of basic rock used, and its particle size distribution.

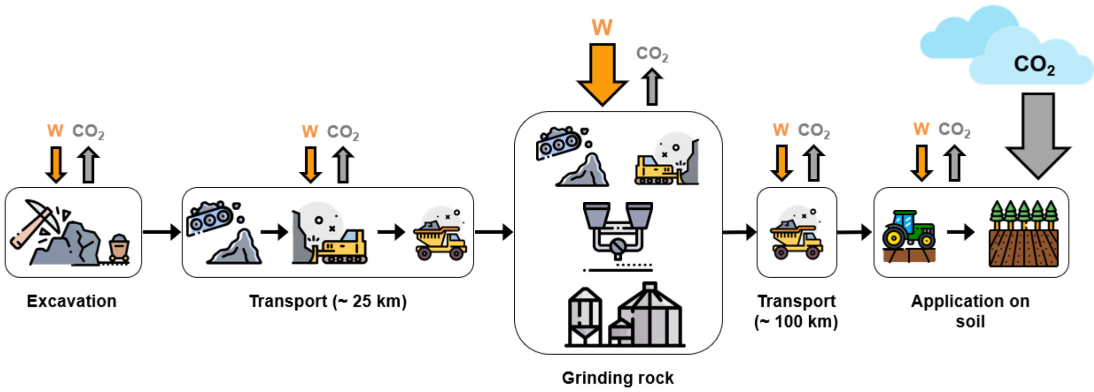

Figure 2: System boundary covering the operations across the EW supply chain. Rocks are excavated and transported to the grinding facility where they are crushed. The ground rock is transported to the area of application and spread on soil.

Note that CDR through rock weathering is a naturally occurring process which is estimated to consume 1.1 Gt CO_2 yr^{-1} today[14]. The global CDR potential of EW is dependent on the amount of basic rock available for weathering reactions. The natural reserves of source rocks containing quicklime, olivine, or other suitable basic minerals have the capacity to sequester thousands of gigatons of CO_2[15,16]. Renforth estimates the overall CDR potential of basic rocks as 0.3 tonne CO_2/tonne rock, which increases to 0.8 tonne CO_2/tonne rock for ultrabasic rocks. Nevertheless, this implies that greater quantities of rock are needed relative to CO_2. Thus, if EW is to be deployed at the gigatonne scale, it would require a mining and grinding industry with the capacity to process several gigatonnes of rock material. To achieve several Gt of CDR, the required additional mining capabilities would mirror that of the global cement industry, which extracts approximately 7 Gt of material per year[17]. This is a profoundly challenging feat to achieve, and ultrabasic rocks may reduce this overall rock material requirement owing to its greater capture potential. For example, minerals in ultrabasic rocks, such as olivine

(Mg_2SiO_4), weather relatively quickly and show a high potential for CO_2 sequestration[18]. However, the weathering of olivine-bearing rocks could release chromium (Cr) and nickel (Ni) into the environment, which could suppress calcium uptake by plants and be toxic in large quantities[19,20]. This creates a trade-off between CO_2 uptake and indirect impacts on the environment, and this needs to be balanced carefully to avoid environmental burden shifting.

Importantly, there are potential co-benefits which favour the deployment of CDR in some cases. Lefebvre reported on previous findings which showed that the addition of basalt rock dust to soil provides a slow release of nutrients, increases yield, rebalances soil pH, increases plant resistance to insects, disease, frost and drought, and increases microorganism growth and earthworm activity[21,22,23,24,25,26,27,28,5]. The corresponding increase in biomass, reduced use of fertilisers, lime[24] and pesticides, and a decrease in soil CO_2 emissions[29] would all contribute to the reduction of the carbon footprint per ha of land associated with basalt addition. But, the scale of these impacts depend on the soil, climate, and plants in the specific region, and are difficult to generalise as part of LCAs.

Unlike DACCS, EW has received less attention in environmental impact assessments with few LCAs conducted to date[30]. There are several assessments of the CDR efficiency of the process depending on the type of rock, but only a single assessment of other lifecycle environmental impacts of EW in the public domain, to the best of the authors' knowledge. Lefebvre et al. investigated the CO_2 capture efficiency of EW by quantifying the amount of EW and mineral carbonation achieved by spreading ground basalt rocks onto agricultural land in Sao Paolo, Brazil. Their system boundary included the extraction of the rock material, its transport to the grinding facility, its comminution into particles of <5 mm, transport from quarries to the fields, and its spreading on the field using agricultural spreaders.

Lefebrvre et al. considered KPIs such as acidification, freshwater ecotoxicity, human toxicity, cumulative energy demand, abiotic depletion, and climate change impacts[5]. Their results suggest that the transport of the ground rock over a distance of 65 km makes the largest contribution to all KPIs, owing to the amount of diesel needed to support the transport fleet[3]. The extent to which this finding is dependent on the particle size distribution is unclear. If smaller particle sizes are used as proposed in Renforth and Beerling, then a greater energy requirement is needed for milling and grinding the rocks, with corresponding impacts on the environmental performance of the CDR technology. Overall, more research is needed to understand the environmental impacts of starting assumptions on rock types, transport distances, particle size distributions, etc., and we explore this as part of the deliverable.

4. Methodology

We conducted an LCA – environmental impacts of inputs and outputs[31] – of the selected NETPs to obtain technical, environmental, and socio-economic KPIs. Figure 3 depicts the phases of the applied LCA methodology. Consistent with previous deliverables[32–34], an attributional modelling approach is used in this deliverable[35]. The functional unit (FU) – the reference unit that quantifies the performance of the studied systems – is defined as one tonne of CO_2 effectively sequestered within the timeframe of the analysis (100 years). Where the secondary functions of the studied NETPs – i.e., the products and services they provide in addition to CDR – substitute equivalent functions provided by other systems, the system boundary expansion method was applied[35].

[3] See section 6 for an overview of the environmental impacts associated with the transport of ground rock to the application sites.

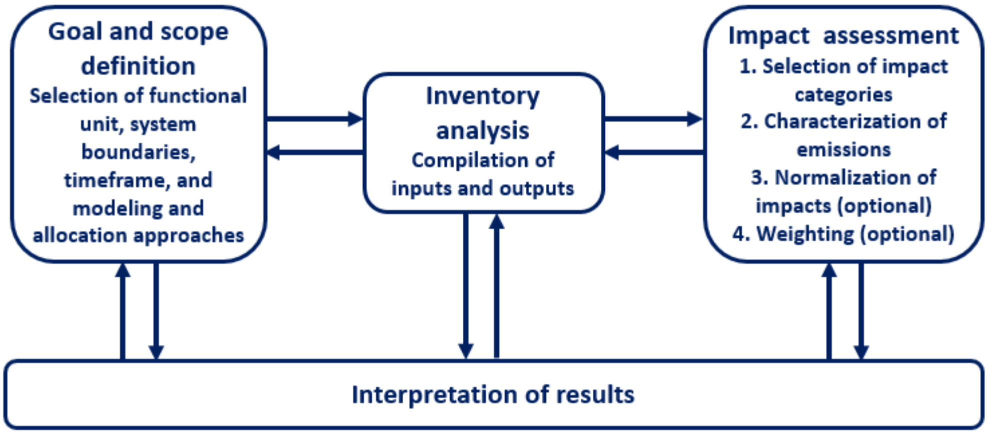

Figure 3: Phases involved in the lifecycle assessment of different technologies (adapted from ISO 14040[31]).

The life cycle models were implemented in SimaPro 9.1.0.8[36] were developed using published data[37–40], and activities from the Ecoinvent 3.5 database[41]. 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}) less the overall life-cycle CO_2 emissions (E_{CO_2}), and S_{CO_2} (equation e1). Note that E_{CO_2} does not include the avoided CO_2 emissions owing to the replacement of other products or services. 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)[42] to quantify the effects of the assessed NETPs on the following impact 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.

Moreover, we applied the ReCiPe 2016 impact assessment method[43] (endpoint level, hierarchist perspective) to evaluate the damage to three areas of protection, namely human health, ecosystem quality, and resource scarcity. Finally, we monetised the environmental impacts by applying the conversion factors from Weidema[44] to the endpoint level impacts.

5. Scenario definition

Here we describe the assumptions used to model the EW and DACCS scenarios. In the EW scenarios, ground rocks (dunite or basalt) are spread over croplands, where the required infrastructure and equipment are assumed to be available[37]. Once the rock materials are dissolved, the silicate minerals react with atmospheric CO_2, which is sequestered as bicarbonate ions, according to reaction R1 (*Me* represents a divalent metal). Runoff transports these ions to the oceans, where their residence time exceeds 100,000 years[45].

$$Me_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2Me^{2+} + 4HCO_3^- + H_4SiO_4 \qquad \text{(R1)}$$

The dissolution of the rock grains is the rate-limiting step of the weathering process. We applied the model developed by Strefler et al.[37] to estimate the minimum grain size that would allow the rock to dissolve within 10 years at 25 °C, and the amount of CO_2 sequestered per tonne of rock within that time period (Table 1). The energy required to grind the rock (Table 1), dependent on the grain size, was estimated with the exponential correlation presented in Strefler et al[37]. The energy and other inputs required for the crushing, mining and spreading operations were taken from the Ecoinvent 3.5 database[41]. We assume a transport distance from the mine to the spreading site of 300 km, consistent with Strefler et al.[37], who found that between 80 and 95% of the agricultural areas available for enhanced weathering are located within this distance from the rock sources.

Table 1. Rock-specific parameters covering the grinding energy requirements and material emissions.

	Dunite	**Basalt**
Grain size (µm)	131	34
Sequestered CO_2 (tonne/tonne rock)	1.1	0.3
Grinding energy (MJ/tonne rock)	22.94	109.97
Released K_2O ($g/m^2/yr$)	0.90	22.24
Released P_2O_5 ($g/m^2/yr$)	0.15	4.26

The compositions of dunite and basalt were taken from the literature[46–48]. The dissolution of the rock grains entails the emission of the minerals and metals contained in the rocks to the agricultural soil. Assuming a high rock application rate of 15 kg/m^2,[37] the amount of K_2O and P_2O_5 released annually in the dunite scenario (Table 1) is lower than the typical fertiliser application rates[49]. Therefore, we assume that the dissolved K_2O and P_2O_5 can replace the same amount of fertilisers in the dunite scenarios. In the basalt scenario, the amount of released K_2O is substantially higher, and therefore only the dissolved P_2O_5 replaces an equivalent amount of fertiliser. We consider that the K_2O released annually in the basalt scenario can only replace 4.45 $g/m^2/yr$ of K_2O fertiliser, which is representative of the K_2O demand of cereals in moderately deficient soils[50].

We assume that the application of the ground rocks to the soil does not involve the occupation or transformation of additional land, since croplands can maintain their original function – crop production. As a model limitation, we do not consider the potential reduction in soil N_2O emissions owing to the application of basalt to the soil[45,51]. Furthermore, we did not consider that under certain soil conditions some cations could react with the produced bicarbonate anions to produce carbonate minerals, which would release part of the captured CO_2[52].

The HTLS-DACCS and LTSS-DACCS models are based on the technologies deployed by the companies *Carbon Engineering*[39] and *Climeworks*[38,40], respectively. In the HTLS-DACCS scenarios, atmospheric CO_2 is absorbed into a basic solution, which is regenerated with high-temperature heat. Here, natural gas supplies high-temperature heat, and the CO_2 derived from the combustion of natural gas is captured and sequestered. In configuration 1 of HTLS-DACCS, additional natural gas is burnt in a turbine to generate electricity. The emissions data of natural gas combustion were taken from the literature[53,54]. The second HTLS-DACCS configuration consumes electricity from the grid or a renewable energy source (wind or solar photovoltaic). The HTLS-DACCS process is based on two connected chemical loops; thus, the intermediate chemical products must be temporarily stored when intermittent energy sources are used.

In the LTSS-DACCS scenarios, CO_2 is adsorbed onto a solid sorbent that is subsequently regenerated with low-temperature heat[55]. Table 2 shows the energy input of the studied DACCS technologies, excluding the energy required to compress and sequester the captured CO_2.

Table 2. Energy consumption of Direct Air Capture, excluding transport and storage (kWh/tonne captured CO_2).

	HTLS-DACCS Configuration 1	**HTLS-DACCS Configuration 2**	**LTSS-DACCS Configuration 1**	**LTSS-DACCS Configuration 2**
Electricity	0	366	700	2,206
Heat	2,447	1,458	3,306	0

We studied two LTSS-DACCS configurations. In the first scenario, the source of low-temperature heat is the excess heat generated in the production of geothermal electricity. As Table 2 shows, the needed electricity to heat ratio is lower than the ratio of electricity to excess heat that can be recovered in the geothermal plant – approximately 1 to 5[56].

We also considered the use of heat pumps based on working fluid R1234ze(E) to supply the low-temperature heat (configuration 2). We estimated the coefficient of performance (COP) with equation e2, where T_1 is the temperature of the heat source (ambient air at 288 K) and T_2 represents the temperature required to desorb the CO_2 (373 K). The efficiency of the heat pump (η_{hp}) is assumed to be 50%, which is within the typical range of efficiencies of industrial heat pumps[57]. With these data, we estimated a COP of 2.2, which leads to a total electricity consumption of 2,206 kWh/tonne CO_2 captured for this LTSS-DACCS configuration. We assessed scenarios powered by the global grid mix, wind, and solar photovoltaic electricity.

$$COP = \frac{T_2}{T_2 - T_1} \cdot \eta_{hp} \qquad \text{(e2)}$$

The adsorbent consumption of the LTSS-DACCS process is 7.5 kg/tonne[38]. The composition of the modelled adsorbent is 47.75% cellulose fiber, 47.75% polyethylenimine and 4.5% epoxy resin[40]. The production of polyethylenimine was modelled based on stoichiometric data and the typical yield (i.e., 87.5%) of the Wenker process[58]. The sodium sulfate generated as a by-product of the process is assumed to be landfilled, whereas the unreacted products are treated in a hazardous waste incineration plant. Lacking more accurate estimates, the energy consumption of the Wenker process was approximated based on the average energy demand of a large multi-product chemical plant, i.e., 3.2 MJ/kg (50% natural gas, 38% electricity and 12% steam)[59]. The adsorbent is landfilled at the end of its lifetime.

We did not include the equipment requirements within any of the DACCS LCA models. On the other hand, given the modular characteristics of all the studied DACCS configurations[39,55], we assumed that the DACCS plants are located next to the sequestration site. The captured CO_2 must be compressed to 150 bar to be injected into the geological reservoir, which consumes 132 kWh of power per tonne[39].

The grid mix used in the foreground activities of our models (to power DACCS, manufacture the LTSS-DACCS sorbent and grind the rocks in the EW scenarios) is the 2030 global electricity mix projected by the IEA in the Announced Pledges Scenario, which assumes that all the climate commitments made by governments around the world will be met on time[60]. We conducted a sensitivity analysis by considering the 2020 global grid mix and the 2040 global electricity mix taken from the Announced Pledges Scenario.

6. Key findings

Here we present the LCA results of the DACCS and EW scenarios. First, we analyse their climate change impacts and CDR efficiencies, shown in Figure 4. The climate change impacts of the greenhouse gases emitted throughout the life cycle of the EW system based on dunite – largely due to rock transportation – are the lowest; this scenario can remove 962 kg CO_2-eq per tonne CO_2 sequestered. The EW scenario deploying basalt requires a larger amount of rock owing to its lower technical potential and smaller grain sizes, thereby increasing the overall energy consumption throughout the process, which leads to the removal of only 850 kg CO_2-eq/tonne CO_2.

The climate change impacts of the DACCS scenarios are strongly linked to the selected energy source. The performance of the LTSS-DACCS scenarios deploying heat pumps is worse than that of the HTLS-DACCS scenarios relying on the same energy source, given their higher energy demand. HTLS- and LTSS-DACCS powered by wind attains the best results (-943 and -924 kg CO_2-eq/tonne CO_2, respectively), followed by HTLS-DACCS deploying solar photovoltaic electricity, LTSS-DACCS based on excess geothermal heat, and HTLS-DACCS using natural gas as a source of heat and electricity (-919, -902, and -862 kg CO_2-eq/tonne CO_2, respectively). The DACCS scenarios deploying electricity from the 2030 grid mix (where fossil fuels account for 44% of the produced electricity) generate the worst performing results for the HTLS and LTSS scenarios. While the LTSS-DACCS configuration using the 2030 mix can only prevent 53 kg CO_2-eq/tonne CO_2, HTLS-DACCS powered by the 2030 electricity mix avoids 807 kg CO_2-eq/tonne CO_2, performing better than the LTSS-DACCS scenario powered by solar photovoltaic, which only averts 771 kg CO_2-eq/tonne CO_2, mainly due to the climate change impacts associated with the production of the photovoltaic panels.

The results of the DACCS scenarios powered by grid electricity significantly change if the grid mix of years 2020 or 2040 are used in the foreground activities. This effect is particularly relevant in the LTSS-DACCS scenario, where the net removal would increase to 380 kg CO_2-eq/tonne CO_2 if the 2040 mix were deployed, and the use of the 2020 mix would not mitigate climate change impacts but generate additional impacts (321 kg CO_2-eq/tonne CO_2).

Regarding the CDR efficiencies, they follow a similar pattern to the climate change impacts. The CDR efficiencies range between 0.84 and 0.96 in the EW scenarios deploying basalt and dunite, 0.11 – 0.93 in the LTSS-DACCS scenarios and 0.85 – 0.98 in the HTLS-DACCS scenarios, with the lowest values obtained in the DACCS scenarios powered by the grid mix and the highest in those reliant on wind electricity.

Figure 5 depicts the other environmental KPIs quantified for the assessed scenarios. The EW scenario based on dunite achieves the lowest impact in five of the fifteen impact categories shown in Figure 5 (photochemical ozone formation, acidification, marine eutrophication, terrestrial eutrophication, and fossil resource use). Nonetheless, this scenario performs poorly on carcinogenic toxicity and freshwater ecotoxicity, mainly because of the release of nickel to the soil as the rock grains dissolve. Although the use of basalt can reduce the carcinogenic toxicity and freshwater ecotoxicity impacts of the enhanced weathering scenarios by 83 and 22% respectively, basalt leads to the highest non-carcinogenic toxicity impacts mainly due to the release of lead, zinc, cadmium, and arsenic to the agricultural soil, and it is one order of magnitude higher than those associated with dunite. Overall, the human toxicity and freshwater ecotoxicity impacts are substantially lower in the DACCS scenarios.

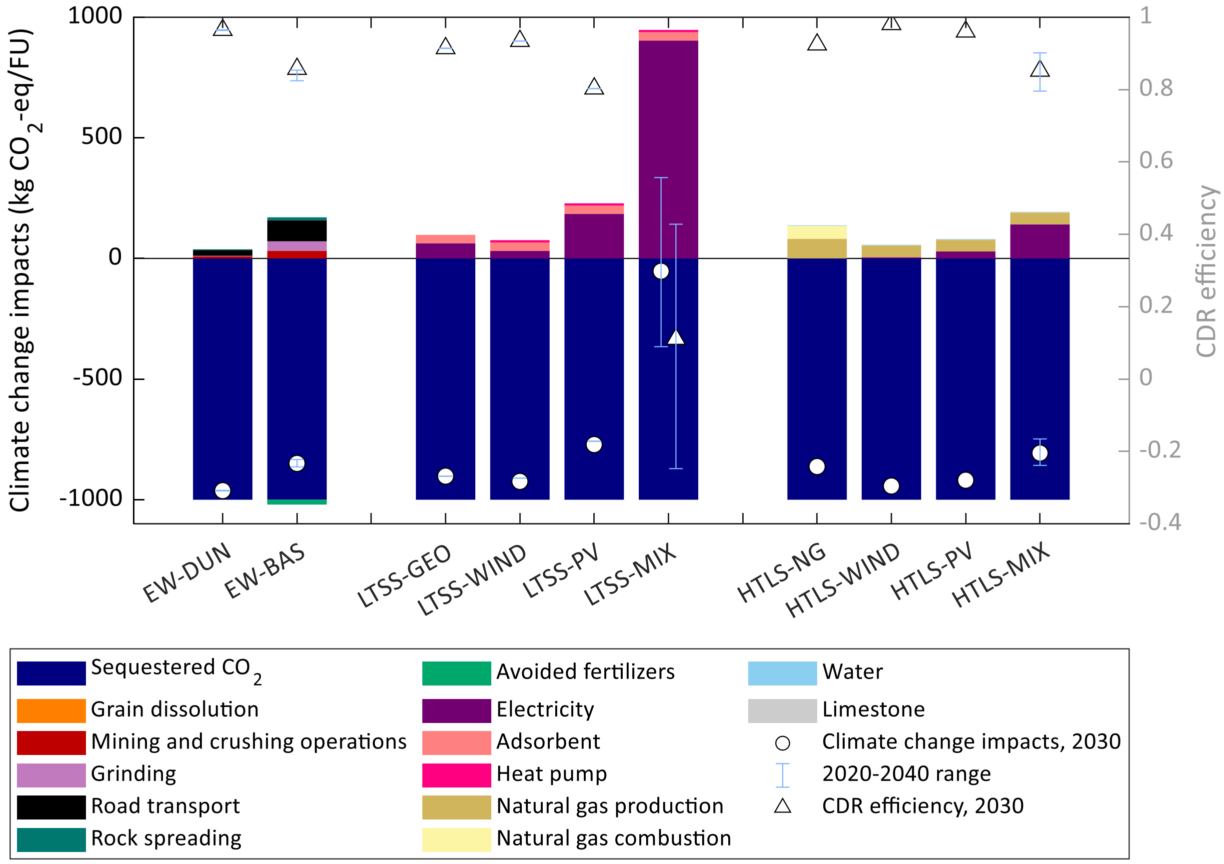

Figure 4: CDR efficiency and climate change impacts per tonne of sequestered CO_2 for the studied scenarios: enhanced weathering based on dunite or basalt (EW-DUN or EW-BAS), LTSS-DACCS powered by geothermal energy (LTSS-GEO), wind (LTSS-WIND), solar photovoltaic (LTSS-PV) or the global electricity mix (LTSS-MIX), and HTLS-DACCS deploying natural gas (HTLS-NG), wind (HTLS-WIND), solar photovoltaic (HTLS-PV) or the global grid mix (HTLS-MIX) as a source of electricity. The results of the EW, LTSS- and HTLS-MIX scenarios are estimated with the global grid electricity of year 2030. The interval ranges represent results for the global electricity mixes of years 2020 and 2040.

HTLS-DACCS powered by wind minimises ozone depletion, ionizing radiation, particulate matter, and non-carcinogenic toxicity impacts. The main side-effects of HTLS-DACCS are its large consumption of water to produce calcium hydroxide, which is an intermediate product within the chemical loop driving the CDR. Similarly, DACCS processes deplete fossil resources when natural gas is used to generate the high-temperature heat, with potential consequences for energy security and independence. These unintended impacts could be minimized by replacing the natural gas with biomethane or using electric furnaces powered by renewable energy.

A high electricity demand in the LTSS-DACCS scenarios deploying heat pumps, combined with the prevalent use of fossil fuels in the 2030 electricity grid render the LTSS-DACCS scenario as the worst performing in nine of the impact categories shown in Figure 5. On the other hand, the use of photovoltaic electricity in the LTSS-DACCS scenarios leads to the highest impacts on land use, and minerals and metals scarcity, given the considerable area required to install the photovoltaic panels, and the metals needed for their construction.

The use of renewable energy sources generates high impacts on carcinogenic toxicity, land use, and minerals and metals use. The scenarios deploying the 2040 electricity mix achieve lower impacts with respect to the base scenarios using the 2030 mix in all categories except for these three, due to the progressive penetration of renewable energy sources.

Figure 6 illustrates the impacts of the studied NETPs on three key areas of protection: human health, ecosystems, and resource scarcity. As Figure 6A shows, the water consumption and emission of pollutants generate some detrimental health effects in all the scenarios. However, all the NETPs but two lead to the net prevention of health impacts due to the averted risk of certain diseases (malnutrition, malaria and diarrhea) and floods linked to global warming. The avoided health impacts range between $7.7 \cdot 10^{-4}$ and $9.0 \cdot 10^{-5}$ DALYs (Disability Adjusted Life Years) per tonne CO_2 sequestered, with the extremes corresponding to HTLS-DACCS powered by wind and LTSS-DACCS powered by solar photovoltaic, respectively; the health effects averted by HTLS-DACCS are greater than those of LTSS-DACCS. In the DACCS scenarios, most of the damaging health effects occur because of the formation of fine particulate matter associated with the energy sources, whereas the health damage of enhanced weathering stems from the toxicity impact linked to the emission of metals to the soil. The NETPs generating net health impacts are enhanced weathering based on basalt ($2.4 \cdot 10^{-3}$ DALY/tonne CO_2) and LTSS-DACCS powered by the grid electricity ($1.5 \cdot 10^{-3}$ DALY/tonne CO_2).

Moreover, as Figure 6B shows, LTSS-DACCS consuming grid electricity is the only NETP configuration causing net impacts on ecosystems ($2.3 \cdot 10^{-6}$ species·yr/tonne CO_2, expressed as the number of species lost integrated over time per tonne CO_2 sequestered), mainly due to the emission of acidifying substances (SO_2, NO_X and NH_3) during the combustion of coal for electricity generation. The other scenarios avert net ecosystem impacts because of the prevented harmful effects of increasing temperatures. The avoided impacts range between $2.6 \cdot 10^{-6}$ species·yr/tonne CO_2 (enhanced weathering with dunite) and $9.8 \cdot 10^{-7}$ species·yr/tonne CO_2 (LTSS-DACCS powered by solar photovoltaic).

The damage to resource availability represents the surplus costs involved in future resource extraction. Figure 6C shows that resource scarcity is predominantly caused by the consumption of fossil resources. All the HTLS-DACCS configurations, dependent on natural gas, attain high values for this KPI (39.4-65.5 €$_{2020}$/tonne CO_2). The LTSS-DACCS scenario powered by the 2030 grid mix also has a significant impact on resource availability (54.5 €$_{2020}$/tonne CO_2), although the more decarbonised 2040 mix could reduce it to 40 €$_{2020}$/tonne CO_2. The enhanced weathering scenario using dunite achieves the best result for this KPI, with only 4.2 €$_{2020}$/tonne CO_2, followed by LTSS-DACCS powered by geothermal and wind energy, with 6.3 and 6.8 €$_{2020}$/tonne CO_2, respectively.

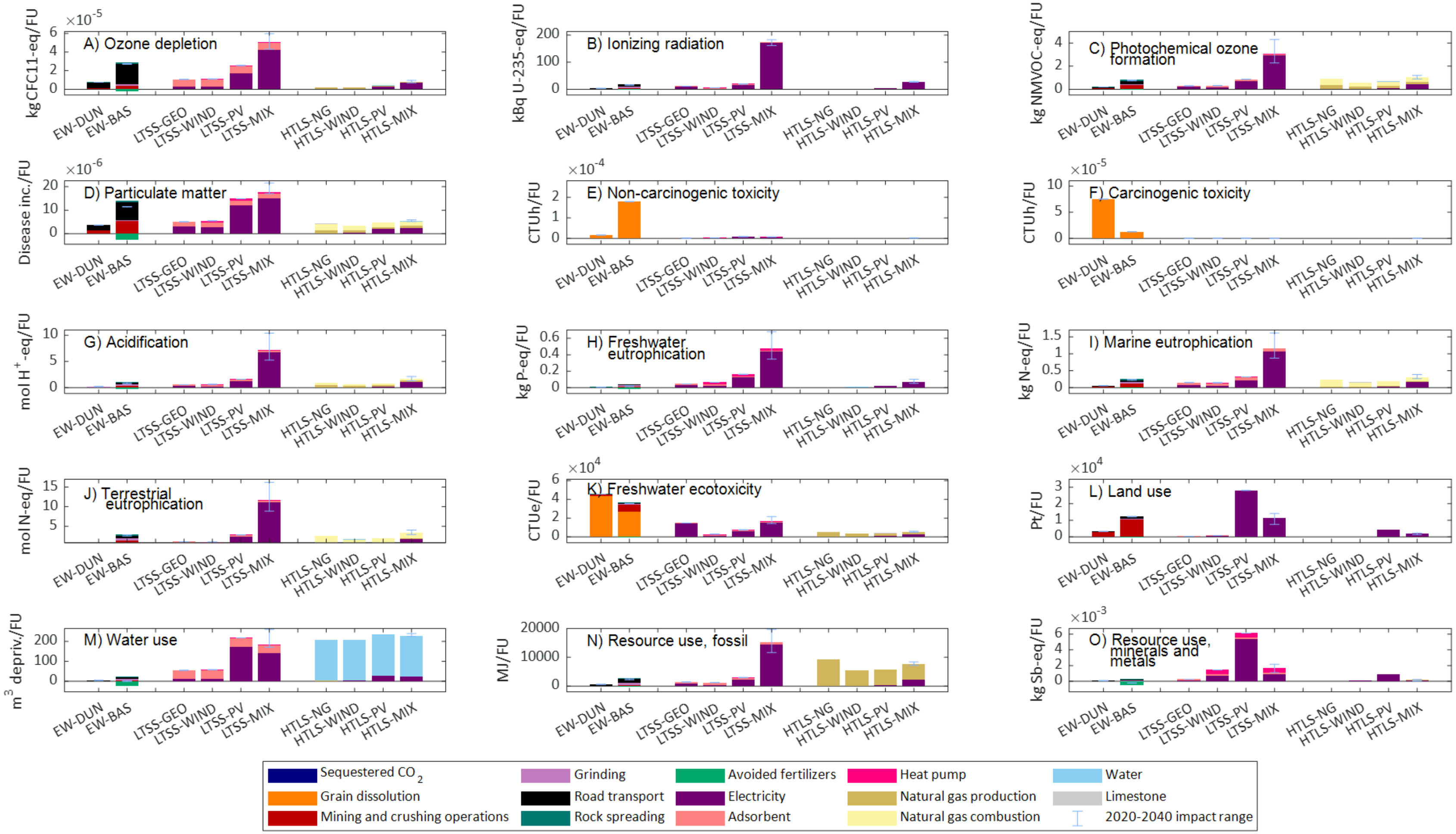

Figure 5: Environmental KPIs per tonne of sequestered CO_2: a) ozone depletion, b) ionizing radiation, c) photochemical ozone formation, d) particulate matter, e) non-carcinogenic toxicity, f) carcinogenic toxicity, g) acidification, h) freshwater eutrophication, i) marine eutrophication, j) terrestrial eutrophication, k) freshwater ecotoxicity, l) land use, m) water use, n) resource use (fossil), o) resource use (minerals and metals) for the studied scenarios: enhanced weathering based on dunite or basalt (EW-DUN or EW-BAS), LTSS-DACCS powered by geothermal energy (LTSS-GEO), wind (LTSS-WIND), solar photovoltaic (LTSS-PV) or the global electricity mix (LTSS-MIX), and HTLS-DACCS deploying natural gas (HTLS-NG), wind (HTLS-WIND), solar photovoltaic (HTLS-PV) or the global grid mix (HTLS-MIX) as a source of electricity. The results of the EW, LTSS- and HTLS-MIX scenarios are estimated with the global grid electricity of year 2030. The interval ranges represent results for the global electricity mixes of years 2020 and 2040.

We estimated the externalities of the assessed NETPs as the monetised impacts on human health, ecosystems, and resource availability (Figure 7). We found that the most attractive scenarios in terms of externalities are LTSS-DACCS powered by geothermal and wind energy, where the prevented externalities amount to 83.7 and 76.4 $€_{2020}$/tonne CO_2 respectively, given the averted impacts on human health and ecosystems, and the minimal damage to resource availability. The externalities avoided by HTLS-DACCS range between 62.5 and 15.2 $€_{2020}$/tonne CO_2 (in the scenarios deploying wind and grid electricity, respectively), whereas the value of the avoided externalities in the enhanced weathering scenario deploying dunite is 39.8 $€_{2020}$/tonne CO_2. Only the two NETPs generating net health damage (enhanced weathering based on basalt and LTSS-DACCS powered by the grid mix) incur additional externalities (219.2 and 226.2 $€_{2020}$/tonne CO_2, respectively).

By comparing the averted externalities to the NETPs costs (compiled in Table 3), we found that the most favorable externalities-to-cost ratio corresponds to the enhanced weathering scenario based on dunite, where externalities could offset 71% of the CDR costs. In fact, this is the only scenario where the estimated CDR cost does not exceed 100 \$/tonne CO_2, the threshold identified in the literature for economic viability[61,62].

Finally, Figure 8 summarises the values of the normalised KPIs that we aim to maximise (Figure 8A) and minimise (Figure 8B). The most appealing NETPs in terms of the studied KPIs are LTSS-DACCS powered by geothermal and wind energy. HTLS-DACCS coupled with renewable energy sources also performs well in most impact categories, at the expense of the substantial consumption of water and fossil resources. The more cost-effective enhanced weathering NETP deploying dunite could also play a role in future CDR pathways; despite generating considerable damage to human health relative to most DACCS scenarios, it leads to the net prevention of health impacts.

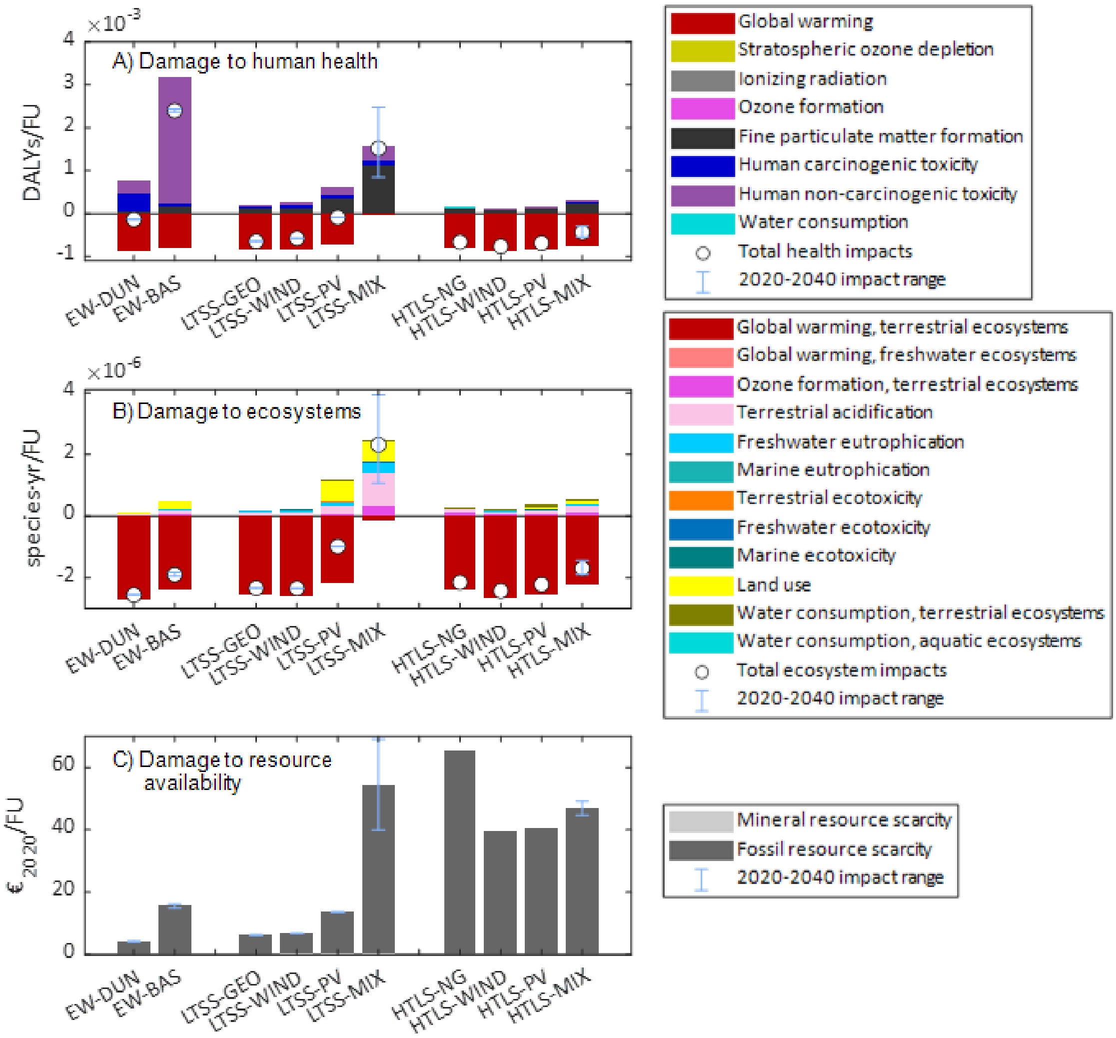

Figure 6: Endpoint KPIs per tonne of sequestered CO_2: a) damage to human health, b) damage to ecosystems, c) damage to resource scarcity for the studied scenarios: enhanced weathering based on dunite or basalt (EW-DUN or EW-BAS), LTSS-DACCS powered by geothermal energy (LTSS-GEO), wind (LTSS-WIND), solar photovoltaic (LTSS-PV) or the global electricity mix (LTSS-MIX), and HTLS-DACCS deploying natural gas (HTLS-NG), wind (HTLS-WIND), solar photovoltaic (HTLS-PV) or the global grid mix (HTLS-MIX) as a source of electricity. The results of the EW, LTSS- and HTLS-MIX scenarios are estimated with the global grid electricity of year 2030. The interval ranges represent results for the global electricity mixes of years 2020 and 2040.

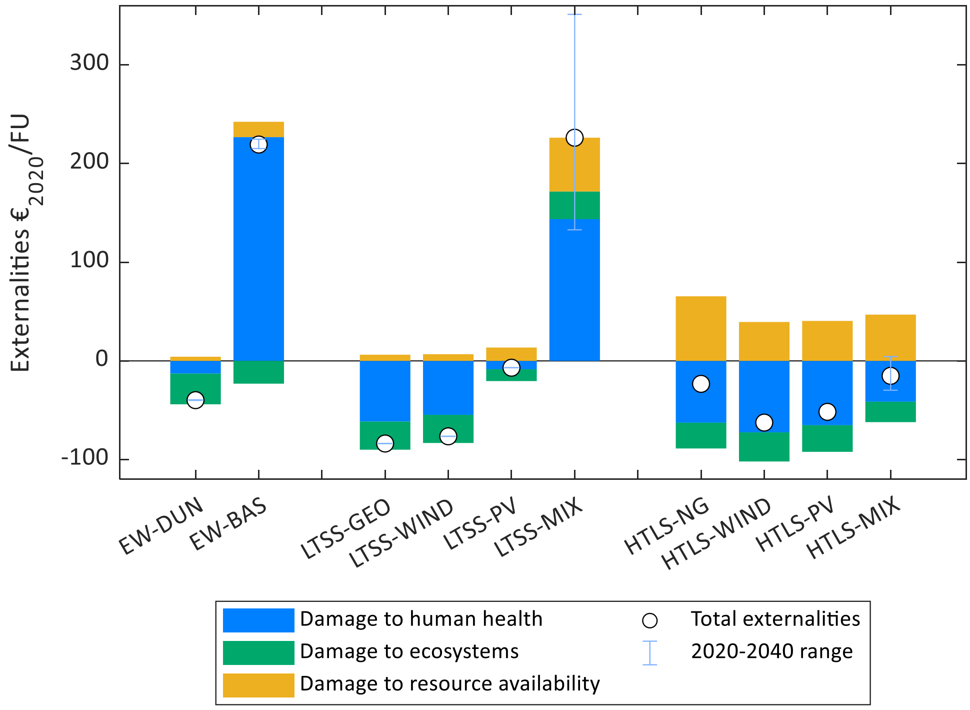

Figure 7: Externalities per tonne of sequestered CO_2 for the studied scenarios: enhanced weathering based on dunite or basalt (EW-DUN or EW-BAS), LTSS-DACCS powered by geothermal energy (LTSS-GEO), wind (LTSS-WIND), solar photovoltaic (LTSS-PV) or the global electricity mix (LTSS-MIX), and HTLS-DACCS deploying natural gas (HTLS-NG), wind (HTLS-WIND), solar photovoltaic (HTLS-PV) or the global grid mix (HTLS-MIX) as a source of electricity. The results of the EW, LTSS- and HTLS-MIX scenarios are estimated with the global grid electricity of year 2030. The interval ranges represent results for the global electricity mixes of years 2020 and 2040.

Table 3. Available cost estimates for the following NETPs: enhanced weathering based on dunite and basalt (EW-DUN and EW-BAS), LTSS- and HTLS-DACCS (unknown energy sources), and HTLSS powered by natural gas (NG) or grid electricity (MIX).

Scenario	**CDR cost ($€_{2020}$/tonne CO_2)**	**Source**
EW-DUN	56	Estimated
EW-BAS	73-182	Estimated[37,52]
LTSS-DACCS	>500	Current[63]
HTLS-DACCS	≈250	Current[64]
HTLS-DACCS (NG)	161-222	Estimated[39]
HTLS-DACCS (MIX)	108-156	Estimated[39]

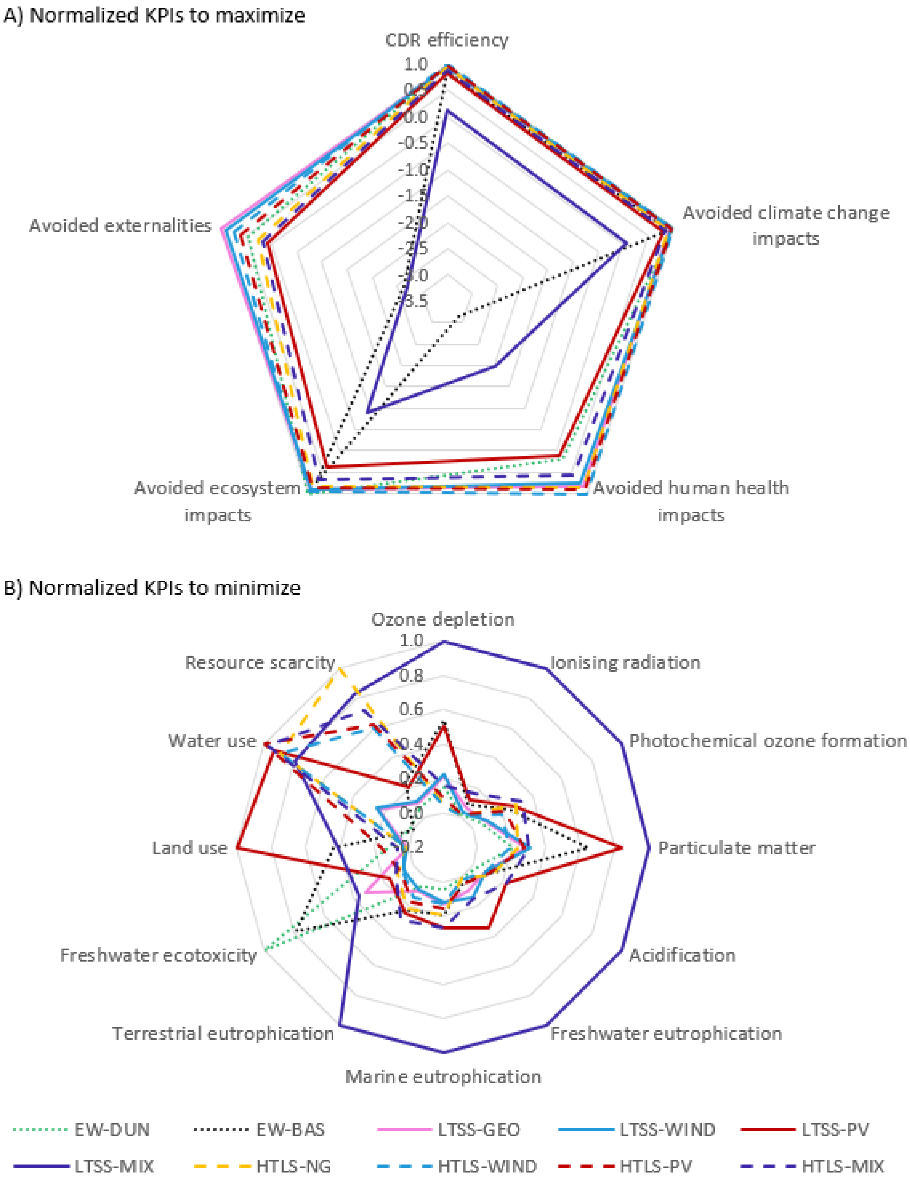

Figure 8: Normalised KPIs. A) KPIs to maximise, B) KPIs to minimise for the studied scenarios: enhanced weathering based on dunite or basalt (EW-DUN or EW-BAS), LTSS-DACCS powered by geothermal energy (LTSS-GEO), wind (LTSS-WIND), solar photovoltaic (LTSS-PV) or the 2030 global electricity mix (LTSS-MIX), and HTLS-DACCS deploying natural gas (HTLS-NG), wind (HTLS-WIND), solar photovoltaic (HTLS-PV) or the 2030 global grid mix (HTLS-MIX) as a source of electricity. The results of the EW, LTSS- and HTLS-MIX scenarios are estimated with the global grid electricity of year 2030.

7. Conclusions and further steps

This deliverable presented a sustainability assessment of DACCS and EW, after identifying the primary research gaps in the academic literature. A full-scale life cycle assessment was used to quantify the environmental performance of DACCS and EW considering their direct impacts, alongside impacts from their supply chains. This has highlighted the potential for EW processes to offer high CDR efficiencies at relatively low costs. EW scenarios using basalt and dunite show high CDR efficiencies of 85% and 96%, respectively. Relative to dunite, the CDR efficiency of basalt rock is lower as a smaller particle size distribution is needed together with greater quantities of rock, increasing energy requirements, and the corresponding carbon footprint.

Importantly, and in line with observations made in literature, EW using dunite (an ultrabasic rock) performs poorly on carcinogenic toxicity, and freshwater ecotoxicity, mainly because of the release of nickel to the soil as the rock grains dissolve. This observation, combined with the relative scarcity of ultrabasic rock formations, was used in favour of EW with basalt in academic literature. However, we find that although basalt can reduce the carcinogenic toxicity and freshwater ecotoxicity impacts of the EW scenarios by 83 and 22%, respectively, it leads to non-carcinogenic toxicity impacts that are one order of magnitude greater than those associated with dunite, because of its higher content of certain metals, chiefly lead, zinc, cadmium, and arsenic. Our analysis suggests that the overall externality cost of EW with basalt renders it less favourable to dunite. Thus, additional analyses are required to understand the regional risks of EW using both basic and ultrabasic rocks before introducing policy measures.

The climate change impacts of the DACCS scenarios are strongly linked to the selected energy source. HTLS-DACCS scenarios outperform LTSS-DACCS owing to their lower energy demand. DACCS using electricity from the 2030 global electricity mix (where fossil fuels account for 44% of the produced electricity) generates the poorest results for both HTLS and LTSS scenarios. In particular, HTLS-DACCS powered by the 2030 electricity mix avoids 807 kg CO_2-eq/tonne CO_2 compared to only 53 kg CO_2-eq/tonne CO_2 using the LTSS-DACCS scenario. The use of electricity with a very low carbon footprint, such as that of wind power, improves the performance of HTLS- and LTSS-DACCS with efficiencies of 94% and 92%. HTLS-DACCS powered by wind minimises ozone depletion, ionizing radiation, particulate matter, and non-carcinogenic toxicity impacts. The main side-effects of the HTLS-DACCS scenarios are their large consumption of water to produce calcium hydroxide as a reaction intermediate.

Most notably, all but two NETPs lead to the net prevention of health impacts due to the averted risks of global warming. In the DACCS scenarios, most of the damaging health effects occur because of the formation of fine particulate matter associated with the energy sources, whereas damage to human health arises from the toxicity impact of the metals released into the soil in the EW scenarios. The two NETPs which generate net harmful health impacts are EW based on basalt and LTSS-DACCS powered by the current global average electricity mix. Thus, harmful health impacts can be avoided through the continued decarbonisation of the electricity mix and careful design of EW supply chains. Similarly, ecosystems impacts are prevented in all cases except where the current grid electricity mix is used. This reinforces the need to integrate alternative generation technologies in the grid to displace the fossil fuel generation mix.

The sustainability analyses presented in this deliverable are scenario-specific, and these findings should be contrasted with more granular regional studies to establish the value of a given NETP for delivering CDR and other co-benefits. NETPs must be tailored to the specific system to ensure their deployment contributes to wider sustainable development goals. A key limitation of an LCA-based sustainability analysis is that the findings are highly sensitive to the quality of the data. This is especially the case for system- and region-specific parameters such as the CO_2 intensity of the fuel and electricity supply, overall transport distances, volumes, etc. LCA impact estimates are historical projections of the performance of the designed systems, mainly because the input parameters evolve over the period of operation of an NETP. There is scope to reduce the uncertainty in the estimated impacts by coupling energy systems models with environmental KPIs. However, the utility of this approach is largely contingent on the accuracy of the energy system models and associated input and output data. Here, the tools and techniques developed in the NEGEM project within WP1, 3, 4 and 7 provide a robust foundation by developing estimates of technical potential based on first principles to generate realistic CDR deployment figures and associated environmental impacts. Future work should consider the impact of learning rates and ongoing technology innovation on the environmental performance of different NETPs.

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

References

1. Olivier, J. G. J. & Peters, J. A. H. W. *Trends in Global CO2 and Total Greenhouse Gas Emissions*. *PBL Netherlands Environmental Assessment Agency* www.pbl.nl/en. (2020).
2. Hanna, R., Abdulla, A., Xu, Y. & Victor, D. G. Emergency deployment of direct air capture as a response to the climate crisis. *Nat. Commun.* **12**, 1–13 (2021).
3. Madhu, K., Pauliuk, S., Dhathri, S. & Creutzig, F. Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. *Nat. Energy* **6**, 1035–1044 (2021).
4. Deutz, S. & Bardow, A. Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nat. Energy* **6**, 203–213 (2021).
5. Lefebvre, D. *et al.* Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil. *J. Clean. Prod.* **233**, 468–481 (2019).
6. Edwards, D. P. *et al.* Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. *Biol. Lett.* **13**, (2017).
7. Tan, R. R. & Aviso, K. B. On life-cycle sustainability optimization of enhanced weathering systems. *J. Clean. Prod.* **289**, 125836 (2021).
8. Cobo, S., Valente, A., Galán-Martín, Á. & Guillén-Gosálbez, G. *Justification of NETPs chosen for the NEGEM project*. (2020).
9. Realmonte, G. *et al.* An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun. 2019* **10**, 1–12 (2019).
10. María Erans *et al.* Direct air capture: process technology, techno-economic and socio-political challenges. *Energy Environ. Sci.* **15**, 1360–1405 (2022).
11. Leonzio, G., Mwabonje, O., Fennell, P. S. & Shah, N. Environmental performance of different sorbents used for direct air capture. *Sustain. Prod. Consum.* **32**, 101–111 (2022).
12. Hartmann, J., Jansen, N., Dürr, H. H., Kempe, S. & Köhler, P. Global CO2-consumption by chemical weathering: What is the contribution of highly active weathering regions? *Glob. Planet. Change* **69**, 185–194 (2009).
13. Taylor, L. L., Beerling, D. J., Quegan, S. & Banwart, S. A. Simulating carbon capture by enhanced weathering with croplands: an overview of key processes highlighting areas of future model development. *Biol. Lett.* **13**, (2017).
14. Ciais, P. *et al. Carbon and Other Biogeochemical Cycles. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (2013).
15. Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S. & Renforth, P. CO2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems. *Front. Clim.* **1**, 7 (2019).
16. Hartmann, J. *et al.* Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* **51**, 113–149 (2013).
17. Renforth, P. & Henderson, G. Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.* **55**, 636–674 (2017).
18. O’Connor, W. K. *et al. Aqueous Mineral Carbonation: Mineral Availability, Pretreatment, Reaction Parametrics, and Process Studies*. *U.S. Department of Energy* https://www.netl.doe.gov/File Library/Research/Coal/NETLAlbanyAqueousMineralCarbonation.pdf (2005) doi:10.13140/RG.2.2.23658.31684.
19. Renforth, P., Pogge von Strandmann, P. A. E. & Henderson, G. M. The dissolution of olivine added to soil: Implications for enhanced weathering. *Appl. Geochemistry* **61**, 109–118 (2015).
20. ten Berge, H. F. M. *et al.* Olivine Weathering in Soil, and Its Effects on Growth and Nutrient Uptake in Ryegrass (Lolium perenne L.): A Pot Experiment. *PLoS One* **7**, e42098 (2012).

21. Campe, J., Kittredge, D. & Klinger, L. *The Potential of Remineralization With Rock Mineral Fines To Transform Agriculture, Forests, Sustainable Biofuels Production, Sequester Carbon, and Stabilize the Climate*. http://remineralize.org/wp-content/uploads/2015/10/ODB1.pdf (2015).
22. Gillman, G. P., Burkett, D. C. & Coventry, R. J. Amending highly weathered soils with finely ground basalt rock. *Appl. Geochemistry* **17**, 987–1001 (2002).
23. Harley, A. D. & Gilkes, R. J. Factors influencing the release of plant nutrient elements from silicate rock powders: a geochemical overview. *Nutr. Cycl. Agroecosystems 2000 561* **56**, 11–36 (2000).
24. Kantola, I. B., Masters, M. D., Beerling, D. J., Long, S. P. & DeLucia, E. H. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biol. Lett.* **13**, (2017).
25. Manning, D. A. C. Mineral sources of potassium for plant nutrition. A review. *Agron. Sustain. Dev. 2009 302* **30**, 281–294 (2012).
26. Nunes, J. M. G., Kautzmann, R. M. & Oliveira, C. Evaluation of the natural fertilizing potential of basalt dust wastes from the mining district of Nova Prata (Brazil). *J. Clean. Prod.* **84**, 649–656 (2014).
27. Ramos, C. G. *et al.* A preliminary evaluation of volcanic rock powder for application in agriculture as soil a remineralizer. *Sci. Total Environ.* **512–513**, 371–380 (2015).
28. Ramos, C. G. *et al.* Evaluation of the potential of volcanic rock waste from southern Brazil as a natural soil fertilizer. *J. Clean. Prod.* **142**, 2700–2706 (2017).
29. Beerling, D. J. *et al.* Farming with crops and rocks to address global climate, food and soil security. *Nat. Plants* **4**, 138–147 (2018).
30. Eufrasio, R. M. *et al.* Environmental and health impacts of atmospheric CO2 removal by enhanced rock weathering depend on nations' energy mix. *Commun. Earth Environ.* **3**, 1–13 (2022).
31. ISO 14040. Environmental Management — Life Cycle Assessment — Principles and Framework (2006).
32. Cobo, S. *et al. Comprehensive sustainability assessment of terrestrial biodiversity NETPs*. (2021).
33. Hurskainen, M., Calvo Serrano, R. & Koponen, K. *Comprehensive sustainability assessment of Bio-CCS NETPs*. (2021).
34. Cobo, S., Guillén-Gosálbez, G., Gundersen, H., Hancke, K. & Golmen., L. *Comprehensive sustainability assessment of marine NETPs*. (2021).
35. European Commission - Joint Research Centre - Institute for Environment and Sustainability. *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance*. (2010).
36. SimaPro. https://simapro.com/ [last accessed: 12/02/2021].
37. Strefler, J., Amann, T., Bauer, N., Kriegler, E. & Hartmann, J. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* **13**, (2018).
38. Deutz, S. & Bardow, A. Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nat. Energy* **6**, 203–213 (2021).
39. Keith, D. W., Holmes, G., St. Angelo, D. & Heidel, K. A Process for Capturing CO2 from the Atmosphere. *Joule* 1–22 (2018) doi:10.1016/j.joule.2018.05.006.
40. Gebald, C., Wurzbacher, J.A., Steinfeld, A. Amine containing fibrous structure for adsorption of CO2 from atmospheric air. WO 2010/091831 Al. (2010).
41. Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).
42. Environmental Footprint method.
43. Huijbregts, M.A.J., et al. *ReCiPe 2016 v1.1. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization.* (2017).
44. Weidema, B. P. Comparing Three Life Cycle Impact Assessment Methods from an Endpoint Perspective. *J. Ind. Ecol.* **19**, 20–26 (2015).
45. Vakilifard, N., Kantzas, E. P., Edwards, N. R., Holden, P. B. & Beerling, D. J. The role of enhanced rock weathering deployment with agriculture in limiting future warming and protecting coral reefs. *Environ. Res. Lett.* **16**, 094005 (2021).
46. Amann, T. *et al.* Enhanced Weathering and related element fluxes - A cropland mesocosm approach.

Biogeosciences **17**, 103–119 (2020).
47. Alloway, B. J. *Heavy metals in soils. Trace metals in metalloids and soils and their bioavailability.* vol. 22 (Springer, 2013).
48. Seydibeyoğlu, M. Ö., Mohanty, A. K. & Misra, M. *Fiber Technology for Fiber-Reinforced Composites*. (Woodhead Publishing, 2017). doi:https://doi.org/10.1016/C2015-0-05497-1.
49. Withers, P. J. A. *Phosphate and potash fertiliser recommendation for cereals: current issues and future needs*. *HGCA Research Review N°40* (1999).
50. Potassium Fertilizer Application in Crop Production.
51. Blanc-Betes, E. *et al.* In silico assessment of the potential of basalt amendments to reduce N2O emissions from bioenergy crops. *GCB Bioenergy* **13**, 224–241 (2021).
52. Beerling, D. J. *et al.* Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature* **583**, 242–248 (2020).
53. Gómez, D. R. et al. Chapter 2. Stationary combustion. in *IPCC guidelines for national greenhouse gas inventories* (2006).
54. European Environment Agency. Energy industries. in *EMEP/EEA air pollutant emission inventory guidebook 2019* (2019).
55. Beuttler, C., Charles, L. & Wurzbacher, J. The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. *Front. Clim.* **1**, (2019).
56. Hirschberg, S., Wiemer, S. & Burgherr, P. *Energy from the Earth. Deep geothermal as a resource for the future?* (2015).
57. Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J. & Bertsch, S. S. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. *Energy* **152**, 985–1010 (2018).
58. Steuerle, U., Feuerhake, R. Aziridines. *Ullmann's encyclopedia of industrial chemistry* vol. 4, 515–522 (2012).
59. Althaus, H. *et al. Life cycle inventories of chemicals. Data v2.0. Ecoinvent* (2007).
60. International Energy Agency. *World Energy Outlook 2021*. (2021).
61. National Academies of Sciences Engineering and Medicine. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* (2019) doi:10.17226/25259.
62. Lackner, K. S. & Azarabadi, H. Buying down the Cost of Direct Air Capture. *Ind. Eng. Chem. Res.* **60**, 8196–8208 (2021).
63. Birnbaum, M. Climeworks Orca plant in Iceland will capture CO2 at big new scale. *The Washington Post* (2021).
64. Direct Air Capture Summit 2021.