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Certification of carbon removals

Part 1: Synoptic review of carbon removal solutions

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CERTIFICATION OF CARBON REMOVALS

Part 1: Synoptic review of carbon removal solutions

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GLOSSARY AND ABBREVIATIONS

Glossary

Additionality: Additionality refers to whether and to what extent the carbon removals project increases removals beyond what would have occurred in the baseline, i.e. in the absence of the project; additionality implies that the removals were caused by the carbon removals mechanism.

Baseline: A counterfactual against which the impact of a removals project is compared, i.e., the baseline describes the carbon removals (and potentially emissions) that would have occurred in absence of the carbon removal project. The baseline can be a quantitative number (e.g., in terms of t CO_2-e) or can refer to a scenario (i.e., a hypothetical reference case that best represents the conditions most likely to occur in the absence of a proposed removals project).

Carbon removal: The withdrawal of greenhouse gases from the atmosphere as a result of deliberate human activities.

Leakage: The net change of anthropogenic emissions/removals that occur outside the project boundary. If leakage occurs (i.e. removals within the project boundary decrease removals outside the project boundary), the overall mitigation impact of the project is reduced; if this is not considered in net quantification of removals, these removals will not all be additional.

Monitoring, Reporting, and Verification (MRV): Refers to the mechanism or methodology's processes, methods, and requirements for quantifying, reporting, and verifying removals.

Nature-based solutions (NBS): Within this report, NBS refers to any carbon removal activity that pre-dominantly relies on natural carbon sequestration processes (e.g., in soil or biomass).

Participants/projects: The actor who implements or manages the carbon removal action.

Permanence: Refers to the longevity of the storage of removals as a result of carbon removal activities.

System boundary: Refers to the removals and emissions that are captured by the methodology and included in the quantification of net removals.

Technology-based solutions (TBS): TBS rely on man-made technologies to capture and/or store carbon from the atmosphere.

Verification: A process for evaluating a statement of historical data and information to determine, if the statement is materially correct and conforms to criteria (ISO, 2019). In the context of carbon removals, this refers to an ex-post evaluation of a removals project or action to confirm the quantified climate impact and ensure alignment with other conditions.

Abbreviations

BECCS: Bioenergy with Carbon Capture and Storage

BECCU: Bioeenergy with Carbon Capture and Utilisation

CAPEX: Capital Expenditure

CCOP: California’s Compliance Offset Program

CCS: Carbon Capture and Storage

CCU: Carbon Capture and Utilisation

CDM: Clean Development Mechanism

CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation

CRC-M: Carbon Removal Certification-Mechanism

DACCS: Direct Air Capture and Carbon Storage
(or synonymously: Direct Air Carbon Capture and Storage)

DACCU: Direct Air Carbon Capture and Utilisation

EOR: Enhanced Oil Recovery

ERF: Emissions Reduction Fund

ETS: Emissions Trading System

IPCC GL: Intergovernmental Panel on Climate Change Guidelines

JI: Joint Implementation

LBC: Label Bas Carbone

LULUCF: Land Use, Land Use Change and Forestry

MRV: Monitoring, Reporting, and Verification

MS: (EU) Member States

NBS: Nature-based Solution

NDC: Nationally Determined Contribution

OPEX: Operational Expenditure

PEFC: Programme for the Endorsement of Forest Certification

PFSI: Permanent Forest Sink Initiative

SFI: Sustainable Forestry Initiative

SOC: Soil Organic Carbon

TBS: Technology-based Solution

TRL: Technology Readiness Level

VCS: Verified Carbon Standard

SUMMARY

Carbon removal certification mechanism for the EU

The European Commission is developing a certification mechanism for nature-based and technology-based carbon removals. To support its development, this report reviews existing solutions for such removals, covering both nature-based solutions (NBS) and technology-based solutions (TBS).

Solutions' potential to remove carbon

To assess the solutions' **potential** to deliver carbon removals in the European context, we investigated among other aspects: solution maturity, estimates of carbon removal potential (tCO$_2$-e), solution costs, practical challenges to deploy the solution at large scale, and permanence aspects of carbon removals delivered by the solution.

Solutions' suitability for certification-based mechanism

To assess the solutions' **suitability** for inclusion in a carbon removal certification mechanism, we investigated among other aspects: existing Monitoring, Reporting & Verification (MRV) frameworks dealing with the solution, solution co-benefits and potential negative externalities, and the scale of projects implementing the solution.

Carbon removal solutions

We assessed the following twelve carbon removal solutions, evaluating their potential to remove carbon and their suitability for deployment within Europe. Each solution is described using a multi-page fiche that covers uncertainty, permanence, cost, monitoring approaches, and other issues; these are included in Annex 1 of the report:

- #1 – Afforestation & Reforestation
- #2 – Agroforestry
- #3 – Peatland rewetting
- #4 – Forest management (including natural forest management and improved plantation Carbone.
- #5 – Increase in soil organic carbon on mineral soils
- #6 – Biochar
- #7 – Biomass in buildings
- #8 – Direct air carbon capture and storage (DACCS)
- #9 – Bioenergy with carbon capture and storage (BECCS)
- #10 – Enhanced rock weathering
- #11 – Carbon capture and storage (CCS)[1]
- #12 – Various Carbon Capture and Utilisation (CCU) routes

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[1] strictly speaking CCS typically only involves capture and storage of CO$_2$ from (fossil) point sources, not directly from the atmosphere. It is included in this study as a reference, in particular for DACCS and BECCS.

Main findings

Main findings from the assessment include:

- No solution stands out as the single most promising one. Solutions differ widely when compared along parameters such as maturity, carbon removal potential, costs, permanence/reversibility risk and co-benefits/negative externalities.
- Some NBS are more mature and are today more cost-effective (per removed amount of carbon) than TBS, yet NBS typically show higher risks in terms of permanence/reversibility than TBS. The quantification of removals of NBS is, furthermore, generally more difficult and less robust than that of TBS in terms of more demanding MRV requirements.

Main methodological findings include:

- Known, inherent assessment challenges became obvious, e.g. assessment criteria of mechanisms/solutions need to reflect differences of mechanisms/solutions by being relatively highly granular (in terms of sub-criteria, range intervals, etc.), yet such granular assessments counteract high-level design recommendations for a mechanism.
- Exact scope and system boundaries for accounting of removals – as defined in existing mechanisms – often differs, making comparisons difficult.
- Cost aspects are often not described with a clear scope/system boundary or with a clear description of to whom those costs incur and when, e.g. during the lifespan of a solution.
- The costs of robustly demonstrating carbon removals through MRV can be significant and should be considered alongside the establishment and operational costs of a solution.

Overall, the report aims to provide a thorough overview of existing carbon removal solutions. By documenting different key characteristics of such removal solutions, the report identifies and evaluates a range of options for the EU certification mechanism, supporting the development of a robust and effective system to incentivise uptake of carbon removals within Europe.

ZUSAMMENFASSUNG

Die Europäische Kommission entwickelt einen Rechtsrahmen für die Zertifizierung der Entfernung von Kohlendioxid aus der Atmosphäre. Um diese Entwicklung zu unterstützen, werden im vorliegenden Bericht bestehende Lösungen geprüft. Die Untersuchung umfasst sowohl natur-basierende Lösungen (nature-based solutions, NBS) und technologie-basierende Lösungen (technology-based solutions,TBS).

Potenzial Kohlendioxid zu entfernen

Um das **Potenzial** der einzelnen Lösungen zu bewerten, wurden folgende Aspekte beleuchtet: Marktreife der Lösung, Abschätzungen des Potenzials Kohlendioxid zu reduzieren (tCO_2-äq), Kosten, Herausforderungen bei der Implementierung , Dauerhaftigkeit der Entfernung von Kohlendioxid, usw.

Eignung der Lösungen für ein Zertifizierungssystem

Um die Eignung der einzelnen Lösungen zu bewerten, wurden folgende Aspekte beleuchtet: der bestehende Rahmen für die Überwachung, Berichterstattung und Verifizierung der Kohlendioxid-Senken, positive und negative Umwelt(neben)effekte und die Größenordnung einzelner Projekte.

Lösungen zur Entfernung von Kohlendioxid aus der Atmosphäre

Folgende zwölf Lösungen zur Entfernung von Kohlendioxid aus der Atmosphäre wurden hinsichtlich Potenzial und Eignung untersucht und in einem Informationsblatt beschrieben (siehe Anhang 1):

- #1 – Aufforstung und Wiederaufforstung
- #2 – Agroforstwirtschaft
- #3 – Wiedervernässung von Mooren
- #4 – Waldbewirtschaftung
- #5 – Erhöhung des organischen Kohlenstoffgehaltes in mineralischen Böden
- #6 – Pflanzenkohle
- #7 – Biomasse in der Bauwirtschaft
- #8 – Kohlenstoffabscheidung und –speicherung aus der Luft
- #9 – Kohlenstoffabscheidung und –speicherung aus Bioenergie
- #10 – Beschleunigte Verwitterung
- #11 – Kohlenstoffabscheidung und –speicherung aus fossilen Quellen
- #12 – Diverse Formen der Kohlenstoffabscheidung und -nutzung

Wesentliche Ergebnisse

Die wesentlichen Ergebnisse der Untersuchungen lassen sich wie folgt zusammenfassen:

- Keine Lösung erweist sich als deutlich vielversprechender als die anderen. Es bestehen deutliche Unterschiede in Marktreife, Reduktionspotenzial, Kosten, Dauerhaftigkeit der Speicherung und Risiko der Umkehrbarkeit der Entfernung, sowie der positiven und negativen Umwelt(neben)effekte.
- Manche NBS sind bereits marktreif und sind, zum heutigen Zeitpunkt, kosteneffizienter als TBS, weisen jedoch geringere Dauerhaftigkeit und ein höheres Risiko der Umkehrbarkeit der Kohlendioxid-Entfernung auf. Darüber hinaus stellt sich auch die Quantifizierung der entfernten Menge für NBS als schwieriger und weniger robust als für TBS heraus.

Die wesentlichen methodischen Ergebnisse für die Entwicklung eines Zertifizierungssystems lassen sich wie folgt zusammenfassen:

- Die Unterschiede in den einzelnen Eigenschaften der jeweiligen Lösungen, legen differenzierte, auf die jeweilige Lösung besser zugeschnittene, Zertifizierungssysteme nahe. Eine solche Differenzierung steht jedoch im Konflikt mit dem Ziel, ein einfaches, breit anwendbares Zertifizierungssystem zu entwickeln.
- Der Umfang und die Systemgrenzen der in der Literatur berichteten Daten zu den einzelnen Aspekten jeder Lösung variiert, wodurch die Vergleichbarkeit erschwert wird.
- Informationen zu Kosten waren oft nicht klar ausgewiesen, insbesondere in Hinblick auf deren Systemgrenzen, wo die Kosten anfallen und zu welchem Zeitpunkt im Lebenszyklus der Lösung. Dies erschwert die Vergleichbarkeit der Daten aus der Literatur.
- Die Kosten für die Überwachung, Berichterstattung und Verifizierung können teils erheblich im Vergleich zu den sonstigen Betriebskosten einzelner Lösungen, insbesondere für NBS ausfallen. Diese sollten bei der Entwicklung eines Zertifizierungssystems berücksichtigt werden.

Dieser Bericht gibt einen umfassenden Überblick über die unterschiedlichen Eigenschaften der einzelnen Lösungen zur Entfernung von Kohlendioxid aus der Atmosphäre. Diese sollen als Grundlage für die Entwicklung eines robusten und effektiven Zertifizierungssystems in der Europäischen Union dienen.

1 INTRODUCTION

EU net-neutrality target 2050

In line with the EU´s obligations under the Paris Agreement, the European Commission presented in November 2018 the EU´s long-term strategy "A Clean Planet for All"[2] which aims at achieving a climate-neutral economy by 2050. This commitment to turn the EU into a society with no net emissions of greenhouse gases (GHG) also forms one of the key cornerstones of the European Green Deal[3] presented in late 2019. This net-neutrality target by 2050 was subsequently enshrined in Article 2 of European Climate Law[4].

Scenarios in "A Clean Planet for All"

For the long-term strategy the Commission carried out an in-depth analysis[5]. It shows that pathways to climate neutrality using a suite of no-regrets options could deliver an 80% reduction in the EUs GHG emissions by 2050 compared to 1990 levels, while a further 10% could be achieved through a combination of all options plus enhanced land and forestry-based sinks. However, 10% of GHG emissions will still remain, notably from agriculture. These residual emissions will need to be offset by the use of negative emission technologies, such as capture and storage of carbon (CCS) from the combustion of biomass (BECCS), if climate neutrality is to be achieved by 2050.

All scenarios analysed by the Commission for the long-term strategy show that there will still be considerable gross emissions of greenhouse gases in 2050. In the scenarios compatible with the 1.5°C goal of the Paris Agreement, achieving the net-zero greenhouse gas objective involves the balancing of 500 to 600 Mt CO_2-e by negative emissions from the LULUCF[6] sector and from carbon removal technologies (Figure 1), notwithstanding the priority given to reduce emissions by enhancing the economy´s energy efficiency and deploying renewable energy.

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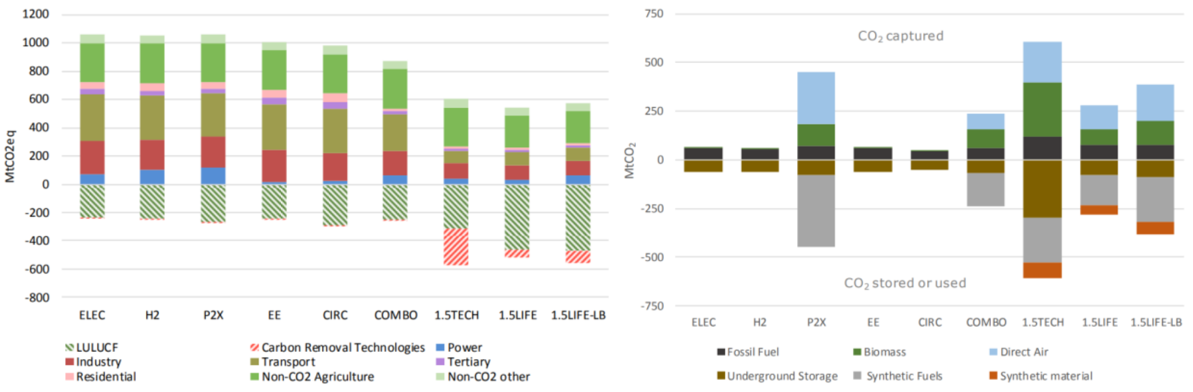
[2] EC, 2018 "A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy" COM(2018)773 final. 28.11.2018.

[3] COM/2019/640, download at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640

[4] Regulation (EU) 2021/1119, https://eur-lex.europa.eu/eli/reg/2021/1119/oj

[5] https://ec.europa.eu/clima/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

[6] LULUCF (Land use, land use change and forestry)



Relevance of carbon removal solutions on carbon net-neutrality in 2050

Source: EC, 2018[5]

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Figure 1. Relevance of carbon removal solutions on carbon net-neutrality in 2050

Nature-based and technology-based solutions in decarbonisation scenarios

The various scenarios and pathways set out in the supporting analysis show that both technology-based carbon removal solutions (TBS) and nature-based carbon removal solutions (NBS) play an important role within all scenarios for decarbonisation. However, the only technological options considered for the scenarios are bio-energy carbon capture and storage (BECCS) and Direct Air CO_2 Capture and Storage (DACCS) while e.g. biochar was not taken into account. CCS of fossil CO_2 emissions also plays a role (noting that such activities can only reduce emissions rather than achieve net negative emissions). The graph shows the extent to which CO_2 Capture and Storage (CCS) or Use (CCU) is implemented in 2050 in the analysed scenarios. Overall, the impact in 2050 of technological carbon removal solutions in combination with underground storage is highest in the 1.5TECH scenario, while LULUCF is seen to remove between 300 and 500 Mt CO_2 in all the 1.5°C scenarios. However, in a further four scenarios CCU in the form of synthetic fuels or materials will require the deployment of removal technologies at a similar level to LULUCF.

Scientists, landowners and entrepreneurs have identified and developed various nature-based (NBS) and technology-based (TBS) carbon removal solutions, each of which differs in potential to remove GHGs from the atmosphere, costs, co-benefits and negative externalities (e.g. biodiversity impacts, farm productivity, land demand, etc.) as well as in the uncertainty in quantifying removals. These solutions pose different challenges and opportunities for a carbon removal certification mechanism, potentially requiring different design elements to ensure that removals are cost-effective and real, additional, and permanent, avoid leakage and negative externalities, and maximise potential for co-benefits.

Potential and Suitability of solutions in a CRC-M

The objective of this study was to systematically evaluate a prioritised list of existing carbon removal solutions in EU (including Norway and the UK), in order to build a solid understanding of two overarching aspects, consistently across NBS and TBS:

- **Potential:** The solution's potential to deliver carbon removals in the EU context[7]. To assess the solution's potential, we investigated among other aspects: solution maturity, estimates of carbon removal potential (tCO_2-e), solution costs, practical challenges to deploy the solution at large scale, and permanence aspects of carbon removals delivered by the solution.
- **Suitability:** The solutions' suitability for inclusion in a carbon removal certification mechanism, including the challenges that the solution would pose for a carbon removal mechanism. To assess solution suitability, we investigated among other aspects: existing Monitoring, Reporting & Verification (MRV) frameworks dealing with the solution, solution co-benefits and potential negative externalities, and the scale of projects implementing the solution.

This report is published alongside a second, related report, which evaluates technology-based and nature-based carbon removal mechanisms and methodologies. This report assesses their potential mitigation impact and appropriateness for widespread implementation in the EU.

McDonald, Hugh et al. (2021): Certification of carbon removals - Part 2: A review of carbon removal certification mechanisms and methodologies

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[7] including Norway and the United Kingdom.

2 METHODOLOGY

Carbon removal solutions include NBS and TBS which can remove carbon from the atmosphere and store it either in natural and/or human-made planetary carbon storage spheres. NBS cover a wide range of potential actions that can enhance biological carbon sinks (e.g. afforestation, peatland rewetting, or soil carbon sequestration). TBS methods involve the use of engineered systems to capture and store carbon in various carbon storage spheres (e.g. direct air capture or point source capture with either storage or utilisation).

Out of a long-list of carbon removal solutions, a prioritized list (also called short-list) was established using six screening criteria:

1. Global carbon removal potential
2. Technological feasibility
3. Availability of data and knowledge
4. Practical feasibility
5. Permanence
6. Costs

The short-list of solutions included in the synoptic assessment is presented in Table 1 (including the definition of each solution) and mapped in Figure 2, according to the source of carbon they draw from, and the carbon storage sphere they enhance.

Table 1. List of short-listed solutions, including definitions.

Nature-based solutions (NBS, short-listed)
#1 – Afforestation & Reforestation – Planting trees/establishing forests in areas where there previously were no trees (afforestation) or conversion of land to forest that previously contained forest but has been converted to other use (reforestation), can effectively remove carbon from the atmosphere by storing it in tree biomass, which if maintained can act as a permanent store. Existing voluntary (e.g. Woodland Carbon Code) and regulatory (NZ Emissions Trading Scheme) mechanisms illustrate the potential. **#2 – Agroforestry** – Relatively low-density planting of woody biomass (e.g. trees, hedges, shrubs etc.) on agricultural land, to remove carbon and deliver co-benefits (e.g. biodiversity, soil and water improvements). While per ha removals are relatively low and MRV is relatively underdeveloped, collectively the Europe-wide carbon removals can potentially be significant at low costs, as illustrated by projects including AgForward, Terraprima, and Carbocage.

#3 – Peatland rewetting[8] – Peatlands are significant stores of carbon, and widely distributed across Europe. As they are drained e.g. for agriculture, urban expansion, they release stored carbon; rewetting drained peatlands can swiftly stop carbon emissions as well as leading to small amounts of sequestration. Existing mechanisms/methods illustrate the potential of certification approaches (e.g. MoorFutures, Max.Moor, IPCC methods). There is considerable overlap with other wetlands-type carbon mitigation/removal options (e.g. blue carbon).

#4 – Forest management (including natural forest management and improved plantation management) – The management of forests to maintain or enhance economic, social, and environmental values of forests can significantly increase a forest's ability to remove carbon from the atmosphere. Its potential suitability for European certified removals is illustrated by certification methodologies developer under the French Ministry for Ecological Transition's Label bas Carbone.

#5 – Increase in soil organic carbon on mineral soils – Mineral soils (i.e. relatively low organic matter soils) on croplands or grasslands cover much of Europe and collectively contain very large amounts of carbon; furthermore, if managed carefully they can increase their carbon content. Management options include cover cropping, improved crop rotations (e.g. through inclusion of legumes and other nitrogen fixing crops), deep rooting crops, conversion from arable to grassland and other management of grazing land and grassland to increase soil organic carbon (SOC) levels. Examples of existing mechanisms include VCS Indigo AG, Gold Standard, and the Australian Emissions Reduction Fund.

Technology-based solutions (TBS, short-listed)

#6 – Biochar – Put simply, biochar is charcoal that is incorporated into soils. The biochar is produced by heating (>350°C) biomass either in absence of oxygen (called pyrolysis), or controlled low-oxygen conditions (gasification). Biomass can come from wood, organic waste, or other natural feedstocks. The resulting biochar is then applied into soils, where it in the right conditions, can remain as a stable storage of carbon, from decades to hundreds of years.

#7 – Biomass in buildings – Use of sustainably-produced biomass materials in buildings and construction to extend the time of carbon storage compared to short-lived uses. Biomass can be sourced from sustainable models of forestry and cultivation, e.g. timber and bamboo for structural foundations, wood, cob, flax, linen, hemp and other forms of cellulose fibre for building envelope insulation. Biomass can also be sourced from reused biomass: e.g.

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[8] In addition to peatland rewetting, we also considered blue carbon (i.e. carbon captured and stored by coastal ocean ecosystems including saltmarshes and estuarine wetlands). We considered these two solutions together given the similarities and overlap in methods and challenges, and the relatively underdeveloped European knowledge base on blue carbon. We excluded other blue carbon solutions (e.g. ocean fertilisation).

cross-laminated timber (CLT), panels, biochar. Using biomass in the built environment enables extending the longevity and security of carbon storage, generated through forestation and agriculture.

#8 – Direct air carbon capture and storage (DACCS) – Use of engineering processes relying on chemical capture to remove CO_2 directly from the atmosphere into a separating agent that is regenerated with heat, water, or both. The CO_2 is subsequently desorbed from the agent and released as a high purity stream. This CO_2 can be stored into geological reservoirs (saline formations, depleted oil and gas fields) via e.g. pipeline transfer, stored in solid formation via carbon mineralisation or utilised by chemical conversion in various products (i.e. DACCU – Direct Air Carbon Capture and Utilisation).

#9 – Bioenergy with carbon capture and storage (BECCS) – Atmospheric CO_2 extraction by plant biomass for use as fuel (combusted or converted), with subsequent sequestration (injection into geological formations) of CO_2 from the biomass-to-energy process. Feedstocks include dedicated bioenergy crops, residual products and forest biomass, and testing is being performed for municipal waste (Waste-to-Energy) and algae. CO_2 captured can alternatively be utilised (i.e. BECCU – Bioeenergy with Carbon Capture and Utilisation).

#10 – Enhanced rock weathering – Enhancement of geochemical processes that naturally absorb CO_2 from the atmosphere. Fine-grained silicate rocks containing calcium or magnesium are spread on land (e.g. cropland) where they react with CO_2 by forming carbonate minerals and hence remove CO_2 from the atmosphere. The method can also be applied to open ocean and coastal zones.

#11 – Carbon capture and storage (CCS)[9] – Integrated chain of technologies that enables capturing CO_2 from the exhausts of power stations or other industrial sources, compressing & transporting CO_2, and storing the CO_2. Storage includes a set of possibilities for injection of CO_2 in dense or liquid form into deep geological formations (i.e. saline formations or depleted oil & gas reservoirs). Another option is in-situ carbon mineralisation[10] which consists in the accelerated conversion of silicate rocks to carbonates in situ below the surface by injection of CO_2 into permeable rock under higher temperatures and pressures at depth.

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[9] strictly speaking CCS typically only involves capture and storage of CO_2 from (fossil) point sources, not directly from the atmosphere. It is included as a reference, in particular for DACCS and BECCS.

[10] Carbon mineralisation was initially included as a separate TBS in the Inception report. Instead here we split Carbon mineralisation into three sub-solutions: surficial carbon mineralisation is the same as enhanced rock weathering, in-situ carbon mineralisation is included in the CCS fiche as one possible storage technology, and ex-situ carbon mineralisation is included in the CCU fiche, under CCU to building products.

#12 – Various Carbon Capture and Utilisation (CCU) routes[11] – Set of technologies involving the utilisation of CO_2 from various sources (e.g. air, biogenic, fossil) in diverse production processes. Some applications include direct use of CO_2 such as in soft drinks production, greenhouses, and in enhanced oil recovery (EOR) where it is used as a working fluid or solvent. Other applications use CO_2 as a feedstock in chemical or biological technologies to convert it into value-added products which then retain CO_2 for different time periods, mainly:

- **Fuels:** carbon in CO_2 used to convert hydrogen into a synthetic hydrocarbon fuel that can be used as gaseous or liquid fuel
- **Chemical building blocks**: carbon in CO_2 used as an alternative to fossil fuels in the production of chemicals that require carbon to provide their structure and properties, e.g. polymers and primary chemicals such as ethylene and methanol, which are building blocks to produce a range of end-use chemicals
- **Building materials**: CO_2 can be used in the production of building materials as feedstock in its constituents (i.e. cement and construction aggregates) via reaction between CO_2 and minerals or waste streams (e.g. concrete waste) to form carbonates. Another way that CO_2 can be used in building materials consists in adding CO_2 to concrete during curing, CO_2 emissions originating from calcination of carbonate rocks during the manufacture of cement (excl. energy-related emissions) can to a certain extent be taken up in the concrete by carbonation depending on availability of CO_2, moisture factors and exposure surface.
- **Other pathways** include e.g. biological production of fuels and chemicals from algae feeding on CO_2 or feeding the CO_2 in greenhouses.

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[11] For CCU in particular it is crucial to identify the relevant baseline and the additionality criteria applied in order to avoid putting the label of being a 'carbon removal solution' on a technology that might at best only be short-term net-zero.

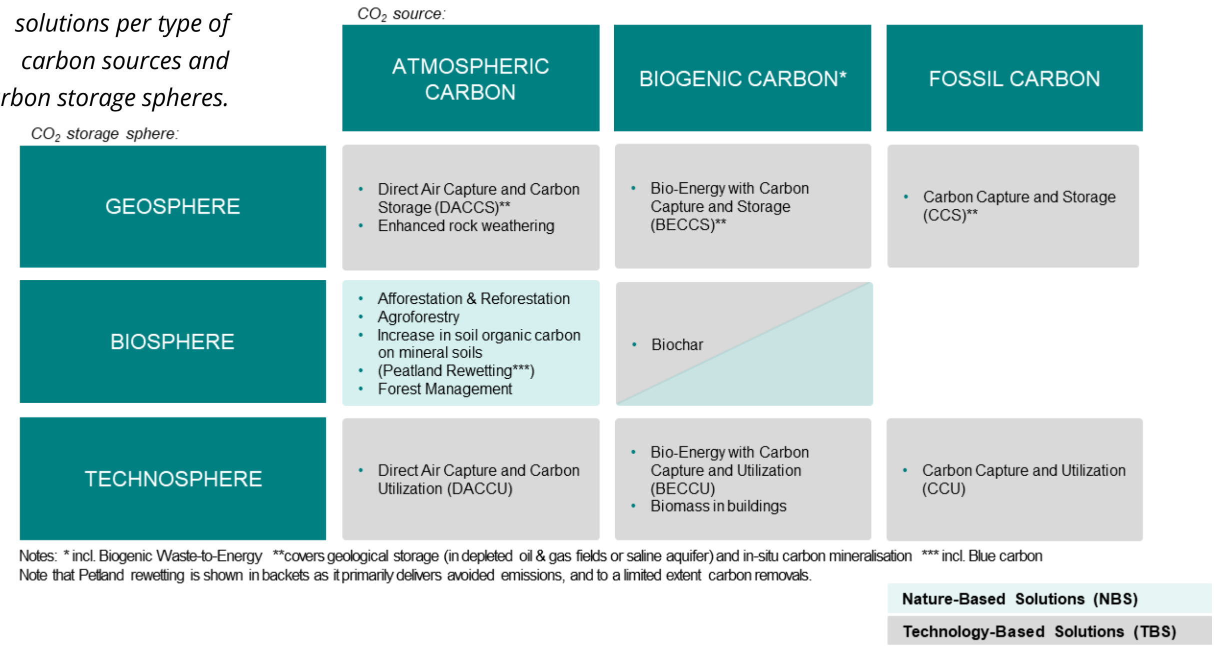

Figure 2. Mapping of solutions per type of carbon sources and carbon storage spheres.

CO₂ storage sphere: / CO₂ source:	ATMOSPHERIC CARBON	BIOGENIC CARBON*	FOSSIL CARBON
GEOSPHERE	• Direct Air Capture and Carbon Storage (DACCS)** • Enhanced rock weathering	• Bio-Energy with Carbon Capture and Storage (BECCS)**	• Carbon Capture and Storage (CCS)**
BIOSPHERE	• Afforestation & Reforestation • Agroforestry • Increase in soil organic carbon on mineral soils • (Peatland Rewetting***) • Forest Management	• Biochar	
TECHNOSPHERE	• Direct Air Capture and Carbon Utilization (DACCU)	• Bio-Energy with Carbon Capture and Utilization (BECCU) • Biomass in buildings	• Carbon Capture and Utilization (CCU)

Notes: * incl. Biogenic Waste-to-Energy **covers geological storage (in depleted oil & gas fields or saline aquifer) and in-situ carbon mineralisation *** incl. Blue carbon
Note that Petland rewetting is shown in backets as it primarily delivers avoided emissions, and to a limited extent carbon removals.

Nature-Based Solutions (NBS)
Technology-Based Solutions (TBS)

Each short-listed solution was systematically researched by the project team and reviewed using the same fiche template (see Annex 2). Each fiche is typically five pages long, covering all aspects relevant to understand potential and suitability for coverage under an EU carbon removal certification mechanism (CRC-M). To complete the fiches, we researched each short-listed solution in a broad corpus of existing scientific and grey (i.e. non-scientific but thoroughly documented) literature. Our investigation focused primarily on available meta-studies, which would typically provide a review of several carbon removal solutions. Additionally, we reviewed a number of scientific articles and other publications focusing on individual solutions.

The field of carbon removal solutions is developing rapidly, and we adopted a snowballing approach, so our literature list grew as new relevant publications were released and identified by our team. The completed fiches can be found in Annex 1, and each fiche includes a full set of references. We collected feedback from experts on the interim findings and on challenges regarding the certification of solutions. Inputs were collected via polls and open discussion.

3 SUMMARY OF KEY CHARACTERISTICS OF CARBON REMOVAL SOLUTIONS

This section provides a consolidated overview of the short-listed solutions' key potential and suitability characteristics, accompanying an overview table of the main characteristics of removal solutions (NBS and TBS) in Table 2 and Table 3. This overview enables to draw a set of cross-cutting considerations.

- **Solution readiness:** NBS are generally more mature, while TBS vary in readiness levels.
- **Carbon removal potential:** Several studies[12] have reviewed the global TBS-related carbon removals potential, although specific EU potentials remain sparse. The EU Horizon 2020 Programme-funded NEGEM project[13] is currently attempting to refine estimates at an EU-level. Their literature review provided indications of carbon removal potentials established by Member States in their climate mitigation strategies. NBS potential can be challenging to calculate due to land competition between different NBS (also for BECCS, in particular from domestic biomass). The carbon removal potential of several TBS depends on geological storage availability. Yet, current estimates of storage capacity in Europe indicate that this is not a limiting factor for deploying these solutions in the near future. Generally, short-term removal potential is highest for NBS, while TBS offer uncertain but potentially high long-term removal potential, or at least closed loop cycling of carbon between atmosphere and technosphere.
- **Actors involved and project scale:** NBS mainly involve the agriculture & forestry sectors, while TBS involve a wide range of actors such as technology developers, industrial & energy sectors, mining sector, and the agriculture & forestry sector. The size of carbon removal projects can vary greatly within solutions and from one solution to the other, e.g. existing DAC installations have capacities ranging from 3 tCO_2 to 4,000 tCO_2 per year with considerable upward potential up to several Mt CO_2 per year for single installations. Some NBS will rely on involvement of thousands of individual landowners.
- **Costs:** Costs per tCO_2 removed are generally lower for NBS than for TBS, although TBS costs are expected to decrease in the future with larger scale deployment, which will have implications for expectations for deployment. For TBS, current cost estimates and their expected developments remain uncertain. For NBS, commonly the most significant cost is opportunity cost of land use, which can be highly specific to local contexts (and policies e.g. Common Agriculture Policy).
- **Practical challenges:** Practical challenges vary. TBS face practical barriers such as energy demand, material demand, infrastructure, enabling legal

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[12] All sources used to conduct the synoptic assessment are included at the bottom of each fiche.

[13] https://www.negemproject.eu/activities/

frameworks, and public acceptance. Competition for land/biomass is a practical challenge for Afforestation & Reforestation and for those TBS relying on biogenic carbon sources (i.e. Biochar, BECCS and Biomass in buildings). The deployment of NBS depends on many small landowners/farmers implementing the NBS, so key practical challenges are farmer interest and knowledge, as well as ensuring that MRV costs remain low.

- **Co-benefits/negative externalities/leakage risks:** Different NBS can offer significant co-benefits (e.g. biodiversity, water and soil quality), but also negative externalities in the same areas as well as land competition depending on the solution (also for some TBS such as BECCS and biomass in buildings). These also face leakage risks as land conversion, and deforestation may occur outside the system boundaries. Other TBS such as DACCS, CCU, and Enhanced Rock Weathering may (significantly) increase energy demand. Co-benefits of TBS are diverse, e.g. enhancement of excess low-carbon energy supply (DACCS), possible higher crop yields (Enhanced Rock Weathering), fostering circular use of carbon (CCU), and material substitution (Biomass in buildings and CCU).
- **MRV frameworks:** Key criteria are measurability, verifiability, and additionality of solutions. MRV and accounting rules already exist for most NBS at national level (IPCC GL, EU LULUCF) and at project-level with a large base of existing project certification methodologies. However, uncertainty of measurements, additionality and baseline emissions are challenging for NBS. MRV of TBS is less mature and requires diverse approaches. For example, MRV rules exist for CCS at national level (IPCC GL), at installation level (EU ETS and CCS Directive), and at project level (CDM provisions for CCS projects). However, the geological storage of carbon captured either directly from air or from biogenic sources falls outside the scope of the EU ETS but could be readily integrated through small modifications to existing rules. On the other hand, biomass in buildings is connected to harvested wood products, for which the IPCC GL suggest various approaches for national accounting that treat the long-term carbon storage function of biomass in buildings differently, and LULUCF Regulation mentions “carbon storage products”. Existing standards provide methods to quantify embodied carbon and biogenic carbon storage in wood products at project-level. Regarding CCU, MRV complexities relate to the breadth of sectors involved and to the risk of double counting or leakage. MRV rules at project-level are emerging for CCU for some building materials and plastics. For both DAC and Enhanced Rock Weathering there are gaps in the IPCC GL, although the former gap is expected to be less challenging than the latter one.
- **Permanence:** For NBS, there is generally a uniform risk of reversals due to natural factors and management issues. Greater variability in reversals risk exists for TBS: carbon utilisation in short-lived products is obviously impermanent storage unless implemented in closed carbon loops, while end-of-life management is critical for biomass in buildings. Carbon storage in appropriately selected and well-managed geological formations or via mineralisation likely offers much lower risk of reversals (see CCS Directive).

Table 2. Summary table of synoptic assessment of short-listed NBS (and Biochar).

Solutions	#1 – Afforestation & Reforestation	#2 - Agroforestry	#3 – Peatland rewetting (also covering Blue Carbon)	#4 – Forest management	#5 – Increase in soil organic carbon on mineral soils	#6 - Biochar
Solution readiness	TRL = 9 Existing wide-scale deployment	TRL = 9 Existing wide-scale deployment	TRL = 9 Existing wide-scale deployment	TRL = 9 Existing wide-scale deployment	TRL = 9 Existing wide-scale deployment	TRL biochar production = 9 TRL biochar application = 7-8 Large-scale trials applying biochar in field conditions required
Carbon removal potential (global, EU)	Global: ranges between 0.5 - 10 GtCO$_2$-eq/yr (2020-2050) 1 - 12Gt CO$_2$-e/yr (2100) EU: 36 MtCO$_2$/yr (2050, carbon price of 150 EUR/t). Some uncertainty.	Global: ranges between 0.1 - 5.7 GtCO$_2$-eq/yr (2020-2050) EU: 7.8 - 234.9 Mt CO$_2$-e/yr (current potential)	Global: Wetland potential (including avoided removals + restoration): 2.7 GtCO$_2$/yr (2030). Coastal wetlands restoration: 0.2 - 0.8 GtCO$_2$/yr (2020-50) Peatland restoration: 0.2 - 0.8 GtCO$_2$/yr (2020-50) EU: 52 - 54 Mt CO$_2$-e/yr (2020; 2020-2050).	Global: potential to mitigate 0.4 – 2.1 GtCO$_2$-eq/yr (2020-2050) EU: 35 - 400 Mt CO$_2$-e/yr (2050)	Global: 2 – 5 GtCO$_2$-eq/yr (2030) EU: 9 – 116 MtCO$_2$-eq/yr (2050)	Global: 0.1 - 6.6 Gt CO$_2$-e/yr (2030-2050) EU: 79 MtCO$_2$-eq/yr (2020-2050) Limited information available on EU potential. 2020 production of biochar: 20,000 t (approximate life cycle impacts of 60,000 tCO$_2$-e)

Solutions	#1 – Afforestation & Reforestation	#2 - Agroforestry	#3 – Peatland rewetting (also covering Blue Carbon)	#4 – Forest management	#5 – Increase in soil organic carbon on mineral soils	#6 - Biochar
Project size	Wide variety of project sizes (from <5ha to 1000s of ha). Average project size in the UK quality assurance standard for woodland creation, "Woodland Carbon Code", is 50ha, with expected total sequestration over 100 years of approx. 19,000 t CO_2-e	Carbon impact per ha and per farm are relatively low (sequestering between 0.09 and 7.29 t C/ha/yr; average EU farm size of 16.6ha).	MoorFutures has projects that range in size from 6.7ha (5800 tCO_2-e over 100 year life of project) to 68ha (39500t CO_2-e over 100 year life of project) (all avoided emissions, not removals). Per ha avoided emissions of 3.5-24 t CO_2-e/ha/yr	On average, forest management in Europe could deliver 0.9-2.5 t CO_2 per ha per year in increased sequestration Forest plot sizes: many 10-500ha, many greater than 500ha). 500ha = 500-1250t/yr.	Depends on farm size. 0.5 and 7 t CO_2 per ha per year, on average. In European context, likely to be anywhere from 10-15ha to several hundred hectares.	Information not available.
Cost[14] (EUR/tCO_2)	EU: Approx. 25Mt CO_2/y sequestration at €50/t and approx. 40Mt CO_2/yr at €150/t (EU)	Very little clear evidence available. Costs differ per specific agroforestry system, the extent of tree planting and local context.	Global: 10-100 USD (2030) EU: 75% of carbon impact from retiring EU croplands on organic soil at costs of € 20/t CO_2-e	Consistent evidence on costs in Europe were not found. Costs are variable.	Cost-effectiveness will vary significantly depending on the regional potential. International estimates find 20% reductions at negative costs, the rest at under 40 USD.	90-120 USD, though high range and uncertainty regarding costs (due to diverse biomass sources, and limited evidence on application).

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[14] CAPEX and OPEX costs per tCO_2 used, excluding MRV and other administration costs.

Solutions	#1 – Afforestation & Reforestation	#2 - Agroforestry	#3 – Peatland rewetting (also covering Blue Carbon)	#4 – Forest management	#5 – Increase in soil organic carbon on mineral soils	#6 - Biochar
Permanence / reversibility risks	Vulnerable to both natural and human-induced disturbances (incl. fire, disease, drought, intentonal change of management). Long-term land contracts, existing laws, making participants liable, discounting/buffers and other legal restrictions can support permanence.	See Afforestation & Reforestation	Some reversibility risks due to intentional/unintentional reversal (i.e. if rewetting reversed). Can be managed through long-term contracts, legal restrictions, liability, ownership change..	See Afforestation and Reforestation	Soil carbon retention time can be short to long-term, depending on management and climate, as well as biophysical conditions. High reversibility concerns; appropriate management is required to avoid reversal. Climate change poses a risk as it can trigger reversal.	Biochar is a relatively stable, long-lasting store of carbon. Risk of reversibility is considered low, especially in dry soils. Modelling studies commonly assume that 80% of carbon persists beyond 100 years There are few long-lasting studies of biochar application and permanence - existing studies rely on short time periods and modelling – therefore, there are uncertainties.

Solutions	#1 – Afforestation & Reforestation	#2 - Agroforestry	#3 – Peatland rewetting (also covering Blue Carbon)	#4 – Forest management	#5 – Increase in soil organic carbon on mineral soils	#6 - Biochar
Practical challenges	Availability of land (competition of land uses). Overlap with other policies (e.g. CAP). Keeping transactions costs low enough to encourage uptake. Relatively high upfront investment cost and initial slow sequestration rates.	Limited interest among farmers due to need for developing new skills, new outputs markets, upfront investments and differing rotation length. Challenging to generalise MRV due to diversity of agroforestry types and impacts. Relatively low carbon removal intensity per ha or participant make it difficult to cover MRV costs.	CAP payments increase opportunity costs for rewetting. Lack of data on extent and location of organic soil areas. Limited knowledge on non-peatland wetlands.	Diversity of forest management approaches: most effective and cost-effective management options will depend on local context. Significant public ownership of forest land (54%)	Long commitment period poses substantial barrier for landowners. Risks associated with changes in production systems, lack of advisory services and available information on economic and productivity benefits of sequestration options. Farmers that lease land have little to no incentive to invest in SOC.	Biomass availability (potential for competition with BECCS, other land use), limited amount of biochar production facilities, uptake by farmers (relies on training and knowledge sharing). Multiple stages in the biochar process pose governance challenges, as do uncertainty of MRV of soil carbon impacts.
Co-benefits	Differ per project; afforestation that results in monodominance could reduce biodiversity, but by focusing on e.g. degraded lands or biodiversity-friendly afforestation has significant co-benefits.	Significant positive impact on biodiversity (including habitat provision, pollinators and insects), reduced soil erosion and improved soil health, flooding protection and reduced nitrate leaching.	Many co-benefits, such as biodiversity conservation, flood protection, improved soil and water quality, protection from coastal storms, as well as cultural ecosystem services	High co-benefits, including ecosystem and biodiversity preservation, as well as water quality and water quantity benefits.	High co-benefits. Improves soil structure and soil fertility, increases water retention capacity of soils and increases resilience to climate change, reduces soil erosion and reduces soil compaction risk.	Expected co-benefits are uncertain but expected to be relatively small; improved soil structure, water holding capacity, reduction in nutrient losses from soils, stabilisation of heavy metals and other toxins.

Solutions	#1 – Afforestation & Reforestation	#2 - Agroforestry	#3 – Peatland re-wetting (also covering Blue Carbon)	#4 – Forest management	#5 – Increase in soil organic carbon on mineral soils	#6 - Biochar
Negative externalities, incl. leakage risks	Potential leakage due to afforestation of productive land, with commercial activities shifting elsewhere (can be managed by targeting non-productive land, discounting).	Low risk of leakage since agroforestry does not fully replace existing arable/animal production (although small impact on output).	Small-medium leakage risk due to activity displacement (though relatively small peatland area, so limited risk). Peatland restoration in-creases methane emissions (though in most contexts in medium and long term net GHG effect is negative).	Leakage affects are low, as forest management occurs on existing forest land and has only small impacts on timber production.	There are concerns about possible unintended impacts on soil health (due to pollutants) if the SOC levels are increased by applying off-farm organic inputs. There may be trade-offs with N20 emissions. Clear estimates for risk of leakage are not available in literature.	Unclear impacts on worms and soil fauna, or broader impacts on biodiversity. precautionary approach should be applied until better scientific understanding of side-effects and long-term impacts. Leakage can occur if biochar biomass production competes with other land uses. Biochar application poses no leakage risks as biochar can be applied to existing crop/grasslands.

Solutions	#1 – Afforestation & Reforestation	#2 - Agroforestry	#3 – Peatland rewetting (also covering Blue Carbon)	#4 – Forest management	#5 – Increase in soil organic carbon on mineral soils	#6 - Biochar
MRV frameworks	MRV frameworks covered by IPCC GL Vol.4 Ch. 4 and LULUCF Regulation. Also many existing voluntary methods (Woodland Carbon Code, Australian ERF, Label bas Carbon) and New Zealand Emissions Trading Scheme.	Limited existing examples of MRV systems for agroforestry except in specific research projects, generalised IPCC GL methods, and LULULCF Regulation.	MRV frameworks provided by IPCC GL Wetlands supplement. Included in LULUCF from 2026. Examples of mature voluntary MRV methods (MoorFutures); though narrow geographic range and dependent on local expertise. Limited other wetland methods in Europe.	MRV frameworks covered by IPCC Guidelines Vol. 4 Ch. 2 and 4, and LULUCF Regulation. Numerous examples of methods in voluntary (e.g. VCS, Label bas Carbone) and regulatory systems (NZ ETS). Some risk of non-additionality.	MRV frameworks covered by IPCC Guidelines Vol. 4 Ch. 2 and LULUCF Regulation. Numerous voluntary methodologies (e.g. VCS, Gold Standard) and small projects; however, relatively high uncertainties.	Revision of the 2006 IPCC guidelines included a specific Annex on estimating biochar impacts on soil carbon. Theoretically would be included in LULUCF accounting (in related land accounting category). One voluntary method (Puro.earth) for biochar production (no method for application).

Table 3. Summary table of synoptic assessment of short-listed TBS (excl. Biochar).

Solutions	#7 – Biomass in buildings	#8 – DACCS	#9 – BECCS	#10 – Terrestrial Enhanced Rock Weathering	#11 - Carbon capture & storage	#12a – CCU – short/medium lifetime	#12b – CCU, long lifetime
Solution readiness	TRL = 8-9 Technically scalable	TRL = 5-7, in certain cases up to 8 Large-scale developments expected by 2050s	TRL = 3-7 in power industry, TRL = 7-9 in bioenergy industry Large-scale developments expected beyond 2020s/2030s	TRL = 1-5, R&D phase, lack of knowledge Deployment at scale by or beyond 2050s	Capture: TRL = 3-9 for conventional storage, TRL = 3-5 for in-situ mineralisation Storage & transport: TRL = 7-9 Near-term deployment in power sector, deployment at industrial installations (e.g. steel or cement) expected from 2030s, large-scale development of in-situ mineralisation not expected before 2050s	Fuels: TRL = 4-9; Chemicals: TRL = 7-9; Algae-based: TRL = 5-8 Near-to medium term commercial opportunities (5 to 20 years)	Building products: TRL = 6-8, esp. reg. cement. Near-term commercial deployment opportunities (3 to 10 years)

Solutions	#7 – Biomass in buildings	#8 – DACCS	#9 – BECCS	#10 – Terrestrial Enhanced Rock Weathering	#11 - Carbon capture & storage	#12a – CCU – short/medium lifetime	#12b – CCU, long lifetime
Carbon removal potential (Global and/or EU)	Global: 70 to 1,100 $MtCO_2$/yr (by 2050) EU: up to 14 $MtCO_2$/yr (2021-2030)	Global: 0.5 to 5 $GtCO_2$/yr (by 2050) EU: up to 264 $MtCO_2$/yr (by 2050)	Global: 0.5 to 5 $GtCO_2$/yr (by 2050) EU: 92 to 276 $MtCO_2$/yr (2050)[15], Biogenic carbon removal from WtE in EU: 40-47 $MtCO_2$/yr	Global: 1 to 4 $GtCO_2$/yr (by 2050) EU: 77 to 206 $MtCO_2$/yr [16]	Cumulative potential: EU: onshore 161 to 1,129 $GtCO_2$, offshore: 141 to 961 $GtCO_2$[17]	Global: for fuels: 1.4 to 2 $GtCO_2$/yr, for chemicals: 0.3 to 0.6 $GtCO_2$/yr (by 2050), for algae-based products: 0.2 to 0.9 $GtCO_2$/yr (by 2050) EU: up to 1,862 $MtCO_2$/yr for methane and up to 1,206 $MtCO_2$/yr for Fischer Tropsch diesel[18]	Global: for building materials: 0.1 to 1.4 $GtCO_2$/yr (by 2050) EU: up to 744 $MtCO_2$/yr

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[15] Minimum value: sum of min. carbon removal potential reported by EU MS, maximum value: most optimistic scenario in EU Clean Planet for All

[16] Minimum value: sum of min. carbon removal potential reported by EU MS, maximum value: most optimistic scenario in Beerling et al. (2020)

[17] Offshore figure includes practically accessible locations only.

[18] Maximum potential based on current product demand and CO_2 binding rates. Realistic potential expected to be much lower.

Solutions	#7 – Biomass in buildings	#8 – DACCS	#9 – BECCS	#10 – Terrestrial Enhanced Rock Weathering	#11 - Carbon capture & storage	#12a – CCU – short/medium lifetime	#12b – CCU, long lifetime
Project size	Varies; examples of Puro Earth-certified manufacturers of wooden building elements deliver net carbon removals at varying rates (from 29 to 541 kgCO_2/m3 of wooden product; 1,102 tCO_2/t of cellulose fibre insulation)	3 tCO_2pa to 4,000 tCO_2pa (based on 15 facilities globally)	3 to 4 $MtCO_2$pa; future WtE projects expected to have limited capture capacities, e.g. 100,000 tCO_2pa at Twence WtE facility	Lack of project examples; land intensity projects estimated below 0.01 ha/tCeq/yr (excl. land requirements in the life cycle)	0.3 to 8.4 $MtCO_2$/yr (based on existing large-scale projects globally); lack of existing in-situ carbon mineralisation projects (CarbFix facilities: 10 to 20 $ktCO_2$/yr)	Uncertain; example of CRI's CCU to fuel facility: 5,600 tCO_2/yr	Uncertain; example of Carbon8's CCU to building aggregates facility: 5,000 tCO_2/yr; example of Iowa City Ready Mix (CarbonCure): 2.7 tCO_2 utilised in 5 months at one plant using CarbonCure Ready Mix (equivalent to 6.5 tCO_2/yr).
Cost[19] (EUR/tCO_2)	Lack of data on CAPEX/OPEX costs, but competitive with other buildings materials with breakeven costs estimated – 40 to 10 USD/tCO_2 (global)	94 to 400 USD/tCO_2[20] (global)	Ethanol production: 20 to 175 USD/tCO_2 avoided[21] (global) Combustion: 88 to 288 USD/tCO_2 avoided (global)	138 to 161 EUR/tCO_2[22] (EU)	Capture (power generation): 36 to 87 USD/tCO_2[23] (global) Capture (industry): 40 to 120 USD/tCO_2 (global)	Methane: 730 to 1,277 EUR/tCO_2[26] (EU) Fischer Tropsch diesel: 470 EUR/tCO_2[20] (EU). Uncertainties.	Building aggregates: 136 to 227 EUR/tCO_2[26] (EU) Concrete curing: 800 USD/tCO_2[26] (global). Uncertainties.

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[19] CAPEX and OPEX costs per tCO_2 used, excluding MRV and other administration costs.
[20] Expected cost for large-scale facilities, inc. compression costs.
[21] Include energy penalty at capture.
[22] Include mining, processing, distribution, transport and spreading on agricultural soils. Based on figures provided for France, Germany, Italy, Spain and Poland.
[23] Include compression costs.
[26] Based on cost of production and CO_2 binding rate in CCU products

Solutions	#7 – Biomass in buildings	#8 – DACCS	#9 – BECCS	#10 – Terrestrial Enhanced Rock Weathering	#11 - Carbon capture & storage	#12a – CCU – short/medium lifetime	#12b – CCU, long lifetime
			Biomass gasification: 30 to 76 USD/tCO_2 avoided (global) Pulp & paper mills: 20 to 70 USD/tCO_2 avoided (global)		Transport: 2 to 24 USD/tCO_2[24] (global) Injection: 1 to 20 EUR/tCO_2[25] (EU)		
Permanence / reversibility risks	50-100 years, reversibility risks related to aging and end-of-life management (can be avoided with e.g. combustion with CCS or conversion to biochar) - yet also risk of double-counting be-tween building application and later W2E+CCS	See CCS	See CCS	Retention expected from months to geological time scale, but lack of understanding of permanence and potential effect of soil saturation	Long-term storage with low reversibility risks, but permanent containment has not yet been fully demonstrated at a large scale in the EU	Short-term, up to 10-year retention, impermanent storage unless implemented in closed carbon loops	Long-term storage, carbonates are inert

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[24] Depend on storage location (offshore vs. onshore) and transport mode (pipeline vs. shipping)

[25] Assuming a mature CCS industry

Solutions	**#7 – Biomass in buildings**	**#8 – DACCS**	**#9 – BECCS**	**#10 – Terrestrial Enhanced Rock Weathering**	**#11 - Carbon capture & storage**	**#12a – CCU – short/medium lifetime**	**#12b – CCU, long lifetime**
Practical challenges	Low demand, supply availability of sustainable timber, lack of expertise and equipment, regulatory obstacles, public acceptance in som countries	Availability of low-carbon energy, availability of sorbent materials and of transport infrastructure	Competition for biomass/water/fertilizer; limited level of public acceptance, distance between biomass sources & power stations	Increasing mining activities, high energy demand, low public awareness, regulatory issues	Lack of public acceptance for onshore storage, legal restrictions, cross-chain risks, scalability of in-situ mineralisation depending on close location or reservoirs	Availability of significant amounts of low-carbon energy, product regulations	Availability of significant amounts of low-carbon energy, product regulations
Co-benefits	Substitution of carbon-intensive building materials (steel and concrete)	Co-location with low-carbon excess energy supply. Comparatively low land area footprint	Generation of energy, energy independence, bio-energy pathways	Increase crop yield; co-deployment with other solutions; potential reuse of waste products from mining and industrial processes	Reuse of existing oil & gas infrastructure	Create public acceptance for CCU; foster circular use of carbon; use of existing infrastructure (power to gas/liquids); solution for energy storage (Power to gas/fuels)	Lower demand for concrete (stronger material)
Negative externalities, incl. leakage risks	Competition for biomass & land, deforestation & land use change, poorly managed forests, and pressure on biodiversity and water resources	High energy demand (heat and power)	Competition for biomass & land, deforestation & land use change, forests managed with weak MRV, and pressure, and pressure on biodiversity and water resources	High energy demand; If mining is involved, induced deforestation, and potential impact on ecosystems and human health	Risk of carbon lock-in on fossil fuel infrastructure; competition for storage with biogenic CO_2; potential risk of water pollution and enhanced seismic activity	High energy demand	No identified potential negative externalities

Solutions	#7 – Biomass in buildings	#8 – DACCS	#9 – BECCS	#10 – Terrestrial Enhanced Rock Weathering	#11 - Carbon capture & storage	#12a – CCU – short/medium lifetime	#12b – CCU, long lifetime
MRV frameworks	MRV guidelines in IPCC GL (Harvested Wood Products) and EU LULUCF, existing standards for embodied and biogenic carbon (EN16449:2014, nascent MRV rules at project-level (Puro)	Lack of MRV frameworks, but low complexity for MRV techniques	Partly covered in EU CCS Directive and EU ETS accounting: biomass is zero-emissions rated (with provisions reg. biomass supply) and negative emissions are not recognised.	Lack of MRV frameworks, and uncertain and complex MRV methods	MRV aspects well covered by EU regulations and IPCC GL, but sophisticated MRV techniques required	Lack of MRV frameworks, but nascent MRV rules at project-level emerging for CCU to plastics (VCS)	Lack of MRV frameworks, but nascent MRV rules at project-level (Puro, VCS)

4 REFERENCES

- COWI, Ecologic Institute, and the Institute for European Environmental Policy (Unpublished report) Analytical support for the operationalisation of an EU Carbon Farming initiative Task 1 and 2 Report: Appendix A: File cards of the schemes and projects. Prepared for DG CLIMA/European Commission under project: CLIMA/C.3/ETU/2018/007
- COWI, Ecologic Institute, and the Institute for European Environmental Policy (2021) Annexes to Technical Guidance Handbook – setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on contract no. CLIMA/C.3/ETU/2018/007 https://op.europa.eu/s/pcDV
- IPCC (2018) Special report: Global Warming of 1.5 °C. https://www.ipcc.ch/sr15/
- ISO (International Standards Organisation) (2019) ISO Standard 14064-2:2019 - Greenhouse gases — Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements. https://www.iso.org/standard/66454.html
- Ramboll et al (2019). Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects, https://op.europa.eu/en/publication-detail/-/publication/7656142c-7083-11e9-9f05-01aa75ed71a1 Annexes to Technical Guidance Handbook – setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on contract no. CLIMA/C.3/ETU/2018/007 https://op.europa.eu/s/pcDV

5 ANNEX 1 – CARBON REMOVAL SOLUTION FICHES

5.1 Fiche: Afforestation & reforestation

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Solution name	**Afforestation & Reforestation**
Introduction	**Brief description of technology** - Planting trees/establishing forests in areas where there previously were no trees (afforestation) or conversion of land to forest that previously contained forest but has been converted to other use (reforestation), to capture CO$_2$. These solutions are ready for large-scale deployment and is already widely practiced throughout the world.[1] Afforestation and reforestation are occasionally collectively referred to as “forestation”.[2] **GHGs targeted (and land use category)** - CO$_2$ (IPCC Forest Land methods include other gases if biomass and for soils are considered)[3] - Land use category: Forest land (final category), cropland, grassland, other land, wetlands (initial category) **Examples of solutions already operational or in planning** - Afforestation/reforestation is already part of many existing certification mechanisms, including Label Bas Carbone, the Woodland Carbon Code, New Zealand Emissions Trading Scheme, and the Australian Reduction Fund.
Potential	
Technology readiness level (TRL)	**Current TRL level** - Afforestation and reforestation are already widespread across Europe - TRL 9
Potential carbon removals	**Global potential** - According to IPCC (2019), the global CO$_2$ removal potential of afforestation and reforestation ranges between 0.50-10 GtCO$_2$-eq yr–1 (based on studies estimating potential per year 2020-2050).[4] - Griscom et al. (2017) estimate the sequestration potential of reforestation in 2030 at 14.6 t CO$_2$ ha^{-1} yr^{-1} for natural forests and 22 t C02-eq ha^{-1} yr^{-1} for plantation forest, with constraints to maintain food supply and avoid additional biodiversity impacts.[5] - According to the Royal Society and Royal Academy of Engineering (2018), by 2100 forestation could deliver global removals of 4-12 GtCO$_2$ pa (conservative versus maximum estimate).[6] Fuss et al (2018) estimate 1-12 GtCO$_2$ pa by 2100.[7] - Potential of 4.9 GtCO$_2$/year at 200 US\$/tCO$_2$ in 2050.[8] Incentivising afforestation through a uniform reward for carbon uptake, could lead to large-scale afforestation (2580 Mha globally) and substantial carbon sequestration (860 GtCO$_2$) at the end of the century (but also a food price increase of 80% by 2050 and a fourfold increase by 2100).[9] **EU potential**

Solution fiche template	
Section	Aspects covered
	• Roe et al. (2021) identify that at a cost of 100 US$/t CO_2, afforestation and reforestation could deliver 18 Mt CO_2/yr (on average between 2020-2050).[10] • EU 2050 long-term strategy modelling suggests that at carbon prices of €150/t, EU forestation could deliver an additional 36 MtCO_2/yr in 2050 (or approximately 25 MtCO_2/yr at €50 prices).[11] • Forest area has increased by 9% since 1990, but the expansion rate is slowing down. Currently, forests cover 35% of Europe's total land area (227 million ha).[12] Röös et al. (2016) estimated that by afforesting spare agricultural land in Western Europe (calculated based on assuming a closing of yield gaps, increased livestock production efficiencies and reduced waste at all stages), the (modelled) annual carbon potential in different scenarios ranged from 90 to 700 Mt CO_2 in 2050.[13] These estimates appear quite high relative to current removals due to afforestation from the last 20 years, which EU GHG inventory identifies as 41 Mt CO_2/y.[14] **Constraints/interaction effects and assumptions** • Competing land uses constitutes a key challenge for both afforestation and reforestation;[15] large-scale implementation of BECCS is expected to compete with forestation, as will demand for harvested wood products and biofuels, as well food production and other ecosystem services.[16] The land intensity of forestation is estimated at around 0.1 ha per tCO_2 pa over 100 years.[17] **Brief description of calculation method and uncertainties** • Carbon removal potential and annual rates depend on the amount of land available (and land competition), location, forest type and management, as well as economic and biophysical constraints. Generally, projects that focus on degraded land or land that was previously forested (and for which no alternative economic or social activity are foreseen) deliver the greatest net benefit. The annual sequestration differs over time, and depending on species and context. To generalise, forests require about 10 years to achieve the maximum sequestration rate; they then reach maturity after around 20 to 100 years (depending on species), at which point removals rates slow and only occur if less wood is harvested than is regrown. Note, see Harvested wood products fiche for discussion of the potential of this solution.[18] **System boundaries and lifecycle emissions considerations** • Climate mitigation impact of forestation depends on biomass accumulation, dead organic matter, and soil carbon. However, some methodologies focus only on above ground biomass carbon stock changes (e.g. New Zealand ETS forestry). For land converted to forest land, IPCC Guidelines assume under Tier 1 a linear increase in dead organic matter from zero and generally an increase in soil carbon (depending on the differences in the pre land use carbon stock and forest carbon stock) but potential for small SOC decreases on mineral soils and large decreases on organic soils, if occurring.[19]
Costs	**Current costs** • Initial costs can be high, but the costs of regeneration and management are low: globally, there is a potential to sequester 1.2 GtCO_2 for under $30 per t$CO_2$ and 0.4 GtCO_2 pa at less than $3 per t$CO_2$.[20] To secure permanent carbon sinks, forests require on-going management. Cost estimates in the scientific literature have increased over time.[21]

Solution fiche template	
Section	Aspects covered
	- Fuss et al (2018) identify that estimated prices depend on whether just implementation costs are considered, or whether they include opportunity costs (e.g. alternative land use). At a global level, their literature review identifies prices of 0-15 USD per tonne CO_2-e for implementation, and 3-160 USD for those considering (location-specific) opportunity costs.[22] - In the EU: The EU 2050 long-term strategy modelling identifies small responses at low prices, with approx. 25Mt CO_2/y sequestration at €50 and approx. 40Mt CO_2/y at €150.[23] - The UK's Woodland Carbon Code could also provide suggestive evidence of expected EU prices at relatively low levels of afforestation: In WCC, costs vary between 6 €/tCO_2-e and 17 €/tCO_2-e for afforestation/reforestation projects. [24] **Project future costs** - With regard to afforestation, future cost estimates vary between 15 to $30 per t$CO_2$for the year 2100.[25] Costs are not expected to change, although opportunity costs may be expected to increase over time as less valuable land is forested. **Energy demand** - Very low. A life cycle study on reforesting mining land indicated emissions of 5.7 tCO_2 per ha over a 34 year span, 2% of the cumulative 334 tCO_2 sequestered over that period. In addition, water requirements are often low because forests are generally not irrigated.[26]
Duration of removals / permanence	**Duration of removals & risks of reversibility** - Afforested areas, including the sequestered carbon, are vulnerable to both to natural- and human-induced disturbances. Examples of the former include floods, wildfires, droughts and pests, the latter renewed deforestation and degradation.[27] **Conditions for permanence and options to manage impermanence** - Long-term land contracts, land deeds, and other legal restrictions can support permanence. Buffer accounts (of 10-30%) are commonly used to guarantee issued credits in voluntary schemes (e.g. in Woodland Carbon Code, Label bas Carbone).
Practical barriers	- The availability of land is a crucial prerequisite for forestation projects to materialize. However, because land owners and farmers depend on their land for income they may prefer to use it for uses with higher economic returns (e.g. agriculture).[28] - Existing forestry laws may pose a barrier. For example, in a number of Member States (e.g. Austria, UK), once land reaches definition of forested land, it cannot be deforested, meaning landowners avoid foresting their land to keep future options open. - Due to the need to involve many individual landowners, keeping transactions costs (e.g. MRV) low is needed to achieve wide scale uptake. Other factors that may obstruct the uptake of afforestation include market barriers, relatively high upfront investment cost, and the time it takes for trees to sequester large amounts of carbon.[29]
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** - Existing certification mechanisms (NZ ETS PFSI, Woodland Carbon Code) generally use look-up tables and calculation spreadsheets to determine the carbon sequestered in an area of forest. Project proponents are required to provide project-specific information such as timing of planting, species, woodland management, soil type etc., which is then used to determine the amount of carbon removals that can be achieved over time. The Woodland Carbon Code uses a 20% buffer system to account for uncertainties.

Solution fiche template	
Section	Aspects covered
	- The certification mechanisms also make the distinction between smaller and larger projects, the latter resulting in a more demanding MRV process; for NZ ETS PFSI larger landowners (>100ha of post-1989 forests) are required every five years to complete a Field Measurement MRV return. This return requires on-site measurement, which are used to generate a participant-specific look-up table, which the participant then uses for emissions returns in the intervening four years before their next quantification. With regard to the Woodland Carbon Code, two quantification methods exist: 1) standard approach (for projects >5ha) and 2) small projects approach (for projects <5ha). The small projects approach is generally simpler, making more assumptions to lower transaction costs (e.g. assumes no leakage, assumes baseline of zero). - IPCC Guidelines[30]: Forest Land chapter and chapter 2 (generic methods) propose two methods for land converted to forest land. Each include methods for calculating change in biomass, dead organic matter, and soil organic carbon (split into mineral/organic soils). The basic calculation principle is based on change in area x emissions factors. I - LULUCF Regulation[31],[32]: Afforested land (i.e. any land converted to forest land) is accounted based on gross-net accounting (i.e. MS are credited for all emissions/removals that occur in the accounting period. Once the afforested area has completed the 20 years transition period (MS can under certain conditions select a longer transition period), the area continues to be accounted under Managed Forest land which is accounted against the Forest Reference Level. The Regulation requires MS to use geographically explicit land use change information (area data) which would also affect afforested land.). This is calculated based on change in forest area (i.e. afforestation – deforestation area). Member States can exclude emissions from extreme events above a natural background level. “Forest land” is defined based on minimum tree height, area, and tree crown cover, which differs by Member State. **Baseline setting methods (including existing baseline data options)** - Generally, projects use a baseline & credit system. The Woodland Carbon requires projects to complete a baseline assessment of the project area when registering. As part of the baselining process, projects >5ha are required are required to consider whether activity shifting could occur due to Woodland creation (e.g. increase in intensity of land use in another area of land owned by the participant as a result of Woodland creation). If this is expected to lead to emissions equivalent to more than 5% of the project, then this must be deducted as part of net sequestration calculation. Baseline setting in case of the NZ ETS PFSI is not required, because they are covered by the ETS cap & trade system. Key references: IPCC Guidelines
Sustainability issues	- **Co-benefits and negative externalities**: Co-benefits differ per afforestation project (afforestation that leads to monodominance could reduce biodiversity, but by focusing on croplands and degraded land could not only positively affect biodiversity, but also improve soil quality and reduce flooding, erosion and eutrophication).[33] Large-scale forestation can directly alter the local temperature and precipitation.[34] - **Side effects/leakage risks**: Leakage due to activity shifting or market leakage: If afforestation occurs on previously productive land (e.g. commercial agriculture), this could lead to shifting of activities elsewhere in the EU or internationally. Note this can be avoided if afforestation only occurs on non-productive land. - To avoid perverse incentives, eligibility should be limited to land that has not been deforested in recent time (e.g. prior to 2010).

Solution fiche template

Section	Aspects covered
Governance aspects	• **Actors involved:** Depends on mechanism. In existing mechanisms, generally farmers and land-owners apply for afforestation projects under applicable carbon removal certification schemes, either alone or as part of groups or through project developers. • **Scale/size of projects**: Existing schemes include small participants (<5ha in Woodland Carbon Code) up to very large individual landowners in NZ ETS (1000s of ha). The average project size of validated participants in the Woodland Carbon Code is 50ha, with expected cumulative lifetime (100 year) sequestration of approx. 19 000t CO_2-e.[35] **Linkage to existing policies and measures/strategies/funding schemes:** • The CAP is the main source of EU funds for forests; 90% comes from the European Agricultural Fund for Rural Development (EAFRD). Over the period 2015-2020, a single specific measure addressed different types of support for investment in forests, covering afforestation and creation of woodland, establishment of agro-forestry systems, prevention and restoration of damage to forests from forest fires, natural disasters and catastrophic events, investment to improve the resilience and environmental value of forest ecosystems and investment in forestry technologies and in the processing, promotion and marketing of forest products. Another measure is to provide rewards for forestry, environmental and climate services and the conservation of forests. Moreover, there is also a provision for measures not-specific to forestry (e.g. Nature 2000 and WFD payments). With their Rural Development Programmes, Member States can decide which measures to implement as well as the financing.[36] While CAP financing is available for forestry, its uptake is relatively limited (for example, only 4.8% of rural development expenditure to forest-related measures.[37] • EU Forestry Strategy: A new strategy will be released in 2021.
Existing certification mechanisms	• Woodland Carbon Code (WCC): incentivises UK land-owners for woodland planting for carbon removal through a voluntary standard. Since 2011 launch, 187 projects covering 8,261ha have been validated, with expected carbon sequestration of 3.4million tCO_2. For more information, see Woodland Carbon Code fiche. • New Zealand Emissions Trading Scheme: afforestation is included in New Zealand's ETS as a carbon removal option (sequestration is rewarded with credits). Since 2008, this has resulted in 18.3 Mt CO_2-e removals. See New Zealand Emissions Trading Scheme and Permanent Forest Sink Initiative fiche for more information • Gold Standard, CCOP, and VCS mechanisms include methodologies for afforestation & reforestation, see those fiches for more information.

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[1] CO_2 removal.org (n.d.). Results. Hyperlink: https://CO2removal.org/assessment/results/

[2] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. royalsociety.org/greenhouse-gas-removal

[3] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use: Chapter 4 Forestry Land. IPCC. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch04_Forest%20Land.pdf

[4] Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate

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interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)]. In press.

[5] riscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

[6] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. royalsociety.org/greenhouse-gas-removal

[7] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

[8] C. Doelman, Jonathan (2020). Afforestation for climate change mitigation: Potentials, risks and trade-offs. Hyperlink: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14887

[9] Kreidenweis *et al*, Ulrich. Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. Hyperlink: https://iopscience.iop.org/article/10.1088/1748-9326/11/8/085001

[10] Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J. et al. (2021): Land-based measures to mitigate climate change: Potential and feasibility by country. Glob Change Biol 27, 6025–6058. Online available at https://doi.org/10.1111/gcb.15873

[11] European Commission (2018) IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATIONCOM(2018) 773A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. https://ec.europa.eu/clima/sites/default/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

[12] Forest Europe (2020) State of Europe's Forests 2020 Accessed 17.05.2021. Hyperlink: https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

[13] Röös *et al.*, Elin. (2016). Protein futures for Western Europe: potential land use and climate impacts in 2050. Hyperlink: https://link.springer.com/article/10.1007/s10113-016-1013-4

[14] European Union (2020) European Union (Convention). 2020 Common Reporting Format (CRF) Table. UNFCCC. Accessed 17.05.2021. https://unfccc.int/documents/227990

[15] CO_2 removal.org. (n.d.). Results.

[16] EASAC (2019) Forest bioenergy, carbon capture and storage, and carbon dioxide removal: an update. https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Commentary_Forest_Bioenergy_Feb_2019_FINAL.pdf

[17] Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, et al. Biophysical and economic limits to negative CO_2 emissions. Nature Climate Change. 2015 Dec 7;6(1):42–50. Available from: http://dx.doi.org/10.1038/nclimate287

[18] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. royalsociety.org/greenhouse-gas-removal

[19] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use: Chapter 4 Forestry Land. IPCC.

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https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch04_Forest%20Land.pdf

[20] Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

[21] CO_2 removal.org. (n.d.). Results.

[22] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

[23] European Commission (2018) IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATIONCOM(2018) 773A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. https://ec.europa.eu/clima/sites/default/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

[24] G. Cevallos, J. Grimault, V. Bellassen (2019). Domestic carbon standards in Europe – Overview and perspectives. Hyperlink: https://www.i4ce.org/wp-core/wp-content/uploads/2020/02/0218-i4ce3153-DomecticCarbonStandards.pdf

[25] Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, et al. Biophysical and economic limits to negative CO_2 emissions. Nature Climate Change. 2015 Dec 7;6(1):42–50. Available from: http://dx.doi.org/10.1038/nclimate2870

[26] Brunori AME, Sdringola P, Dini F, Ilarioni L, Nasini L, Regni L, et al. Carbon balance and Life Cycle Assessment in an oak plantation for mined area reclamation. Journal of Cleaner Production. 2017 Feb;144:69–78. Available from: http://dx.doi.org/10.1016/j.jclepro.2016.12.116 **and** Liu, Y, Guo, M. Environmental load analysis of forestation and management process of Larix olgensis plantation by life cycle analysis. Journal of Cleaner Production. 2017 Jan;142:2463–70. Available from: http://dx.doi.org/10.1016/j.jclepro.2016.11.029

[27] CO_2 removal.org. (n.d.). Results.

[28] The Royal Society and Royal Academy of Engineering (2018).

[29] S. Thomas, P. Dargusch, S. Harrison, J. Herbohn.Why are there so few afforestation and reforestation clean development mechanism projects? Land Use Policy, 27 (2010), pp. 880-887 and D. Diaz, K. Hamilton, E. Johnson State of the Forest Carbon Markets 2011: From Canopy to Currency. Ecosystem Marketplace Report

[30] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use: Chapter 4 Forestry Land. IPCC. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch04_Forest%20Land.pdf

[31] EU Parliament and EU Council (2018) REGULATION (EU) 2018/841 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG

[32] Böttcher, Hannes, Carina Zell-Ziegler, Anke Herold, Anne Siemons (2019) EU LULUCF Regulation explained Summary of core provisions and expected effects. ÖkoInstitut. https://www.oeko.de/fileadmin/oekodoc/Analysis-of-LULUCF-Regulation.pdf

[33] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. royalsociety.org/greenhouse-gas-removal

[34] [1] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. royalsociety.org/greenhouse-gas-removal

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[35] Own calculations based on Woodland Carbon Code (2021) Land carbon registry. Accessed 13.05.2021. https://www.woodlandcarboncode.org.uk/uk-land-carbon-registry

[36] European Parliament (n.d.). The European Union and Forests. Hyperlink: https://www.europarl.europa.eu/factsheets/en/sheet/105/the-european-union-and-forests

[37] European Commission (2019) COMMISSION STAFF WORKING DOCUMENT EVALUATION of the Regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005 concerning the forestry measures under Rural Development. SWD(2019) 389 final. https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/key_policies/documents/ext-study-forestry-measures-swp_2019_en.pdf

5.2 Fiche: Agroforestry

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Scheme name	**Agroforestry**[27]
Introduction	**Brief description of the solution** • Agroforestry is a land management system in which woody perennials (trees or shrubs) are planted alongside agricultural crops and/or livestock.[1] Carbon removal occurs through increase in woody biomass, in soil carbon and in dead organic matter. Traditional agroforestry systems are highly variable and adapted to local soils, climate conditions and farming systems; examples include large areas of dehesa and montado on drylands Spain and Portugal, permanent crop and pastoral systems in south-eastern Europe and the wood pastures and bocage (hedgerow) landscapes of the northern Member States. Agroforestry systems in the EU fall into two broad groups: • livestock agroforestry systems, integrating trees and the grazing of animals in a mutually beneficial way, where plant diversity is greater than conventional grassland. • arable agroforestry systems, integrating the cultivation of woody perennials with arable or horticultural crops at field scale. • a third category of agroforestry with high value trees, which overlaps with both livestock agroforestry systems and arable agroforestry systems. **GHGs targeted (and land use category)** • Predominantly CO_2 stored in woody elements. However, The AGFORWARD project, a recent EU Horizon research project on agroforestry, noted that the introduction of agroforestry could reduce GHG emissions from the associated agricultural land use, including a decline in nitrogen-based emissions from the land on which the trees are planted.[2] • **Land use category:** Cropland, Grassland, Forest land (depending on national definitions of Forest land) **Examples of solutions already operational or in planning** • Agroforestry is widely implemented across Europe. • However, there are few examples of result-based payment schemes or certification mechanisms for agroforestry, which are an early stage of development or piloting and designed for local or regional implementation. e.g. projects in the Montado in Portugal (developed by the University of Evora); the CarboCage 3-year pilot hedgerow scheme (funded by the publicly-funded Ecological Transition Agency in the Pays de la Loire region of north-west France); and an initiative by the Coop retailer in Switzerland to support farmers within its supply chain to plant trees on their land to deliver GHG emission reductions.[3] • Existing carbon removal mechanism for afforestation, such as Woodland Carbon Code, could also serve as models.

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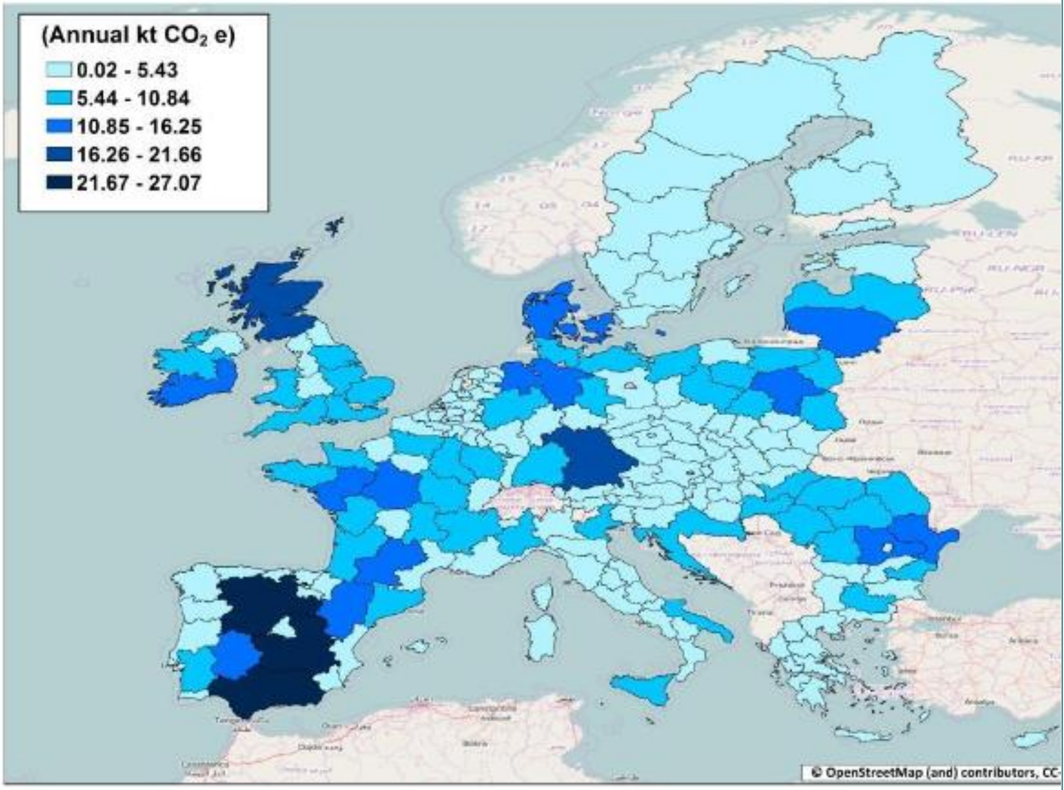
[27] This fiche draws heavily on the Agroforestry Case Study (Lead authors: Catherine Bowyer and Clunie Keenleyside, IEEP) from COWI, Ecologic Institute & IEEP (2021) Annexes to Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby https://op.europa.eu/s/o13a

Solution fiche template	
Section	Aspects covered
Potential	
Technology readiness level (TRL)	**Current TRL level** • Agroforestry is already being implemented across Europe • TRL 9
Potential carbon removals	**Global potential** • According to IPCC (2019), the global CO_2 removal potential of agroforestry ranges between 0.11-5.68 $GtCO_2$-eq yr^{-1}.[4] **EU potential** • Using the LUCAS database and tree cover density data, AGFORWARD estimated that agroforestry covers about 15.4 million hectares in the EU, equivalent to 8.8% of the Utilised Agricultural Area or 3.6% of the territorial area. This is predominantly livestock agroforestry (15.1 million hectares) with less arable agroforestry (0.36 million hectares).[5] Figure 1 shows distribution of agroforestry removal potential across Europe. • If agroforestry was only introduced on EU arable/grassland where there are already multiple environmental pressures (8.9% of total European farmland), EU annual removals could be 7.78 and 234.85 Mt CO_2-e per year (sequestering between 0.3 – 27 t CO_2-e ha−1 yr−1)[6]. These differ by the type and age of the agroforestry: for example in the Mediterranean newly planted shrublands can capture 3 t CO_2-e/yr in the first five years, declining to 0.3 tCO_2-e/yr after fifteen years; olive and fruit trees capture 1.1 t CO_2-e/yr in first five years down to 0-0.1 t CO_2-e/yr after fifteen years.[7] • Roe et al (2021) conclude that at a cost of 100US$/t CO_2-e, agroforestry could sequester 50 Mt CO_2-e per year (average, 2020-2050).[8]  *Figure 1 Mitigation potential of agroforestry at NUTS 2 level, kt CO_2e/y[9]*

Solution fiche template	
Section	Aspects covered
	Constraints/interaction effects and assumptions (e.g. land use requirements, contingencies regarding other solutions) • Potential land-use competition with alternative removals solutions (e.g. afforestation, BECCS etc.). However, this will be less than other NbS solutions, as agroforestry does not compete with agricultural production (it combines production with tree planning).[10] **Brief description of calculation method and uncertainties** • The EU calculation focuses only on the 8.9% of EU forest land where there are multiple environmental pressures (which the agroforestry could address at the same time as sequestering carbon) not all potentially appropriate land[11], so should be considered a lower bound. • The calculation includes only above-ground biomass and does not consider soil carbon impacts. However, these can be (as) large in different contexts (e.g. different prior land-use, and different agroforestry system). Feliciano et al. (2018) evaluate 86 papers globally on agroforestry and find for example that changing grassland to silvo-pastural delivers above ground biomass of 1.7 t CO_2-e/y and soil carbon removals of 4.4 CO_2-e/y, though these have high variance and are based on few studies (n=2 and 9, respectively).[12] **System boundaries and lifecycle emissions considerations** • Agroforestry has uncertain effects on soil carbon (see previous section). • Agroforestry also affects the carrying capacity for animals, and can therefore lead to changes in animal emissions from a whole farm unit (i.e. avoided emissions).
Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs) • Very little clear evidence. It is difficult to generalise regarding costs of agroforestry, as they differ according to specific agroforestry system (e.g. silvo-arable, silvo-pastural), extent of tree planting (e.g. single hedgerow or multiple alleys), and in particular due to the local context, especially the alternative land use (and its profitability).[13] The lack of existing market mechanisms means there are no existing market prices for agroforestry for climate. • Graves et al (2017) asses 42 model farms across Spain, France, and the Netherlands (assuming no grants) and found that silvoarable was the most profitable use in 23 cases (relative surplus was distributed around €40 ha-1/y)[14]. This results was sensitive to grants and discount rates. This suggests that in some contexts agroforestry may already have price incentives, without considering carbon removals. **Projected future costs** • Unclear. Depend principally on interactions with CAP and alternative land-use. More long-term monitoring and evaluation required.[15] **Energy demand** • Low
Duration of removals / permanence	**Duration of removals & risks of reversibility** • Agroforestry faces significant removal/reversibility risk due to intentional removal of woody biomass or mismanagement, or unintentional reversal due to extreme events. Agroforestry can take more time to deliver GHG benefits than other interventions[16] (IPCC, 2019), and the permanence of the carbon sequestered depends on the type of trees and their end use. **Conditions for permanence and options to manage impermanence** • Long-term land contracts, and other legal restrictions can support permanence. Buffer accounts (of 10-30%) are commonly used to guarantee issued credits in voluntary afforestation schemes, and could feasibly be used here.

Solution fiche template	
Section	Aspects covered
Practical barriers	• Overcoming farmer resistance adopting new agroforestry: with the exception of a few Member States (notably France), there has been very limited interest among farmers with little or no experience of agroforestry due to need for developing new skills, entering new output markets, upfront investment, and differing rotation lengths. Uptake of CAP support for establishment and maintenance of agroforestry systems has been very low.[17] • Diversity of agroforestry types and impacts makes it challenging to generalise. • Relatively low carbon removal intensity per ha or participant may make it challenging to economically carry out MRV for certification mechanisms.
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** • There are limited existing examples of MRV systems for agroforestry, which are diverse and where impacts depend on local context. Some areas and approaches are better studied than others, e.g. LIFE Medinet project provides good average carbon stock and stock change data for Mediterranean olive tree, shrubland, fruit tree, and vineyards, though with significant uncertainty[18]. Agroforestry poses some MRV challenges due to the diversity of agroforestry types and the importance of context (e.g. prior land use), plus the relatively low removals per ha to cover MRV costs (e.g. compared to afforestation, peatlands). ◦ MRV would need to take account of above –ground biomass and soil carbon change over time. Above-ground biomass can be assessed using similar methodologies to those proposed for afforestation e.g. use of look-up tables that estimate carbon removals based on observable characteristics of agroforestry, drawing on locally-specific data. Remote sensing and aerial photographs could potentially be used (along with Common Agriculture IACS and Land Parcel Identification System data). Soil carbon change is more challenging, and would rely on empirical models or measurement by soil sampling (which is costly). ◦ Existing projects typically rely on local specialist advisors, who assess baseline land use and agroforestry establishment, provide advice, and then visit regularly to establish quality and health of woody species.[19] • **IPCC methodology:** The 2019 update to the IPCC Guidelines states that whether agroforestry land is recorded as forestry land or crop/grass land, depends on national definitions of forestry land (i.e. tree cover %, tree height, minimum width). Calculations would then follow the respective chapters. For example, agroforestry with crops that does not meet forestry definitions follows cropland calculation methods[20], requiring calculation of change in carbon storage in above and below-ground biomass, dead organic matter, and soils. Separate approaches are provided for land remaining cropland and land becoming cropland. Tier 1 approaches use country specific land-use and management data along with defaults; Tier 2 include national level data on stock change factors, reference C stocks, climate regions, soil types, and/or the land management classification system; and Tier 3 use detailed soil inventory methods (for SOC), high resolution data (for biomass), and models. • **LULUCF-R**[21]: Agroforestry areas would, depending on the national definitions, be either accounted under managed cropland, managed grassland or managed forest land. The accounting for these three categories is net-net (for managed cropland/grassland against a historical base period, for managed forest land against a projected forest reference level). Note that land use changes to a new category require to use geographically explicit land use data (e.g. if a grassland is converted to agroforestry in cropland). **Baseline setting methods** (including existing baseline data options)

Solution fiche template	
Section	Aspects covered
	● Existing pilot methods rely on specialist advisors to set baseline based on site visits. ● Copernicus Small Woody Features[28] dataset can be potentially used, as the 2020 update maps linear structures of woody vegetation (including hedgerows and patches of woody features). EEA is exploring potential to use this dataset for monitoring in the context of the Common Agricultural Policy (CAP). Aerial photographs are used within the CAP IACS system to calculate tree densities and landscape features. **Key references** IPCC GL 2006: Chapter 4 Forestry, Chapter 5 Cropland, Chapter 6 Grassland, Chapter 2 Generic Methods
Sustainability issues	**Co-benefits and negative externalities** ● Agroforestry delivers significant biodiversity, and wildlife co-benefits (including habitat provision, pollinators and insects), reduced soil erosion and in many contexts improved soil health, flooding protection and reduced nitrate leaching.[22] There are mixed impacts on economic outcomes (see costs section) ● Understanding of side effects/leakage risks ● Leakage due to displacement of production: Relatively low, as agroforestry does not fully replace existing arable/animal production. However, it can in many situations result in reduced output, which can pose leakage risk.
Governance aspects	**Actors involved** ● Individual farmers **Scale/size of projects** ● Small: the carbon impact per ha and per farm are relatively low (sequestering between 0.09 and 7.29 t C/ha/yr and average EU farm size of 16.6ha)[23], [24]. **Linkage to existing policies and measures/strategies/funding schemes** [25] ● **Climate policy:** Although the EU LULUCF accounting rules include mandatory land accounting from 2021 of GHG fluxes from managed forest land, managed cropland and managed grassland, current capacities of Member States to report complete and accurate emissions and removals vary considerably. ● **Biodiversity policy:** large areas of long-established agroforestry systems are of high natural and cultural value and identified as habitat types Community interest under Annex I of the Habitats Directive, with an obligation for Member States to maintain these in favourable conservation status. The Biodiversity Strategy 2030 recommends that the uptake of agroforestry support measures should be increased. ● **CAP policy:** specific support for the establishment of new agroforestry has been one of the optional EAFRD measures under Pillar 2 of the CAP since 2007. In the current period (2014-20) this measure was extended to include support for maintenance of both newly established and existing agroforestry, but levels of programming by Member States and uptake by farmers remain low, compared to the measure supporting afforestation. New agroforestry established with RDP support is one of the options for Ecological Focus Areas under the Pillar 1 greening requirements. Due to the diversity of agroforestry practices, there is limited knowledge about the total support for agroforestry under CAP.[26]

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[28] https://land.copernicus.eu/news/small-woody-features-march-2020-update

Solution fiche template	
Section	Aspects covered
Existing certification mechanisms	The CarboCage project in France is a publically-funded project (2016-2020) developing and implementing a method for carbon storage through sustainable hedge management, where carbon removals will be sold in local voluntary carbon markets. - Other projects include: Coop project (Switzerland), where the Coop retailer has been supporting farmers within its supply chain to plant trees on their land to deliver GHG emission reductions, and crediting the removals against Coop emissions. Other ongoing research projects include one focussed on the Montado (by University of Evora) and CarboHedge (by Thunen Institut).[27]

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[1] EEA (n.d.). Agroforestry (webpage). Hyperlink: https://www.eea.europa.eu/help/glossary/eea-glossary/agroforestry

[2] García de Jalón, S., A. Graves, J.H.N. Palma, A. Williams, M.A. Upson, P.J. Burgess (2017) Modelling and valuing the environmental impacts of arable, forestry and agroforestry systems: a case study. Agroforestry Systems, vol. 92, no. 4, pp. 1059-1073.

[3] COWI, Ecologic Institute & IEEP (2021) Annexes to Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby https://op.europa.eu/s/o13a

[4] Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)]. In press.

[5] den Herder, M., G. Moreno, M.R. Mosquera-Losada et al. (2016) Current extent and trends of agroforestry in the EU27. Deliverable Report 1.2 for EU FP7 AGFORWARD Research Project (613520).

[6] Kay, S., C. Rega, G. Moreno et al. (2019) Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy, vol. 83, pp. 581–593

[7] LIFE Medinet (2018) Carbon emissions and sequestration in agriculture and grasslands in the Mediterranean. Project LIFE Medinet report. Accessed 17.05.2021. https://d9093529-fca9-49b3-9cb2-06489a8ffcb3.filesusr.com/ugd/f00191_6f11b9ea9f3d46f9882952e233565968.pdf

[8] Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J. et al. (2021): Land-based measures to mitigate climate change: Potential and feasibility by country. Glob Change Biol 27, 6025–6058. Online available at https://doi.org/10.1111/gcb.15873

[9] Martineau H., J. Wiltshire, J. Webb, K. Hart, C. Keenleyside, D. Baldock, H. Bell, J. Watterson (2016) Effective performance of tools for climate action policy - metareview of Common Agricultural Policy (CAP) mainstreaming. Report for European Commission – DG Climate Action.

[10] The Royal Society and Royal Academy of Engineering (2018).

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[11] Kay, S., C. Rega, G. Moreno et al. (2019) Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy, vol. 83, pp. 581–593

[12] Feliciano, D., Ledo, A., Hillier, J., & Nayak, D. R. (2018). *Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agriculture, Ecosystems & Environment, 254, 117–129.* doi:10.1016/j.agee.2017.11.032

[13] Paul Burgess (Lead), Ulrich Schmutz, Fabien Balaguer, Martijn Boosten, Judit Csikvari, Yousri Hannanchi, Ralf Pecenka, Javier Poza Llorente, Mati Sepp, Andrea Vityi (2017) EIP-AGRI Focus Group

Agroforestry MINIPAPER: Financial Impact of Agroforestry. https://ec.europa.eu/eip/agriculture/sites/default/files/fg22_mp6_financials_2017_en.pdf

[14] Graves AR, Burgess PJ, Palma JHN, Herzog F, Moreno G, Bertomeu M, Dupraz C, Liagre F, Keesman K, van der Werf W Koeffeman de Nooy A, van den Briel JP (2007). Development and application of bioeconomic modelling to compare silvoarable, arable and forestry systems in three European countries.

Ecological Engineering 29: 434-449.

[15] EIP-AGRI Focus Group Agroforestry (2017) EIP-AGRI Focus Group Agroforestry: introducing woody vegetation into specialised crop and livestock systems – Final Report. EIP AGRI. https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_agroforestry_final_report_2017_en.pdf

[16] IPCC (2019)

[17] COWI, Ecologic Institute & IEEP (2021) Annexes to Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby https://op.europa.eu/s/o13a

[18] LIFE Medinet (2018) Carbon emissions and sequestration in agriculture and grasslands in the Mediterranean. Project LIFE Medinet report. Accessed 17.05.2021. https://d9093529-fca9-49b3-9cb2-06489a8ffcb3.filesusr.com/ugd/f00191_6f11b9ea9f3d46f9882952e233565968.pdf

[19] COWI, Ecologic Institute & IEEP (2021) Annexes to Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby https://op.europa.eu/s/o13a

[20] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use: Chapter 5 Crops Land. IPCC. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_05_Ch5_Cropland.pdf

[21] EU Parliament and EU Council (2018) REGULATION (EU) 2018/841 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG

[22] Kay, S., C. Rega, G. Moreno et al. (2019) Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy, vol. 83, pp. 581–593

[23] Kay, S., C. Rega, G. Moreno et al. (2019) Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy, vol. 83, pp. 581–593

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[24] EUROSTAT (2018) Agriculture, forestry and fishery statistics, 2018 addition. doi: 10.2785/340432. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agriculture,_forestry_and_fishery_statistics

[25] COWI, Ecologic Institute & IEEP (2021) Annexes to Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby https://op.europa.eu/s/o13a

[26] Mosquera-Losada, M. R.; Santiago-Freijanes, J. J.; Pisanelli, A.; Rois-Díaz, M.; Smith, J.; den Herder, M.; Moreno, G.; Ferreiro-Domínguez, N.; Malignier, N.; Lamersdorf, N.; Balaguer, F.; Pantera, A.; Rigueiro-Rodríguez, A. et al. (2018): Agroforestry in the European common agricultural policy. In: Agroforestry Systems 92 (4), pp. 1117–1127. DOI: 10.1007/s10457-018-0251-5.

[27] COWI, Ecologic Institute & IEEP (2021) Annexes to Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby https://op.europa.eu/s/o13a

5.3 Fiche: Peatland rewetting

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Scheme name	**Peatland rewetting** (and wetland restoration)[29]
Introduction	**Brief description of the technology** - The rewetting of peatlands and wetlands predominantly avoids emissions, rather than removing carbon from the atmosphere. As peatlands and wetlands are drained (e.g. for agriculture, urban expansion) or degrade, they release stored carbon (and nitrous oxide). Rewetting or restoring drained peatlands swiftly stops the release of this carbon into the atmosphere (i.e. avoided emissions). Rewetting also leads to sequestration through plant growth and increases in carbon stock, although these are small and variable and only occur over longer timescales[1]. - Peatlands (also called mires, moors, meadows, organic soils) are any land that, when not drained, has a soil layer near the surface consisting of poorly aerated organic material which is water saturated (or would be in the absence of drainage) for 30 consecutive days or more in most years (referred to as a histic layer)[2]. IPCC definitions of 'organic soil' do not set a minimum peat thickness[3], though some certification mechanisms (e.g. Peatland Code) require peat thickness of 50cm[4]. Wetlands is a broader term that includes peatlands as well as floodplains and coastal saltmarshes[5]. - Peatland rewetting/restoration involves restoring water levels, predominantly by blocking ditches. Peatlands can either be conserved or potentially used productively whilst wet (paludiculture).[6] - Coastal wetland restoration[30] (commonly categorised as "blue carbon") involves expansion of saltmarshes and seagrass meadows. Internationally, this also includes mangroves. **GHGs targeted (and land use category)** - CO_2, N_2O, and CH4 - Note: carbon dioxide and nitrous oxide emissions decrease with rewetting[7], while methane emissions increase with rewetting – though the overall affect is reduced radiative forcing[8]. **Landuse category:** Wetlands, Forest land, Cropland, Grassland. **Examples of solutions already operational or in planning** - Peatland rewetting is widespread across Europe.

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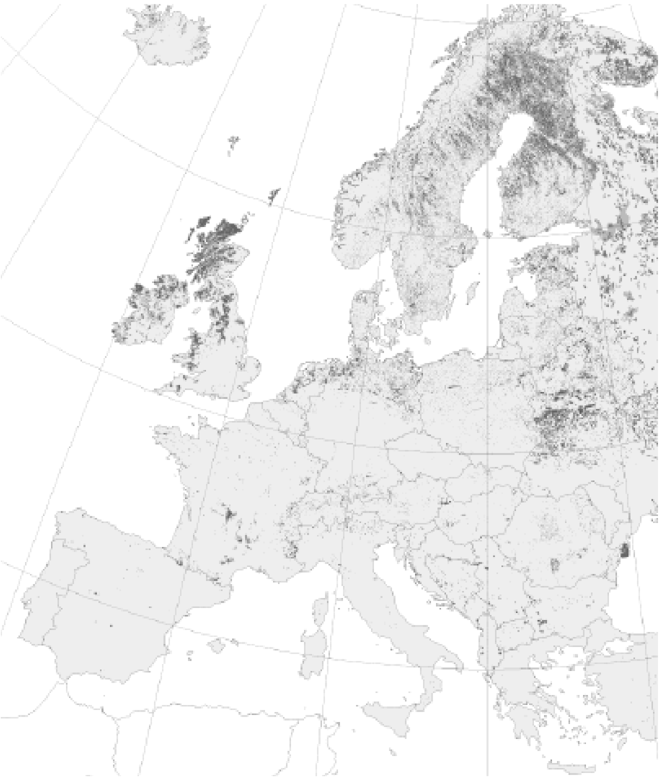
[29] In this fiche, we draw heavily on Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby

[30] In this fiche, we provide limited insights into coastal wetland restoration. We do not draft a separate "blue carbon" fiche as there is currently little focus and only limited knowledge on them within Europe as a carbon removal option.

Solution fiche template	
Section	Aspects covered
	• Peatland rewetting is also covered by voluntary certification mechanisms, such as MoorFutures in Germany, which since establishment in 2010 has projects with lifetime removals of 68,889t/CO_2-e. Other regional examples include Peatland Code in the UK (first project validated in 2018) and MaxMoor in Switzerland (active since 2017), among others[9]. Verra's Verified Carbon Standard also has five methods for peatland rewetting or related.[10] See existing certification mechanisms section for more information.
Potential	
Technology readiness level (TRL)	**Current TRL level** • Peatlands rewetting is already being implemented across Europe, as evidenced by MoorFutures, MaxMoor, Peatland Code and other projects. • TRL level 9
Potential carbon removals	**Global potential** • Currently, degraded peatlands emit 2Gt CO_2 per year (equivalent to 5% of total anthropogenic CO_2 emissions)[11]. • In total, Griscom et al (2017) estimate that wetlands (including peatlands as well as coastal wetlands) can achieve mitigation potential of 2.7 GtCO_2/y by 2030. This is predominantly avoided emissions, composed of avoided coastal wetland impacts (0.3 Gt CO_2-e/y), coastal wetland restoration (0.84Gt CO_2-e/y), avoided peatland impacts (0.75Gt CO_2-e/y), and peatland restoration (0.8Gt CO_2-e/y).xii IPCC Special Report on Land reaches similar conclusions, estimating coastal wetlands restoration potential of 0.2-0.84 Gt CO_2 equivalent (CO_2e) per year, peatland restoration of 0.15-0.8 Gt CO_2-e per year.xiii **EU potential** • EU Peatland drainage alone in is responsible for annual emissions of 220Mt CO_2-e/y.xiv Of these, a Perez Dominguez et al (2020) estimate that retiring croplands currently operating on organic soils would have a carbon impact of 51.7 Mt (i.e. in terms of avoided emissions).[12] Additionally, halting extraction of peat (e.g. for gardening soils) could avoid emissions of 9 Mt CO_2 annually.[13] Roe et al. (2021) estimate that at a cost of US$100/t CO_2-e, rewetting and restoring peatlands in Europe would deliver mitigation of 54 Mt CO_2-e per year (average over 2020-2050).[14] • In per ha terms, MoorFutures method identifies avoided emissions of 3.5-24 t CO_2-e/ha/yr (depending on vegetation and water level). [15]

Solution fiche template	
Section	Aspects covered
	 *Figure 1 Composite peatland map of Europe (Tanneberger et al, 2017)* - Potential differs considerably across Europe. There are 593,727km^2 of peatlands in Europe, of which approximately 46% are degraded[16]. As Figure 1 illustrates, peatlands occur more commonly in northern Europe. The degree of degradation differs considerably across European countries, for example only 2% of Germany's peatlands are mires (i.e. in a healthy state where they are producing peat) compared to 84% of Norway's peatlands[17]. **Constraints/interaction effects and assumptions** - Potential land use competition with BECCS, afforestation, and land competition from agriculture. However, given the relatively small wetland/peatland areas, competition will be relatively lowxviii. **Brief description of calculation method and uncertainties** - The global numbers assume that peat and wetlands identified as degraded have already lost 50% of their stored carbon. The EU numbers are calculated based on the CAPRI model (including CO_2 and N20), and represent maximum technical potential (based on retiring all of the croplands on organic soil across the EU). **System boundaries and lifecycle emissions considerations** - System boundaries must be broad enough to capture any ecological leakage (i.e. where ditch blocking affects neighbouring areas).xix
Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs) - Perez Dominguez et al (2020) estimates that 75% of carbon impact from retiring EU croplands on organic soil at costs of €20/t CO_2-e (where costs are calculated based on opportunity cost of concurrent use).[18] Note this opportunity cost does not include the direct costs of rewetting.

Solution fiche template	
Section	Aspects covered
	- Peatland and wetland restorations are relatively low cost. Direct costs for peatland restoration are in the range of \$10-\$100 per tCO_2, excluding opportunity costs[19]. - At a global scale, Griscom et al (2017) estimate that 29% of realistic potential can be achieved at costs of <\$10/tCO_2-e, and 57% can be achieved at <\$100/tCO_2-e[20]. **Projected future costs** - Costs are not expected to change[21], although opportunity costs may be expected to increase over time as less valuable land is rewet. **Energy demand** - Energy demand is zero
Duration of removals / permanence	**Duration of removals & risks of reversibility** - Variable (0-50 years or >100years, depending on management). Peatlands and wetlands can store carbon indefinitely but only if they continue to be managed for storage. They are subject to impermanence if humans reverse storage (e.g. re-drain peatlands or fail to maintain) and to some natural disasters (e.g. wetlands may be effected by ocean storms) or sea level rise[22]. **Conditions for permanence and options to manage impermanence**[23] - Long-term land contracts, land deeds, and other legal restrictions can support permanence. Buffer accounts (of 10-30%) are commonly used to guarantee issued credits in voluntary schemes.
Practical barriers	- Potential for peatland rewetting to displace local food production. However, as peatland areas are relatively small, the global impacts will be limited[24]. - Interactions with Common Agricultural Policy payments increase opportunity costs of retiring land for rewetting (see Governance aspects below). - Lack of data: many countries are lacking data on the extent and location of organic soil areas
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties**[25] - Existing certification mechanisms use indicators to estimate avoided emissions resulting from rewetting (in CO_2-e, considering CO_2 and CH4). These indicators are based on a scientific consensus that emissions can be relatively reliably estimated based on land use, water table depth, vegetation cover, and climatics/phytogeograhic region. These relationships (based on expert judgement, project-, region-, or national-level reference data) are used to estimate emissions factors for different land types (and water table depths, vegetation cover) (existing mechanisms categorise land into 4-10 categories, each with a corresponding emissions factor). Avoided emissions are then calculated by summing change in land classification area x difference in emissions factor. - MRV relies on expert judgement to develop emissions factors for local context, and to classify land categories, potentially limiting short-term upscaling. - Real time onsite measurement is not feasible/cost-effective (would cost €10,000/ha/yr).

Solution fiche template	
Section	Aspects covered
	IPCC Guidelines[26]: The 2013 Wetlands Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories provides specific guidance for calculating GHG fluxes from wetlands in six categories (drained inland soils, rewetted organic soils, coastal wetlands, inland wetlands on mineral soils, constructed wetlands for wastewater treatment). These categories cross across land use categories (e.g. forestry, croplands, etc.) and for each, different guidance is provided for landuses that are staying the same (e.g. grassland remains grassland) or change (e.g. grassland becomes forestry land). Most relevant for this solution is Chapter 2: Drained Inland Organic Soils and 3: rewetted organic soils. Emissions on drained organic soils are calculated as on-site emissions (i.e. area x Tier 1 emissions factors, which are given per land-use category, whether soil is nutrient poor or rich, and climatic zone e.g. highest is temperate drained fallow croplands, 14 t/CO_2-e per year), offsite emissions via waterborne carbon losses (Tier 1 emissions factors for boreal, temperate, tropical – e.g. 0.3t C/ha/yr), and non C02 emissions (methane and nitrous oxide). Tier 2 methods require country or regional specific emissions factors and more differentiated soil data, while Tier 3 methods require comprehensive models. **Baseline setting methods** (including existing baseline data options) ● Different options: MoorFutures calculates a forward-looking baseline scenario based on historical data and expert opinion. Given local economic/social context, they assume that current use is the most likely future use and therefore use current use as baseline. Baselines are reset every 10 years.[27] VCS method assumes that restoration/rewetting is additional if the activity penetration level in the local region is below a certain threshold. **Key references** ● IPCC Guidelines: 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands and 2019 update
Sustainability issues	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts) ● Co-benefits: Peatland restoration delivers multiple environmental co-benefits, including biodiversity conservation, flood protection, improved soil and water quality, and protection from coastal storms, as well as cultural ecosystem services.[28] The average annual value of these services ranges from $3000-14,800. [29] ● Negative externalities: peatland restoration increases methane emissions (though the net GHG effect is negative) [30]. **Understanding of side effects/leakage risks** ● Leakage due to activity shifting or market leakage: If peatland restoration occurs on previously productive land (e.g. commercial agriculture, forestry, or peat extraction), this could lead to shifting of activities elsewhere in the EU or internationally. Note this can be avoided if rewetting only occurs on non-productive land[31]. Market leakage (i.e. when rewetting shifts supply/demand equilibriums in related markets (e.g. peat), increasing production and emissions elsewhere), could occur ● Ecological leakage: If rewetting of project area lowers the water table level elsewhere, emissions from peatlands could simple leak to this area. To manage this, project boundaries must be sufficiently broad to capture expected water-level changes in baselines[32].
Governance aspects	● **Actors involved:** Individual landowners (e.g. farmers) ● **Scale/size of projects:** MoorFutures has projects that range in size from 6.7ha (5800 tCO_2-e over 100 year life of project) to 68ha (39500t CO_2-e over 100 year life of project).[33] Internationally, the VCS project "Tropical Peatland Conservation and Restoration in Katingan-Mentaya, Indonesia, for Biodiversity Conservation and Climate Mitigation and Adaptation" aims to conserve 149,800ha (plus 155,869 ha of mixed use buffer zone) (up to an average 7.4million tCO_2-e per year)[34].

<table>
<tr><th colspan="2">Solution fiche template</th></tr>
<tr><td>Section</td><td>Aspects covered</td></tr>
<tr><td></td><td>- **Linkage to existing policies and measures/strategies/funding schemes**
  - Common Agricultural Policy: CAP rules 2014-2020 exclude pillar 1 direct payments for rewetted peatlands (as land must be maintained in a state “suitable for grazing or cultivation”, with no exception for paludiculture (i.e. farmed wet peatlands). This provides a large disincentive for rewetting.[35]
  - Birds and Habitats Directives (and associated Natura 2000 protection) providing some protection for habitats, including existing wetlands and peatlands.
  - LULUCF Regulation: Forest land, cropland and grasslands which include drained organic soils are accounted for under managed forest land, managed cropland and managed grassland (net-net accounting with base period and forest reference level). In addition from 2026-2030 it is mandatory for all MS to account for managed wetlands which include peat extraction areas. For this accounting category also a net-net approach is applied with a historical base period (2005-2009). However, there are some countries that already voluntarily account for managed wetlands in the first accounting period (e.g. Ireland).</td></tr>
<tr><td>Existing certification mechanisms</td><td>- MoorFutures in Germany, a voluntary offset standard which since establishment in 2010 has projects with lifetime removals of 68,889t/CO_2-e.
- Peatland Code in the UK, aims to have 2 million ha of UK peatlands under restoration management by 2040.
- MaxMoor in Switzerland focuses on restoring degraded peatlands that are no longer in agricultural use, with estimated potential of avoiding up to 19,000t CO_2-e per year.
- Verra’s Verified Carbon Standard has five methods for peatland/wetland rewetting and coastal restoration[36]. Most relevant for the EU is VM0036 Methodology for Rewetting Drained Temperate Peatlands v1.014 (published in 2017), as of time of writing, there were no registered projects for this methodology in the Verra registry[37].</td></tr>
</table>

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[1] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby.

[2] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby.

[3] Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. & Troxler, T.G. (eds.) (2014) 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. IPCC, Switzerland, 354 pp.

[4] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby.

---

[5] Taillardat P, Thompson BS, Garneau M, Trottier K, Friess DA. 2020 Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface Focus 10: 20190129. http://dx.doi.org/10.1098/rsfs.2019.0129

[6] Dinesen, Lars and Peter Hahn (2019) Draft Ramsar Technical Report on peatland restoration and rewetting methodologies in Northern bogs. RAMSAR CONVENTION ON WETLANDS 22nd Meeting of the Scientific and Technical Review Panel. Accessed: 08/04/2021 https://www.ramsar.org/sites/default/files/documents/library/strp22_7.2_draft_rtr_peatland_restoration_e.pdf

[7] Liu, H., Wrage-Mönnig, N. & Lennartz, B. (2020) Rewetting strategies to reduce nitrous oxide emissions from European peatlands. Commun Earth Environ 1, 17. https://doi.org/10.1038/s43247-020-00017-2

[8] Günther, A., Barthelmes, A., Huth, V. et al. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat Commun 11, 1644 (2020). https://doi.org/10.1038/s41467-020-15499-z

[9] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby.

[10] Verra (2021) VCS Methodologies (webpage). Accessed 08.04.2021. https://verra.org/methodologies/

[11] Joosten H, Sirin A, Couwenberg J, Laine J, Smith P (2016) The role of peatlands in climate regulation. In: Bonn A, Allott T, Evans M, Joosten H, Stoneman R (eds) Peatland restoration and ecosystem services - science, policy and practice. Cambridge

University Press, Cambridge, pp 63–76

[12] Pérez Domínguez, I.; Fellmann, T.; Witzke, P.; Weiss, F.; Hristov, J.; Himics, M.; Barreiro-Hurlé, J.; Gómez-Barbero, M.; Leip, A. (2020): Economic assessment of GHG mitigation policy options for EU agriculture, A closer look at mitigation options and regional mitigation costs - EcAMPA 3 (EUR, 30164). Luxembourg: Publications Office of the European Union

[13] European Commission (2020): Impact Assessment, Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people ({SWD(2020) 177 final} -). European Commission (ed.). https://ec.europa.eu/transparency/regdoc/rep/10102/2020/EN/SWD-2020-176-F1-EN-MAIN-PART-1.PDF

[14] Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J. et al. (2021): Land-based measures to mitigate climate change: Potential and feasibility by country. Glob Change Biol 27, 6025–6058. Online available at https://doi.org/10.1111/gcb.15873

[15] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby.

[16] Tanneberger et al. (2017) The Peatland Map of Europe. Mires and Peat, Volume 19 (2017), Article 22, 1–17. DOI: 10.19189/MaP.2016.OMB.264

[17] Tanneberger et al. (2017) The Peatland Map of Europe. Mires and Peat, Volume 19 (2017), Article 22, 1–17. DOI: 10.19189/MaP.2016.OMB.264

---

[18] Pérez Domínguez, I.; Fellmann, T.; Witzke, P.; Weiss, F.; Hristov, J.; Himics, M.; Barreiro-Hurlé, J.; Gómez-Barbero, M.; Leip, A. (2020): Economic assessment of GHG mitigation policy options for EU agriculture, A closer look at mitigation options and regional mitigation costs - EcAMPA 3 (EUR, 30164). Luxembourg: Publications Office of the European Union

[19] Royal Society & Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[20] Griscom, B. Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, David Shoch, Juha V. Siikamäki, Pete Smith, Peter Woodbury, Chris Zganjar, Allen Blackman, João Campari, Richard T. Conant, Christopher Delgado, Patricia Elias, Trisha Gopalakrishna, Marisa R. Hamsik, Mario Herrero, Joseph Kiesecker, Emily Landis, Lars Laestadius, Sara M. Leavitt, Susan Minnemeyer, Stephen Polasky, Peter Potapov, Francis E. Putz, Jonathan Sanderman, Marcel Silvius, Eva Wollenberg, Joseph Fargione (2017) Natural climate solutions. Proceedings of the National Academy of Sciences Oct 2017, 114 (44) 11645-11650; DOI: 10.1073/pnas.1710465114

[21] Royal Society & Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[22] [1] Royal Society & Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[23] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby.

[24] IPCC (2019) Special Report on Climate Change and Land. https://www.ipcc.ch/srccl/

[25] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) *Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU* Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby

[26] IPCC (2013) 2013 Supplement to the 2006 IPCC Guidelines for

National Greenhouse Gas Inventories: Wetlands. Accessed 19.05.2021. https://www.ipcc-nggip.iges.or.jp/public/wetlands/index.html

[27] Joosten, H., Burst, K., Couwenberg, J., Gerner, A., Holsten, B., Permien, T., Schäfer, A., Tanneberger, F., Trepel, M., Wahren, A. (2015). MoorFutures® Integration of additional ecosystem services (including biodiversity) into carbon credits – standard, methodology and transferability to other regions. BfN-Skripten 407. https://www.bfn.de/fileadmin/BfN/service/Dokumente/skripten/Skript407.pdf

[28] Royal Society & Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[29] Royal Society & Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

---

[30] Günther, A., Barthelmes, A., Huth, V. et al. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat Commun 11, 1644 (2020). https://doi.org/10.1038/s41467-020-15499-z

[31] von Unger, Ignio Emmer, Hans Joosten, John Couwenberg (2019) Designing an International Peatland Carbon Standard: Criteria, Best Practices and Opportunities. UBA (German Enviornment Agency) CLIMATE CHANGE 42/2019. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-28_cc-42-2019_sca_peatland_standards_0.pdf

[32] von Unger, Ignio Emmer, Hans Joosten, John Couwenberg (2019) Designing an International Peatland Carbon Standard: Criteria, Best Practices and Opportunities. UBA (German Enviornment Agency) CLIMATE CHANGE 42/2019. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-28_cc-42-2019_sca_peatland_standards_0.pdf

[33] MoorFutures (2021) MoorFutures: Projects (webpage). Accessed 08.04.2021. https://www.moorfutures.de/projekte/

[34] Wetlands International (2018) Tropical Peatland Conservation and Restoration in Katingan-Mentaya, Indonesia, for Biodiversity Conservation and Climate Mitigation and Adaptation flyer. file:///H:/Downloads/Flyer-Restoration-Katingan-Mentaya-FINAL.pdf

[35] Olesen, Asger Strange and Sarah Pyndyt Andersen (2021) Peatland Restoration and Rewetting – a carbon farming case study in COWI, Ecologic Institute and IEEP (2021) Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby

[36] Verra (2021) VCS Methodologies (webpage). Accessed 08.04.2021. https://verra.org/methodologies/

[37] Verra (2021) Verra Registry: VCS (webpage). Accessed 08.04.2021 https://registry.verra.org/app/search/VCS

5.4 Fiche: Forest management

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Scheme name	**Forest management**
Introduction	**Brief description of the technology** - Forest management (commonly also referred to “sustainable” or “improved”[31],[1] forest management) refers to measures to increase carbon sequestration in biomass or soils on existing natural and plantation forest land. Key measures include better harvesting practices (e.g. technical and protective measures to reduce emissions per unit of timber), decreasing harvest intensity (i.e. longer forest rotations), reduced disturbances (e.g. fire/pest management), and measures to increase biomass growth (e.g. thinning, drainage, replanting with new species), among other measures targeting increased carbon sequestration. **GHGs targeted** (and land use category, if appropriate) - CO_2 (IPCC Forest Land methods include also methods for CH4/N_2O from biomass burning and N_2O from soils))[2] **Land use category:** Forest land **Examples of solutions already operational or in planning** - Forest management is already widespread across Europe. See existing certification mechanisms section below.
Potential	
Technology readiness level (TRL)	**Current TRL level** - Sustainable forest management is already being implemented across Europe - TRL 9
Potential carbon removals	**Global potential** - IPCC (2019) estimates that forest management has the potential to mitigate 0.4–2.1 $GtCO_2$-eq yr–1 (based on studies estimating potential per year 2020-2050)[3] - Griscom et al (2017) estimates that the sequestration potential of forest management in 2030 at 2.11 GtC02-eq yr-1, including natural and plantation forest management and fire management.[4] **EU potential** - Nabuurs et al (2017) estimates that forest management within the EU can deliver an additional 171 Mt CO_2-e yr^{-1} by 2050[5], relative to then current forest management[32]. Various other studies suggest forest management within the EU could deliver between 150-400 Mt CO_2-e yr-1by 2050, with higher numbers seeming optimistic.[6] Roe et al (2021) report that technical potential of improved forest management would be 244 Mt CO_2-e per year but that only 35 Mt CO_2-e per year would be feasible at a cost of US$100/t.[7] - Constraints/interaction effects and assumptions (e.g. land use requirements, contingencies reg. other solutions)

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[31] “Improved” and “sustainable” forest management often infer forest management for other social and environmental objectives, beyond carbon sequestration.

[32] As defined by the by the July 2016 European Commission LULUCF policy proposal.

Solution fiche template	
Section	Aspects covered
	- Forest management offers large and cost-effective carbon-removal opportunities that do not require changes in land use or tenure, many of which could be implemented in the short-term. Some activities would not reduce wood yield (such as reduced impact of logging), whereas others would (such as extended harvest cycles).[8] However, forest management faces competition from other land uses (such as commercial agriculture), which are often financially more attractive in the short term. The latter leads to deforestation and land-use changes.[9] **Brief description of calculation method and uncertainties** - Carbon removal potential depends on the area of forest land remaining forest land (i.e. deforestation rates), forest age structure (with older forests having less potential for additional sequestration), existing forest type and management. [10] There are also biophysical limits to the level of sequestration, though these limits are not yet pressing in Europe.[11] **System boundaries and lifecycle emissions considerations** - Forest management affects biomass, soil carbon, and dead wood and litter carbon pools, with largest impact on above and below-ground biomass. For forest land remaining forest, Tier 1 IPCC Guidelines assume no change in dead organic matter or soil carbon; for land converted to forest land, IPCC Guidelines predict increase in dead organic matter and generally increased soil carbon but also with potential for small SOC decreases on mineral soils and large decreases on organic soils.[12] The 2020 VCS methodology for Improved Forest Management includes above and below-ground biomass but generally excludes other pools/gases (with dead wood included if change expected to be significant and N_2O soil emissions included if fertilisation measures are implemented, or other gases if forest fire management is implemented).[13].
Costs	**Costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs) - Consistent evidence on costs in Europe were not found. Costs are highly variable, depending on opportunity cost of decreased timber output, as well as specific management costs. The California compliance offset programme, which includes improved forest management methods, incentivizes these activities at current prices of €13.67[14] (Badgeley et al, preprint) (note: see MRV section for significant criticism of these offset credits). - Griscom et al. (2017) conclude that globally about 60% of the technical potential could be achieved at the cost of up to $100/ton (up to 1.2 $GtCO_2$), a third of which (approximately 0.4 Gt) under $10/ton.[15] **Projected future costs** - Costs are not expected to change significantly over time. **Energy demand** - Resource requirements, such as energy, vary based on the type of forest-management activities that are implemented and are generally comparable to conventional logging.[16]
Duration of removals / permanence	**Duration of removals & risks of reversibility** - Forested areas, including the sequestered carbon, are vulnerable to both natural- and human-induced disturbances. Nature disturbances include floods, wildfires, droughts and pests; human-induced disturbances include deforestation and degradation.[17] **Conditions for permanence and options to manage impermanence**

Solution fiche template	
Section	Aspects covered
	- Long-term land contracts, land deeds, and other legal restrictions can support permanence. Discounting (of approx. 10-30%) is commonly used to guarantee issued credits in voluntary schemes (e.g. VCS methods, Label bas Carbone).
Practical barriers	- The maintenance of forest land as forest land is a crucial prerequisite for forest management projects. This is potentially threatened by higher economic returns for other land uses in some contexts.[18] - The most effective and cost-effective forest management options will depend on local context (e.g. existing forest management, forest age structure, forest type, as well as local practices and knowledge); forest management will therefore need to be adaptive to local context. [19] It must also be responsive to different ownership and management structures across the EU.
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** - **Existing methodologies:** Many forest management methodologies rely on forest growth and yield modelling (to estimate change in carbon storage). However, the most recent VCS methodology (Methodology for Improved Forest Management) requires no modelling. Instead, it estimates carbon sequestration ex post by measuring change in stocks within project boundaries compared to non-treatment plots outside project boundaries. The method requires field measurements of biomass and dead wood, as well as monitoring of other factors (such as fertilizer application).[20] - **IPCC Guidelines**[21]: The Forest land chapter 4 and chapter 2 propose methods for forest land remaining forest land. This includes methods for calculating change in biomass, dead organic matter, and soil organic carbon (split into mineral/organic soils). For forest land remaining forest land, all EU Member States use at least Tier 2 (i.e. country-specific data) to quantify emissions/removals from carbon pool living biomass. Tier 1 methods are commonly used to calculate other pools, e.g. only half of the Member States apply Tier 2 or above for dead wood/litter, only 6 apply Tier 2 for mineral soil carbon, and only 8 apply Tier 2 methods for organic soil carbon.[22] - **LULUCF Regulation**[23], [24]: Forest land remaining forest land is accounted under the category Managed Forest land and is based on net-net accounting (i.e. Member States compare actual emissions/removals on managed forest land to the projected forest reference level, which is based on 2000-2009 historical emissions/removals and considers changes in factors, e.g. age class distribution. It should be noted that under the Regulation, Harvested Wood Products (from Managed Forest Land) are also included in the Forest Reference Levels and are accounted together with the Managed Forest Land category. **Baseline setting methods (including existing baseline data options)** - Gaming of baseline setting represents a significant risk for forest management methodologies. Generally, they are calculated in comparison to a reference baseline level (any increase in sequestration/decrease in emissions beyond this baseline are assumed additional). There are two main baseline setting methods, both subject to uncertainty and risk of being gamed by participants:

Solution fiche template	
Section	Aspects covered
	• Project-specific baselines: Projects are required to calculate a unique baseline for their project. The VCS Methodology for Improved Forest Management first establishes a baseline for the project area (based on random samples); it then identifies paired control plots outside of the project areas (selected to match the sample plots in terms of "biophysical and anthropogenic factors driving stock change"); these control plots then serve as the baseline.[25] Project-specific baselines can be difficult to evaluate and gamed such that the performance baseline is too low (and over-crediting occurs).[26] These baseline can also be expensive to establish, thus adding to transaction costs. • Standardised baseline: Methodologies set common rules for eligibility and setting participant baselines. An example is the VCS Methodology for Improved Forest Management through Reduced Impact Logging, where the baseline is equal to regionally-specific reduced impact logging performance standards (i.e. for each monitored parameter (improved directional felling, reduced road width, etc.), a regional average is calculated); if participants achieve better results than this regional standard, the difference is recognized as sequestration/avoided emissions.[27] This is at risk of bias through adverse selection, i.e. where project developers know more than regulators (e.g. they know how their own logging practices compare to the regional standard) and have an incentive to systematically include forest land that naturally outperforms the assumptions underpinning the method (i.e. the regional standard), systematically resulting in non-additional credits.[28] In Improved Forest Management projects that are developing offset credits for the California's compliance offset programme, adverse selection has resulted in a net over-crediting equal to 30% of all credits generated from the method.[29] **Key references** • IPCC GL (2006) Volume 4, Chapter 4: Forest land and Chapter 2 on Generic Methods • and e.g. VCS (2020) Methodology for Improved Forest Management and VCS Methodology for Improved Forest Management through Reduced Impact Logging
Sustainability issues	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts) • Forest management can deliver significant co-benefits, including ecosystem and biodiversity preservation, as well as water quality and water quantity benefits.[30] **Understanding of side effects/leakage risks** • Leakage affects are low, as forest management occurs on existing forest land and has only small impacts on timber production.
Governance aspects	**Actors involved:** • Forests are publically and privately held, in varying sizes. 46.5% of EU forest land is privately owned. More than 2 million privately held forest plots are small (<10ha), though in terms of land area, the majority of privately held land is in medium-sized plots (10-500ha), and many larger plots (12 million ha in plots greater than 500ha). Publically-owned forests are larger, with more than 60 million ha in plots greater in size than 500ha). **Scale/size of projects** • Nabuurs et al (2017) estimates that on average, forest management in Europe could deliver 0.9-2.5 t CO_2 per ha per year in increased sequestration.[31] For large forestry plots of 500ha, this would imply 500-1250t/yr per participant. **Linkage to existing policies and measures/strategies/funding schemes**

Solution fiche template	
Section	Aspects covered
	● The CAP is the main source of EU funds for forests; 90% comes from the European Agricultural Fund for Rural Development (EAFRD). Over the period 2014-2020, a single specific measure addressed different types of support for investment in forests, covering afforestation and creation of woodland, establishment of agro-forestry systems, prevention and restoration of damage to forests from forest fires, natural disasters and catastrophic events, investment to improve the resilience and environmental value of forest ecosystems and investment in forestry technologies and in the processing, promotion and marketing of forest products. Another measure is to provide rewards for forestry, environmental and climate services and the conservation of forests. Moreover, there is also a provision for measures not-specific to forestry (e.g. Natura 2000 and Water Framework Directive payments). With their Rural Development Programmes, Member States can decide which measures to implement as well as the level of payments that landowners receive.[32] ● EU Forestry Strategy: A new strategy will be released in 2021. The Revised LULUCF-Regulation will have a significant impact. The July 2021 Commission proposal contains only minor changes to the 2021-25 period, relatively similar but more ambitious Member State targets for 2030, and a requirement for the LULUCF sector to offset the agricultural section by 2035 (i.e. net emissions of “land” sector would be zero)[33]. The revised regulation primarily focuses on targets, with implementation to meet these targets left to the Member States.
Existing certification mechanisms	● In Europe: Label Bas Carbone has a methodology for converting coppice forests into uneven-aged high stands. Also some overlap with Woodland Carbon Code. ● International methods include e.g. VCS, which has a general methodology for improved forest management, as well as a number of specific methods including reduced impact logging, fire management, forest conversion, avoided forest degradation, extension of rotation age and other.[34]

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[1] Griscom BW, Cortez R. The Case for Improved Forest Management (IFM) as a Priority REDD+ Strategy in the Tropics. Tropical Conservation Science. August 2013:409-425. doi:10.1177/194008291300600307

[2] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use: Chapter 4 Forestry Land. IPCC. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch04_Forest%20Land.pdf

[3] Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)]. In press.

[4] riscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

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[5] Nabuurs, G.; Delacote, P.; Ellison, D.; Hanewinkel, M.; Hetemäki, L.; Lindner, M. (2017): By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. In: Forests 8 (12), p. 484. DOI: 10.3390/f8120484.

[6] Böttcher, Hannes, Judith Reise, Klaus Hennenberg (2021) Exploratory Analysis of an EU Sink and Restoration Target. Öko-Institut e.V. Accessed 07.05.2021. Available: https://www.oeko.de/fileadmin/oekodoc/GP-Sink-Target.pdf

[7] Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J. et al. (2021): Land-based measures to mitigate climate change: Potential and feasibility by country. Glob Change Biol 27, 6025–6058. Online available at https://doi.org/10.1111/gcb.15873

[8] Griscom et al. 2017

[9] FAO (n.d.). Sustainable forest management. Hyperlink: http://www.fao.org/forestry/sfm/en/

[10] Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)]. In press.

[11] Nabuurs, GJ., Lindner, M., Verkerk, P. et al. First signs of carbon sink saturation in European forest biomass. Nature Clim Change 3, 792–796 (2013). https://doi.org/10.1038/nclimate1853

[12] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use: Chapter 4 Forestry Land. IPCC. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch04_Forest%20Land.pdf

[13] VCS (2020) METHODOLOGY FOR IMPROVED FOREST MANAGEMENT v1.0. https://verra.org/wp-content/uploads/2020/08/FFCP_Methodology_10Aug2020.pdf

[14] Badgley et al (preprint) Systematic over-crediting in California's forest carbon offsets program. bioRxiv preprint posted April 29, 2021. doi: https://doi.org/10.1101/2021.04.28.441870

[15] Griscom et al 2017 Online Supplement, Table S4

[16] Belenky, Maria, Graham, Peter, Langley, Claire (2018). CREATING NEGATIVE EMISSIONS - The Role of Natural and Technological Carbon Dioxide Removal Strategies. Hyperlink: https://climateadviser.wpengine.com/wp-content/uploads/2018/06/Creating-Negative-Emissions_Climate-Advisers_June-2018-copy.pdf

[17] CO_2 removal.org. (n.d.). Results.

[18] The Royal Society and Royal Academy of Engineering (2018).

[19] Lazdinis, M., Angelstam, P. & Pülzl, H. Towards sustainable forest management in the European Union through polycentric forest governance and an integrated landscape approach. Landscape Ecol 34, 1737–1749 (2019). https://doi.org/10.1007/s10980-019-00864-1

[20] VCS (2020) METHODOLOGY FOR IMPROVED FOREST MANAGEMENT v1.0. https://verra.org/wp-content/uploads/2020/08/FFCP_Methodology_10Aug2020.pdf

[21] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use: Chapter 4 Forestry Land. IPCC. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch04_Forest%20Land.pdf

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[22] EEA (2019) Annual European Union greenhouse gas inventory 1990–2017 and inventory report 2019. EEA/PUBL/2019/051. https://unfccc.int/documents/194921

[23] EU Parliament and EU Council (2018) REGULATION (EU) 2018/841 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG

[24] Böttcher, Hannes, Carina Zell-Ziegler, Anke Herold, Anne Siemons (2019) EU LULUCF Regulation explained Summary of core provisions and expected effects. ÖkoInstitut. https://www.oeko.de/fileadmin/oekodoc/Analysis-of-LULUCF-Regulation.pdf

[25] VCS (2020) METHODOLOGY FOR IMPROVED FOREST MANAGEMENT v1.0. https://verra.org/wp-content/uploads/2020/08/FFCP_Methodology_10Aug2020.pdf

[26] Badgley et al (preprint) Systematic over-crediting in California's forest carbon offsets program. bioRxiv preprint posted April 29, 2021. doi: https://doi.org/10.1101/2021.04.28.441870

[27] VCS (2016) VM0035 Methodology for Improved Forest Management through Reduced Impact Logging v1.0. https://verra.org/wp-content/uploads/2018/03/VM0035-RIL-C-Methodology-v1.0.pdf

[28] Badgley et al (preprint) Systematic over-crediting in California's forest carbon offsets program. bioRxiv preprint posted April 29, 2021. doi: https://doi.org/10.1101/2021.04.28.441870

[29] Badgley et al (preprint) Systematic over-crediting in California's forest carbon offsets program. bioRxiv preprint posted April 29, 2021. doi: https://doi.org/10.1101/2021.04.28.441870

[30] Belenky, Maria, Graham, Peter, Langley, Claire (2018). CREATING NEGATIVE EMISSIONS - The Role of Natural and Technological Carbon Dioxide Removal Strategies. Hyperlink: https://climateadviser.wpengine.com/wp-content/uploads/2018/06/Creating-Negative-Emissions_Climate-Advisers_June-2018-copy.pdf

[31] Nabuurs, G.; Delacote, P.; Ellison, D.; Hanewinkel, M.; Hetemäki, L.; Lindner, M. (2017): By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. In: Forests 8 (12), p. 484. DOI: 10.3390/f8120484.

[32] European Parliament (n.d.). The European Union and Forests. Hyperlink: https://www.europarl.europa.eu/factsheets/en/sheet/105/the-european-union-and-forests

[33] European Commission (2021) REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review. COM(2021) 554 final. https://ec.europa.eu/info/sites/default/files/revision-regulation-ghg-land-use-forestry_with-annex_en.pdf

[34] Verra (2021) VCS: Methodologies (webpage). Accessed 07.05.2021 https://verra.org/methodologies/

5.5 Fiche: Increase in soil organic carbon on mineral soils

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Scheme name	**Increase in soil organic carbon on mineral soils**[33]
Introduction	**Brief description of the solution** • Historically soil organic carbon (SOC) stocks on mineral soils under agricultural use have been decreasing. The underlying driver of historical losses is the negative balance of carbon inputs and outputs, resulting from simplification of crop rotations, removal of crop residues, separation of arable and livestock farming (reduced circularity at farm level), as well as soil erosion losses. Without changes to current management a large share of agricultural soils will continue losing C. [1] To maintain and increase SOC stocks, a positive balance of C inputs to soils compared to losses of C from soils is needed. Management practices that have the most significant potential for the maintenance and sequestration of SOC on mineral soils vary according to climate and biophysical conditions (soil type) and the production system involved. The largest potential is associated with: 1) cover cropping; 2) improved crop rotations (e.g. through inclusion of legumes and other nitrogen fixing crops); 3) deep rooting crops 4) conversion from arable to grassland; 4) organic farming; 5) and management of grazing land and grassland to increase SOC levels. • The potential may be highest where soils have been degraded (through intensive arable farming or overgrazing on grasslands), and where there are also sufficient nutrients available, such as Mediterranean or cool/temperate regions in Europe.[2] The potential may be lower in areas with lower precipitation and limited biomass growth due to water scarcity. The SOC sequestration potential and the most relevant practices in specific contexts need to be worked out at a more granular scale to take account of the spatial and temporal complexity, reflecting soil types, climate, and management conditions.[3] • For some options that increase SOC content (in particular, application of manure or compost) there is not a net removal of CO_2 from the atmosphere, but rather shifting of C within the system.[4] To ensure that SOC sequestration/maintenance has additionality, only practices which really sequester additional C (not move C in the system) should be allowed. This means cropping choices, but not organic inputs such as compost, manure, off-farm municipal compost, or biochar. On grasslands, improvement of grass sward can sequester additional SOC. **GHGs targeted** (and land use category) • Improvements in SOC levels (t CO_2eq) and the full GHG balance associated with soil management (i.e. CO_2, N_2O emissions associated with tillage or fertiliser application). The schemes in place have the option of full GHG balance, but this is not a compulsory requirement.

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[33] This fiche draws heavily on the Soil Organic Carbon Case Study (Lead author: Ana Frelih-Larsen, Ecologic Institute) from COWI, Ecologic Institute & IEEP (2021) Annexes to Technical Guidance Handbook - setting up and implementing result-based carbon farming mechanisms in the EU. Report to the European Commission, DG Climate Action on Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby https://op.europa.eu/s/o13a

Solution fiche template	
Section	Aspects covered
	Land use category: Cropland, grassland[34] **Examples of solutions already operational or in planning** - Numerous examples of existing methodologies and mechanisms in EU and overseas, including VCS Indigo Ag, Gold Standard, Australian Emissions Reduction Fund, among others (see Existing certification mechanisms below)
Potential	
Technology readiness level (TRL)	**Current TRL level** - The methods are already being implemented across Europe - TRL 9
Potential carbon removals	**Global potential** - The potential for increasing soil organic carbon in agricultural soils is highly variable and ranges between 0.5 and 7 t CO_2 per ha per year.[5] [6] [7] Estimates of the global technical SOC sequestration potential vary from 2,000 to 5,000 Gt CO_2 per year[8], where these estimates also include SOC sequestration component in avoided forest conversion, reforestation, peatland management, and coastal wetland restoration. The global estimate for SOC sequestration focused on cropland and grasslands, including cover cropping, avoided grassland conversion, grazing (optimal intensity, legumes in pastures), is 930 Mt CO_2eq/year.[9] **EU potential** - The estimates for additional SOC sequestration on EU cropland range from 9 Mt[10] to 58 Mt[11] to 116 Mt CO_2-e per yr.[12] The emissions per year are expected to decline by 39% for the total sum of mineral and organic soils even in absence of management changes.[13] **Constraints/interaction effects and assumptions:** - Saturation level and risk of reversal are limitations. The total realistic mitigation potential is difficult to assess as it is highly region and soil type specific. Clay soils and soils with lower current SOC content have a higher potential to sequester carbon. - There remain uncertainties around the estimates and the technologically achievable potential may be more constrained.[14] **System boundaries and lifecycle emissions considerations** - The complexity of climate, biophysical interactions (C and N cycles) and management practices, means that more robust estimates need high spatial resolution tools.[15] The choice of measures that are included in aggregate assessments varies, for example in some reduced tillage is still included, in others it is excluded.
Costs	**Current/projected costs** - Globally, implementation costs are estimated to be negative for around 20% of the potential and below US$ 40/ tCO_2eq^{-1} for the remainder, making such measures cost-effective compared to other GHG removal technologies.[16] However, the cost-effectiveness will vary significantly depending on the regional potential.[17] Reduced tillage may have cost-saving benefits for farmers (reduced fuel use), but the overall impact on SOC sequestration has been questioned. [18]

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[34] Grassland schemes focus on grasslands involved e.g. manure / slurry, improved grazing, which result in N20 and CH4 emissions from livestock management; these approaches must consider whole system impacts (e.g. include a farm audit) to capture full climate impacts.

Solution fiche template	
Section	Aspects covered
	- In the EU, some measures have higher opportunity costs (in particular, conversion from arable to grassland has high opportunity costs of changing from productive arable land). For example, the Bavarian RDP offers annual payments of 900Euro/ha for conversion of arable land to grassland in high erosion risk areas. - There are substantial regional variations in financial viability of SOC management measures. When changes to existing land use are considered, several measures are cost-effective. One assessment shows that crop rotations (with legumes) lead to improved farm gross margins in Spain but not in Scotland,[19] or cover crops can either improved farm margins although on the whole they would worsen the farm margins. **Energy demand** - Very low
Duration of removals / permanence	**Duration of removals & risks of reversibility** - Soil carbon retention time can be short to long-term, depending on management and climate, as well as biophysical conditions. In some soil types and some climatic conditions, the option can be a relatively short-term option, i.e. changes can be observed after 5 to 10 years, whilst in others very long time spans are needed to identify significant changes in soil carbon - Reversibility concerns are strong; management needs to be maintained to avoid reversal (e.g. the cropping patterns maintained, reduced tillage maintained – if land is ploughed up, reversal can be very quick). Climate change also poses a risk, as it will affect biomass growth: likely to negatively impact SOC in the Mediterranean, with potential for longer growing seasons in Northern Europe increasing SOC. **Conditions for permanence and options to manage impermanence** - The permanence of the option requires strict requirements around the time that land managers commit to maintaining the improved SOC levels.
Practical barriers	- Requirements around permanence (long commitment period) pose substantial barrier for uptake of commitments. - Lack of financial or regulatory incentives, risks associated with changes in production systems, lack of advisory services and available information on economic and productivity benefits of sequestration options are some of the key barriers to increased uptake of SOC sequestration measures.[20] - An important economic barrier is also land leasing, where farmers who lease land have little to no financial incentive to invest in maintaining or increasing SOC management.[21] - The maintenance and increase in SOC, even though it affects soil fertility, is generally not reflected in market prices, although it may be reflected in land cadaster price categories (e.g.[22]).
Suitability	

Solution fiche template	
Section	Aspects covered

MRV	• **Monitoring** of the soil organic carbon can be either 1) predicted via empirical / process models, or 2) measured via soil sampling. The monitoring of SOC via sampling at field level is very costly due to inherent heterogeneity at each field. There is also uncertainty associated with modelling / upscaling carbon sequestration rates from long-term agricultural experiments (LTEs) to EU level. Another source of uncertainty are inaccuracies in the assessment of current stock levels since estimates are based on a comparison to the existing stock and current stocks are not necessarily available with sufficient accuracy. Overall, it is likely that large shares of the effect of management change are undetected and invisible in MS national GHG inventories due to a lack of data on management practices for the whole time series which prevents MS from applying the Tier 1 method which would allow to report estimates for remaining Cropland and remaining Grassland. This implies that there might be a substantial lack of data to define accurate baselines.
	• The high costs of MRV may involve financial risks to farmers. Cost-benefit calculations per hectare improve with economies of scale, which may limit participation of smaller farmers[35]. Future developments are anticipated to reduce these costs.
	• In estimating SOC levels via modelling, sources of uncertainties are cumulative, need to be identified, and uncertainties estimated in quantitative terms. Uncertainties, for example, relate to: limited understanding of factors that influence SOC quantity and stability, time of sampling, sampling depth, processing of data, assumptions and input data in modelling of SOC stock changes, lack of data on current / existing levels of SOC.
	• New technological developments are emerging that have potential to reduce costs of MRV and increase certainty in assessments, for example (and not limited to):
	  ◦ proximal sensing (infrared spectroscopy – its potential reduction in accuracy can be countered by increased sample numbers and data quantity); [23]
	  ◦ isotope technology to enable detection of short-term changes; [24]
	  ◦ handheld field scanners[36].

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[35] The Australian experience indicates that the break-even size for grazing systems to participate in the Carbon Farming Initiative is currently 40 ha, with 100 ha being the commercial minimum.

[36] "The field reflectometer devices are integrated with an easy-to-use mobile app allowing users to collect spectral data and sample information while simultaneously recording their GPS position. These collated data are recorded in the app and automatically pushed to a cloud server whenever an internet connection is available. During model development, a subset of soil samples (~20%) are sent for traditional, highly accurate laboratory analysis, such as gas chromatography-mass spectrometry. This subset of data is then used to build machine learning models relating lab-measured soil carbon levels to the data collected with the field reflectometer. Additionally, freely available remote-sensing data are integrated into these models to improve estimates" (https://www.quickcarbon.org)

Solution fiche template	
Section	Aspects covered

	IPCC Guidelines[25]: IPCC GL 2019 Refinement Vol. 4 Ch. 2 Tier 1 approach for mineral soils calculate soil carbon storage in comparison to a reference carbon stock condition (defined as non-degraded, unimproved land under native vegetation). Calculations are then based in terms of transition from either reference or previous management state (where transition is assumed to occur linearly over 20 years). Depending on data availability, Tier 1 national accounts should consider different climate zones, soil types, and management practices, and apply default emissions factors. Tier 2 methods use nationally-specific management systems (at finer levels of categorisation), climate region and soil carbon categorisation, stock-change factors. Tier 3 methods consist of models developed to better capture annual variabilities (i.e. do not assume constant annual C stock change) and better capture long-term effects. Generally, IPCC uses a mineral soil carbon depth of 30cm.
	LULUCF Regulation[26]: The LULUCF Regulation requires Member States to account for emissions and removals from Managed Cropland and Managed Grassland which include changes in soil carbon. Managed cropland/grasslands are accounted for by using a net-net comparison to a historic baseline from 2005-2009
	Baseline setting methods (including existing baseline data options)
	• Typically, baseline is set:
	  • Through one-off on-site measurements to establish SOC stocks;
	  • This has the advantage of higher accuracy; but higher costs,
	  • Through a model-based calculation to estimate the baseline SOC stocks
	  • The calculation should be conservative and sufficiently robust for the specific context, farming system and management involved;
	  • It can be ground-truthed with measurements.
	• Verra offers the option of calculating baseline for the average of 3 years prior to start of the project, using local emissions factors and IPCC GL equations. Baseline is updated after 10years. For both methods it is important that information on historical management practices is available in order to understand and correctly calculate the project-induced carbon stock changes. However, in practice this historical data is limited if available at all. One year baselines can be misleading due to variability of soil carbon stocks across different sites (e.g. due to soil type, biophysical conditions) and over time, which makes it difficult to be confident about the impact of management measures on soil carbon stocks.
	Key references
	• IPCC Guidelines: Generic methodologies applicable to multiple landuses

Sustainability issues	**Co-benefits/negative externalities** • Maintaining and enhancing SOC stocks has important co-benefits by 1) improving soil structure and soil fertility; 2) increasing water retention capacity of soils and increasing resilience to climate change; 3) reducing soil erosion and 4) reducing soil compaction risk. The benefits related to soil quality and climate change adaptation are even more significant than the overall mitigation effect.[27] Because of uncertainties around mitigation potential and these significant co-benefits, some argue that the option should be primarily promoted as an adaptation option[28]. • There are concerns about possible unintended impacts on soil health if the SOC levels are increased by applying off-farm organic inputs, such as municipal compost or biogas digestate, which contain pollutants (hormones, microplastics, heavy metals). Biochar application also carries potential risks for soil health, while also not having a clear positive impact over the whole life cycle. This means that these practices with potential side effects should not be promoted / eligible for support as part of this option.

Solution fiche template	
Section	Aspects covered
	• There may be trade-offs with N_2O emissions; i.e. increase in SOC may cease to offset N_2O emissions when the system approaches a new SOC storage equilibrium.[29] There are also uncertainties about the impact on the water balance of agro-ecosystems, in particular under arid conditions.[30] If cover crops are removed using pesticides, there are potential negative impacts on water quality. **Leakage risks** • With conversion of arable land to grassland or extending the perennial phase of crop rotations, there is some risk of leakage because it can lead to a reduction in arable. [31] However, annual yields may also increase due to improved soil quality and soil health. Soil quality is also a consideration in terms of yield stability. Clear quantitative relationships between SOC levels and yields, however, are not available in literature. Clear estimates of risk of leakage associated with SOC sequestration are also not available in literature. • SOC sequestration is seen to have a positive impact on food security, not only through the maintenance of productive capacity of soils but also because it would mean that agriculture as a whole does not as drastically need to reduce the production levels, meaning that mitigation does not affect available calories as much.[32]
Governance aspects	**Stakeholders:** • Existing projects vary in the number of organisations involved. Some include collaboration among various stakeholders, others are very small. Typically the following types are included: ◦ an organisation that takes responsibility of the overall coordination of the project; ◦ an advisory branch that recruits farmers, and accompanies them in developing the management strategy for their farm; ◦ an auditing / monitoring branch that takes the samples and monitors the results; ◦ a scientific partner that provides guidance on the use of appropriate sampling protocols and supports potential estimates; ◦ one or more funding partners that provide funding for project development, and depending on the payment scheme, also the financing for farm payments; ◦ advisory parties to the project (for example, farmers' groups or environmental stakeholders). **Scale/size of projects** • Projects will vary depending on farm size. In European context, likely to be anywhere from 10-15ha to several hundred hectares. **Linkage to existing policies and measures/strategies/funding schemes** (e.g. CAP) • In previous CAP, various instruments were already available to support soil management and SOC improvements, in particular agri-environment-climate measure and organic farming measures, as well as investment measures (non-productive and machinery investments). In future CAP, conditionality (Good agriculture and environment conditions), the eco-schemes and agri-environment-climate measures can all support SOC management.
Existing certification mechanisms	Indigo AG: VCS (2020) VM0042 Methodology for Improved Agricultural Land Management, v1.0. https://verra.org/wp-content/uploads/2020/10/VM0042_Methodology-for-Improved-Agricultural-Land-Management_v1.0.pdf[33]. • GoldStandard Soil Organic Carbon Framework Methodology (published January, 2020 • Label Bas Carbon, France

Solution fiche template	
Section	Aspects covered
	- Several smaller EU initiatives, e.g: https://www.carbocert.de/, https://positerra.org/, https://www.oekoregion-kaindorf.at/humusaufbau.95.html

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[1] Wiesmeier, M., S. Mayer, J. Burmeister, R. Hübner, I. Kögel-Knabner (2020a). Feasibility of the 4 per 1000 initiative in Bavaria: A reality check of agricultural soil management and carbon sequestration scenarios. Geoderma, vol. 369, 114333.

[2] van Groenigen, J. W., C. van Kessel, B.A. Hungate, O. Oenema, D.S. Powlson, K. J. van Groenigen (2017), Sequestering Soil Organic Carbon: A Nitrogen Dilemma. Environmental Science Technology, vol. 51, pp. 4738–4739.

[3] FAO (2017) Unlocking the potential of soil organic carbon. Outcome Document. Food and Agriculture Organization of the United Nations, Rome.

[4] Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.-S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; Soudi, B.; Soussana, J.-F.; Whitehead, D. et al. (2020): The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. In: Ambio 49 (1), pp. 350–360. DOI: 10.1007/s13280-019-01165-2. https://link.springer.com/article/10.1007/s13280-019-01165-2

[5] Smith, P. (2016): Soil carbon sequestration and biochar as negative emission technologies. In: Glob Change Biol 22 (3), pp. 1315–1324. DOI: 10.1111/gcb.13178. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.13178

[6] Roe, S.; Streck, C.; Obersteiner, M.; Frank, S.; Griscom, B.; Drouet, L.; Fricko, O.; Gusti, M.; Harris, N.; Hasegawa, T.; Hausfather, Z.; Havlík, P.; House, J. et al. (2019): Contribution of the land sector to a 1.5 °C world. In: Nature Climate change 9 (11), pp. 817–828. DOI: 10.1038/s41558-019-0591-9.

[7] Poeplau, C.; Don, A. (2015): Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. In: Agriculture, Ecosystems & Environment 200, pp. 33–41. DOI: 10.1016/j.agee.2014.10.024.

[8] Bossio, D. A.; Cook-Patton, S. C.; Ellis, P. W.; Fargione, J.; Sanderman, J.; Smith, P.; Wood, S.; Zomer, R. J.; Unger, M. von; Emmer, I. M.; Griscom, B. W. (2020): The role of soil carbon in natural climate solutions. In: Nature Sustainability 3 (5), pp. 391–398. DOI: 10.1038/s41893-020-0491-z. https://www.nature.com/articles/s41893-020-0491-z

[9] Bossio, D. A.; Cook-Patton, S. C.; Ellis, P. W.; Fargione, J.; Sanderman, J.; Smith, P.; Wood, S.; Zomer, R. J.; Unger, M. von; Emmer, I. M.; Griscom, B. W. (2020): The role of soil carbon in natural climate solutions. In: Nature Sustainability 3 (5), pp. 391–398. DOI: 10.1038/s41893-020-0491-z. https://www.nature.com/articles/s41893-020-0491-z

[10] Frank, S.; Schmid, E.; Havlík, P.; Schneider, U. a.; Böttcher, H.; Balkovič, J.; Obersteiner, M. (2015): The dynamic soil organic carbon mitigation potential of European cropland. In: Global Environmental Change 35, pp. 269–278. DOI: 10.1016/j.gloenvcha.2015.08.004. https://www.researchgate.net/publication/282529832_The_dynamic_soil_organic_carbon_mitigation_potential_of_European_cropland

[11] Lugato, E.; Bampa, F.; Panagos, P.; Montanarella, L.; Jones, A. (2014): Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. In: Global change biology 20 (11), pp. 3557–

3567. DOI: 10.1111/gcb.12551. https://www.onlinelibrary.wiley.com/doi/full/10.1111/gcb.12551

[12] Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J. et al. (2021): Land-based measures to mitigate climate change: Potential and feasibility by country. Glob Change Biol 27, 6025–6058. Online available at https://doi.org/10.1111/gcb.15873

[13] Frank, S.; Schmid, E.; Havlík, P.; Schneider, U. a.; Böttcher, H.; Balkovič, J.; Obersteiner, M. (2015): The dynamic soil organic carbon mitigation potential of European cropland. In: Global Environmental Change 35, pp. 269–278. DOI: 10.1016/j.gloenvcha.2015.08.004. https://www.sciencedirect.com/science/article/pii/S095937801530025X

[14] Batjes, N. H. (2019): Technologically achievable soil organic carbon sequestration in world croplands and grasslands. In: Land Degradation & Development 30 (1), pp. 25–32. DOI: 10.1002/ldr.3209. https://onlinelibrary.wiley.com/doi/10.1002/ldr.3209

[15] Lugato, E.; Bampa, F.; Panagos, P.; Montanarella, L.; Jones, A. (2014): Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. In: Global change biology 20 (11), pp. 3557–3567. DOI: 10.1111/gcb.12551. https://www.onlinelibrary.wiley.com/doi/full/10.1111/gcb.12551

[16] Sykes, A. J.; Macleod, M.; Eory, V.; Rees, R. M.; Payen, F.; Myrgiotis, V.; Williams, M.; Sohi, S.; Hillier, J.; Moran, D.; Manning, D. A. C.; Goglio, P.; Seghetta, M. et al. (2020): Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. In: Global change biology 26 (3), pp. 1085–1108. DOI: 10.1111/gcb.14844. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.14844

[17] Alexander, P.; Paustian, K.; Smith, P.; Moran, D. (2015): The economics of soil C sequestration and agricultural emissions abatement. In: SOIL. 2015 (1), 2015, pp. 331–339. https://ui.adsabs.harvard.edu/abs/2015SOIL....1..331A/abstract

[18] Powlson, D. S.; Stirling, C. M.; Jat, M. L.; Gerard, B. G.; Palm, C. A.; Sanchez, P. A.; Cassman, K. G. (2014): Limited potential of no-till agriculture for climate change mitigation. Nature Climate Change, 4(8), 678-683. DOI: 10.1038/NCLIMATE2292.https://www.semanticscholar.org/paper/Limited-potential-of-no-till-agriculture-for-change-Powlson-Stirling/9a0c29601cfcc5c73b23e8ee9c8596b3af383207

[19] Glenk, K.; Shrestha, S.; Cairstiona F.E. Topp; Berta Sánchez; Ana Iglesias; Camilla Dibari; Paolo Merante (2017): A farm level approach to explore farm gross margin effects of soil organic carbon management. In: Agricultural Systems, pp. 33–46.

https://www.sciencedirect.com/science/article/pii/S0308521X16303614

[20] Claessens, L.; Frelih-Larsen, A.; Ittner, S.; Tarpey, J.; Olesen, J. E.; Graversgaard, M.; Madari, B. E.; Razafimbelo, T.; Kontoboytseva, A.; Nciizah, A.; Swanepoel, C.; Katto, C.; Verchot, L. et al. (2019): CIRCASA DELIVERABLE D2.2: "Assessing barriers and solutions to the implementation of SOC sequestration options". In collaboration with Arias Navarro, C., 2019. https://www.researchgate.net/publication/336218943_Assessing_barriers_and_solutions_to_the_implementation_of_SOC_sequestration_options

[21] Amundson, R.; Biardeau, L. (2018): Opinion: Soil carbon sequestration is an elusive climate mitigation tool. In: Proc. Natl. Acad. Sci. U.S.A. 115 (46), pp. 11652–11656. DOI: 10.1073/pnas.1815901115. https://www.pnas.org/content/115/46/11652

[22] Gebeltová, Z.; Malec, K.; Maitah, M.; Smutka, L.; Appiah-Kubi, S. N. K.; Maitah, K.; Sahatqija, J.; Sirohi, J. (2020): The Impact of Crop Mix on Decreasing Soil Price and

---

Soil Degradation: A Case Study of Selected Regions in Czechia (2002–2019). Sustainability, 12(2), 444. DOI: 10.3390/SU12020444. https://www.mdpi.com/2071-1050/12/2/444

[23] FAO (2017) Unlocking the potential of soil organic carbon. Outcome Document. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/i7268e/i7268e.pdf

[24] FAO (2017) Unlocking the potential of soil organic carbon. Outcome Document. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/i7268e/i7268e.pdf

[25] IPCC (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4 – Agriculture, Forestry and Other Land Use: Chapter 2 Generic methodologies applicable in multiple landuse categories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Generic%20Methods.pdf

[26] Böttcher, Hannes, Carina Zell-Ziegler, Anke Herold, Anne Siemons (2019) EU LULUCF Regulation explained Summary of core provisions and expected effects. ÖkoInstitut. https://www.oeko.de/fileadmin/oekodoc/Analysis-of-LULUCF-Regulation.pdf

[27] Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.-S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; Soudi, B.; Soussana, J.-F.; Whitehead, D. et al. (2020): The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. In: Ambio 49 (1), pp. 350–360. DOI: 10.1007/s13280-019-01165-2. https://link.springer.com/article/10.1007/s13280-019-01165-2

[28] Amundson, R.; Biardeau, L. (2018): Opinion: Soil carbon sequestration is an elusive climate mitigation tool. In: Proc. Natl. Acad. Sci. U.S.A. 115 (46), pp. 11652–11656. DOI: 10.1073/pnas.1815901115. https://www.pnas.org/content/115/46/11652

[29] Lugato, E.; Leip, A.; Jones, A. (2018): Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. Nature Climate Change, 8(3), 219-223. DOI: 10.1038/S41558-018-0087-Z.

[30] Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.-S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; Soudi, B.; Soussana, J.-F.; Whitehead, D. et al. (2020): The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. In: Ambio 49 (1), pp. 350–360. DOI: 10.1007/s13280-019-01165-2. https://link.springer.com/article/10.1007/s13280-019-01165-2

[31] Thamo, T.; Pannell, D. J. (2016): Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage, and permanence. In: *Climat Policy* (16:8), pp. 973–992. https://www.researchgate.net/publication/283165092_Challenges_in_developing_effective_policy_for_soil_carbon_sequestration_perspectives_on_additionality_leakage_and_permanence

[32] Frank, S.; Havlík, P.; SOUSSANA, J.-F.; Wollenberg, E.; Obersteiner, M. (2017): The potential of soil organic carbon sequestration for climate change mitigationand food security (CCAFS Info Note), 2017. https://ccafs.cgiar.org/resources/publications/potential-soil-organic-carbon-sequestration-climate-change-mitigation

[33] VCS (2020) VM0042 Methodology for Improved Agricultural Land Management, v1.0. https://verra.org/wp-content/uploads/2020/10/VM0042_Methodology-for-Improved-Agricultural-Land-Management_v1.0.pdf

5.6 Fiche: Biochar

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Scheme name	**Biochar**
Introduction	**Brief description of the solution** • Put simply, biochar is charcoal that is incorporated into soils. The biochar is produced by heating (>350°C) biomass either in absence of oxygen (called pyrolysis), or controlled low-oxygen conditions (gasification). Biomass can come from wood, organic waste, or other natural feedstocks. The resulting biochar is then applied to soils, where in the right conditions can remain as a stable store of carbon for hundreds of years. **GHGs targeted** (and land use category) • Carbon dioxide (CO_2) **Land use categories:** • For biomass feedstock: forest land, cropland; • For application: cropland, grassland **Examples of solutions already operational or in planning** • In 2020, in Europe there were 72 biochar production plants in operation, capable of producing 20,000t of biochar annually.[1] Currently, 69% of European production (including Switzerland) occurs in four countries (in decreasing order of production volume): Germany, Sweden, Switzerland, Austria.[2]
Potential	
Technology readiness level (TRL)	**Current TRL level** • Biochar production: 9 • Biochar application: 7-8 – still missing large-scale trials of applying biochar in field conditions.[3]

Potential carbon removals	**Global potential**
	• Wide range of potential global potentials. IPCC (2019) estimate 0.03-6.6 Gt CO_2-e/yr (for papers with a timescale of 2030-2050).[4]
	• Griscom et al (2017) estimate that biochar could deliver 1.1 Gt of carbon removals by 2030, assuming that approx. 80% of biochar carbon persists for 100+ years and no impact on methane or nitrous oxide emissions. [5]
	• Estimates of future potential are higher than 2030/2050 estimates. Fuss et al. (2018) estimate a "sustainable"[37] range of 0.5-2Gt CO_2-e/yr in 2050, while longer term scenarios are higher, e.g. up to 2.6-4.8 GtCO_2-e/yr in 2100.[6]
	EU potential
	• Limited information on EU potential. National potential for biochar has been identified in two national strategies:[7]
	  ◦ Netherlands: 1 Mt CO_2-e/yr (2050)
	  ◦ Ireland: 15 Mt CO_2-e/yr (2050)
	• Roe et al (2021) estimate that in Europe, biochar produced using crop residues could mitigate 79 Mt CO_2-e/yr (average 2020-2050).[8]

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[37] i.e. limited by availability of feedstock

Solution fiche template	
Section	Aspects covered
	Constraints/interaction effects and assumptions ● Biochar extent depends on availability of feedstock biomass. For example, Griscom et al (2017) restrict their models to an availability of 30 EJ/yr of biomass, which accords to half of current unused above-ground crop residues.[9] This can be in competition with other carbon removal solutions, such as BECCS. ● Calculation of potential also depends on assumptions around interaction of biochar with soils and specific local conditions.[10] The reported studies take different approaches, for example, Griscom et al (2017) assumes no methane or nitrous oxide impacts. [11] ● If biochar is applied at high rates, it darkens the soil and can lead to potential albedo effect, where the decreased radiation of the sun impacts the mitigation effect in terms of global warming.[12] **System boundaries and lifecycle emissions considerations** ● Key factors determining lifecycle emission of biochar include: 1) biomass preparation (type and collection of biomass, transportation and processing); 2) pyrolysis process (including the production and avoided emissions associated with side-products such as syngas or bio-oil); 3) application on land and soil carbon impacts.[13] ● The full lifecycle climate impacts of 1 tonne of biochar are difficult to generalise due to the diverse sourcing, production, and application contexts. In some cases the full lifecycle emission have been found to be net positive.[14] ● Biochar application affects soil carbon storage (referred to as the "priming effect"): the impact is highly uncertain, depending on soil properties, biochar characteristics, and application rates. Overall, the priming effect is expected to be slightly negative (i.e. decrease soil carbon storage within the soil) (especially in short term) though potentially positive (i.e. increasing soil carbon storage within the soil) in the longer term (more than 10 years).[15] However, the science behind priming is considered relatively uncertain in many contexts; greater research needed.[16] The pathways behind biochar impact on soil are still unclear and are likely to differ in different contexts (i.e. different biochar, different application rates, different soils): positive priming is theorized to occur by having biochar support microbial growth (by supporting co-metabolism of microbes in the soil or by providing habitats for micro-organisms), or by favorably changing soil pH, water holding capacity, or nutrient availability; negative priming is theorized to occur by absorbing matter into the biochar or by stabilizing soil matter (and therefore blocking its uptake and storage of carbon)[17]. ● Biochar also affects methane and nitrous oxide emissions. However, the impacts depend on context (e.g. prior condition of soil, where degraded lands will see higher soil carbon increases), crop production (e.g. applying biochar to rice paddies appears to decrease nitrous oxide emissions but increase methane, with the inverse true in pasture systems).[18] The uncertainties are high. The mechanisms by which biochar interacts with methane are highly uncertain, in dry soils the proposed mechanism is that biochar increases soil aeration and therefore methane capture; alternatively, in wet soils, biochar can act as a source of methane in some contexts[19].
Costs	**Current/projected costs**

Solution fiche template	
Section	Aspects covered
	- High range and uncertainty regarding costs. The wide range of projected costs is due to importance of local context and diverse biomass sourcing, biochar production, and application costs. The reported ranged commonly includes negative costs as well as high positive costs. For example, Smith (2016) reports costs of -830 – 1200USD/t CO_2 (where negative costs imply a net benefit for the making and application of biochar), though these rely on optimistic estimates of the co-benefits of biochar application. - Fuss et al (2018) conclude mean prices of 90-120USD t/CO_2. [20] - Puro.earth market prices one tonne of removals through biochar at 97-150€/tCO_2-eq[21] - Cost estimates depend significantly on impacts on agronomic benefits.[22] Some studies have found that soil carbon application in the tropics can increase yields by 10-25%, while in temperate climates yield impacts are moderate/trivial.[23], [24] More studies in EU context are necessary. **Energy demand** - Biochar production can produce electricity (and/or heat[25]) as a by-product of the pyrolysis process. The amount depends on the specific method used to produce biochar. Suggested range approximately 30-50 GJ/tC of biochar.[26]
Duration of removals / permanence	**Duration of removals & risks of reversibility** - Biochar is a relatively stable, long-lasting store of carbon. A 2014 survey estimated mean residence time of 107 years, with a range of 3-891 years; decomposition rates are lower (permanence is higher) with higher pyrolysis temperature and higher soil clay content.[27] Modelling studies commonly assume that 80% of carbon persists beyond 100 years[28], though other studies estimate rates of 97%[29]. Risk of reversibility is considered low.[30] There are few long-lasting studies of biochar application and permanence - existing studies rely on short time periods and modelling – therefore, there are uncertainties. **Conditions for permanence and options to manage impermanence** - Permanence is higher for biochar produced at higher temperatures. Soil condition also matters: wetter soils and cooler temperatures are associated with longer lasting biochar storage.[31] Accordingly, options for increasing permanence is to require higher pyrolysis temperatures (e.g. higher than 650 degrees C), and eligibility restrictions to dry, low temperature soils/locations.
Practical barriers	- Biomass availability: there is potential for competition with in particular BECCS for biochar feedstock. [32] - Biochar production facilities (in the EU, 2020 production was only 20,000t of biochar annually, across 72 facilities). This has doubled since 2018.[33] - Relatively high scientific uncertainty about the impacts of applying biochar to soils (in terms of impact on soil carbon, as well as yield, soil health, etc.). - Biochar application depends on wide scale uptake by farmers, which will rely on training and knowledge sharing. - Multiple stages in biochar process make it potentially challenging for MRV and governance (e.g. feedstock sourcing, biochar production, biochar application).
Suitability	

Solution fiche template	
Section	Aspects covered
MRV	• **MRV of biomass sourcing and production:** It is relatively straightforward to carry out MRV on biochar feedstock and the production of biochar. Puro.earth[34] has developed a methodology for certifying biochar removals. The method relies on European Biochar Certificate guidance[35] to identify a positive list of biomass feedstock sources (limited to waste products e.g. wood processing offcuts, manure, etc). The method then focuses on the production process, setting minimum standards for the production e.g. fossil-fuel heating is prohibited, a minimum of 70% of excess waste-heat must be utilised (e.g. to dry biomass or for district heating); these elements are assessed by an independent verifier inspecting the production facility. The method also sets minimum standards for the resulting biochar, e.g. that stable carbon content must be over 50%, and that certain indicators of stability exceed minimum standards (e.g. the molar H/Corg ratio, an indicator of the degree of carbonisation and therefore of the biochar stability must be less than 0.7). The quantification of removals is calculated using lifecycle analysis, including everything up to and including the biochar production (feedstock, transport and processing, production process); these methods result in estimates that approx. 3 t CO_2-e are removed per tonne of biochar. The method excludes subsequent transport of biochar and, most significantly, emissions from end use (e.g. application of biochar); the only limit is that biochar cannot be used for energy. • **MRV of biochar application:** Is more uncertain, as illustrated by American Carbon Registry rejecting a biochar methodology due to unacceptable uncertainty regarding the stability of soil carbon sequestration in fields treated with biochar. The method had proposed modelling this based on the molar H/Corg ratio, but experts concluded that this was insufficiently robust.[36] **IPCC Guidelines**[37]: IPCC GL 2019 Refinement Vol. 4 Appendix 4. The 2019 revision of the 2006 IPCC guidelines included a specific annex focused on estimating biochar impacts on soil carbon. Biochar sequestration cannot be calculated in the same way as other soil carbon calculations as the timescales are considerably longer (more than 100 years for biochar, compared to standard IPCC GL timelines of 20 years). The annex provides a basis for developing a tier 1 methodology in the future. It is a top-down method consisting of two key calculation elements: 1) organic carbon content factor of biochar, which is calculated based on the biochar production i.e. the feedstock (e.g. animal manure, wood, etc.) and the production method (pyrolysis or gasification)[38]; 2) the fraction of biochar remaining after 100 years, which the method proposes depends only on the temperature of pyrolysis[39]. The method assumes that application rate does not matter. • **LULUCF Regulation**: Theoretically it would be included in the accounting (in the related land accounting category in which the biochar is applied) as it is not explicitly excluded according to the Regulation. However, so far no MS are known that explicitly report biochar application in their national GHG inventories. • **Baseline setting methods** (including existing baseline data options)

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[38] The default values for organic carbon content for biochar produced through pyrolysis range from 0.35-0.77, with 95% confidence interval width of approx. 50%

[39] Values: Low temp 350-400°C (0.65), medium 450-600°C (0.80), and high >600°C (0.89) with 95% confidence interval width of approx. 13%

Solution fiche template	
Section	Aspects covered
	• If methods do not quantify soil carbon impacts (i.e. focus exclusively on soil carbon content of biochar), then baseline of zero is appropriate. If soil carbon (and impact of other GHG gases) are to be considered, see Soil Carbon Fiche for baseline methods. **Key references** • IPCC (2019 IPCC GL 2019 Refinement Vol. 4 Appendix 4 Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development • Puro (2020) CO2 Removal Marketplace GENERAL RULES: Annex A Biochar Methodology.
Sustainability issues	**Co-benefits/negative externalities**[38] • **Co-benefits:** Improved soil structure, water holding capacity, reduction in nutrient losses from soils, stabilisation of heavy metals and other toxins. However, these are expected to be relatively small. • Unclear impacts on worms and soil fauna, or broader impacts on biodiversity.[39] • Given long lifetime of soil carbon, precautionary approach should be applied until better scientific understanding of side-effects and long-term impacts. • As by-products, the production of biochar results in bio-oil or –gas, which can be used to offset fossil fuel use, along with heat, which can offset other (carbon-intensive) heating sources. Together these by-products can increase the positive climate impact of biochar in some settings[40]. **Leakage risks** • Biochar production: leakage can occur if biochar biomass production competes with other land uses. However, if biochar is produced exclusively from waste biomass (e.g. wood processing, crop offcuts or manure), this can be avoided. Note: in terms of potential, Griscom et al 2017) estimate that globally approximately 1.1 Gt CO_2-e/yr can be achieved exclusively using waste feedstock, implying higher levels of potential are associated with leakage risk through land competition.[41] • Biochar application: as biochar can be applied to existing crop/grasslands without displacing existing land-use, biochar application poses no leakage risks. Some studies find that biochar can be applied at rates of 30-60t/ha, which would allow the estimated global potential of approx. 2 Gt. CO_2-e/yr to be applied on existing global area of crop/grassland.[42]

Governance aspects	**Stakeholders:**
	• Different stakeholders are involved at different stages:
	  ◦ Feedstock: Feedstock can be sourced from existing agricultural operations e.g. wood processing, crop or forest offcuts, animal manure, among others.
	  ◦ Production: The European Biochar Industry identifies 72 plants in Europe in 2020, ranging in size from micro (<100t) – very large (>2000t). [43]
	  ◦ Application: Application carried out by individual landowners.
	Scale/size of projects
	• Depends on point of obligation:
	  ◦ Biochar production point of obligation: annual output of biochar plants ranges from <100t - >2000t. [44]
	  ◦ Application point of obligation: Studies suggest application rates of 30-60t biochar/ha. [45]
	Linkage to existing policies and measures/strategies/funding schemes (e.g. CAP)

Solution fiche template	
Section	Aspects covered
	• CAP: Land-use practices in the EU are driven by the Common Agricultural Policy, the shape of which is currently being negotiated for the period 2021-2027. We could find no evidence of biochar support in existing discussions or previous iterations of the CAP.[46] • EU Fertilising Products Regulation: In 2019, biochar was approved for use on organic farms in the EU.[47]
Existing certification mechanisms	• Puro.earth: Has seven different sellers of biochar credits, with prices ranging from €96-150/tCO$_2$-e. Total amount of removals is unclear. • Other: Verra is creating a biochar methodology for VCS, to be ready for public review in Q4 2021.[48]

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[1] European Biochar Industry (2021) European Biochar Market Report 2020. Accessed 10.05.2021. https://www.biochar-industry.com/wp-content/uploads/2021/02/Market-Overview_public_2021-02-17_V1.01.pdf

[2] European Biochar Industry (2021) European Biochar Market Report 2020. Accessed 10.05.2021. https://www.biochar-industry.com/wp-content/uploads/2021/02/Market-Overview_public_2021-02-17_V1.01.pdf

[3] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

[4] Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)]. In press.

[5] riscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

[6] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

[7] NEGEM (2021) D8.1 Stocktaking of scenarios with negative emission technologies and practices. Accessed 11.05.2021. https://www.negemproject.eu/wp-content/uploads/2021/02/NEGEM_D_8_1-1.pdf

[8] Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J. et al. (2021): Land-based measures to mitigate climate change: Potential and feasibility by country. Glob Change Biol 27, 6025–6058. Online available at https://doi.org/10.1111/gcb.15873

[9] Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

[10] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

---

[11] Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

[12] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

[13] Homagain, K., Shahi, C., Luckai, N. et al. Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. For. Ecosyst. 3, 21 (2016). https://doi.org/10.1186/s40663-016-0081-8

[14] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[15] Wang J, Xiong Z and Kuzyakov Y 2016 Biochar stability in soil: meta-analysis of decomposition and priming effects GCB Bioenergy 8. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12266

[16] Tammeorg, P., Bastos, A.C., Jeffery, S., Rees, F., Kern, J., Graber, E.R., Ventura, M., Kibblewhite, M., Amaro, A., Budai, A., Cordovil, C.Md.S., Domene, X., Gardi, C., Gasco, G., Hoŕ ak, J., Kammann, C., Kondrlova, E., Laird, D., Loureiro, S., Martins, M. A.S., Panzacchi, P., Prasad, M., Prodana, M., Puga, A.P., Ruysschaert, G., Sas- Paszt, L., Silva, F.C., Teixeira, W.G., Tonon, G., Delle Vedove, G., Zavalloni, C., Glaser, B., Verheijen, F.G.A., 2017. Biochars in soils: towards the required level of scientific understanding. J. Environ. Eng. Landsc. Manag. 25, 192–207. https://doi.org/10.3846/16486897.2016.1239582.

[17] Singh, B., Cowie, A. Long-term influence of biochar on native organic carbon mineralisation in a low-carbon clayey soil. Sci Rep 4, 3687 (2014). https://doi.org/10.1038/srep03687

[18] Smith, Pete (2016) Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology (2016) 22, 1315–1324, doi: 10.1111/gcb.13178

[19] Jeffery, S., Verheijen, F. G. A., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. Soil Biology and Biochemistry, 101, 251–258. doi:10.1016/j.soilbio.2016.07.021

[20] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

[21] puro.earth (2021) Puro.earth Carbon Removals (webpage). Accessed 11.05.2021. https://puro.earth/services/

[22] EASAC (2018) Negative emission technologies: What role in meeting Paris Agreement targets? EASAC policy report 35

[23] Morgan, Holly, Saran Sohi and Simon Shackley (2020) Biochar: An Emerging Carbon Abatement and Soil Management Strategy. In: Oxford Research Encyclopedia of Environmental Science, Oxford University Press.

[24] Hepburn, Cameron, Ella Adlen, John Beddington, Emily A. Carter, Sabine Fuss, Niall Mac Dowell, Jan C. Minx, Pete Smith & Charlotte K. Williams (2019) The technological and economic prospects

for CO_2 utilization and removal. Nature. Vol 575.

[25] Azzi, E. S., Karltun, E., & Sundberg, C. (2019). Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm. Environmental Science & Technology. doi:10.1021/acs.est.9b01615

[26] Smith, P. (2016) Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22(3), 1315–1324. doi:10.1111/gcb.13178

---

[27] Wang J, Xiong Z and Kuzyakov Y 2016 Biochar stability in soil: meta-analysis of decomposition and priming effects GCB Bioenergy 8. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12266

[28] Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

[29] Wang J, Xiong Z and Kuzyakov Y 2016 Biochar stability in soil: meta-analysis of decomposition and priming effects GCB Bioenergy 8. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12266

[30] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[31] Wang J, Xiong Z and Kuzyakov Y 2016 Biochar stability in soil: meta-analysis of decomposition and priming effects GCB Bioenergy 8. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12266

[32] Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters (13) 06. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f

[33] European Biochar Industry (2021) European Biochar Market Report 2020. Accessed 10.05.2021. https://www.biochar-industry.com/wp-content/uploads/2021/02/Market-Overview_public_2021-02-17_V1.01.pdf

[34] puro (2020) CO_2 Removal Marketplace GENERAL RULES: Annex A Biochar Methodology. Accessed 11.05.2021 https://static.puro.earth/live/uploads/tinymce/Puro-Rules-Methodologies_v1.4_2020_May_12.pdf

[35] European Biochar Certificate (undated) Positive list of permissible biomasses for the production of biochar. Accessed 11.05.2021. Available http://www.european-biochar.org/biochar/media/doc/feedstock.pdf

[36] American Carbon Registry (undated) A Methodology for Biochar Projects: Scientific Peer Review Comments and Responses. Accessed 11.05.2021. https://americancarbonregistry.org/carbon-accounting/standards-methodologies/methodology-for-emissions-reductions-from-biochar-projects/biochar-methodology-scientific-peer-review-comments-and-response-final.pdf

[37] IPCC (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4 – Agriculture, Forestry and Other Land Use: Appendix 4 Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Ap4_Biochar.pdf

[38] Expert Group for Technical Advice on Organic Production (2018) Final report on fertilisers. Directorate-General for Agriculture and Rural Development. Accessed 11.05.2021 https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/final-report-egtop-fertilizers-iii_en.pdf

[39] Tammeorg, P., Bastos, A.C., Jeffery, S., Rees, F., Kern, J., Graber, E.R., Ventura, M., Kibblewhite, M., Amaro, A., Budai, A., Cordovil, C.Md.S., Domene, X., Gardi, C., Gasć o, G., Hoŕ ak, J., Kammann, C., Kondrlova, E., Laird, D., Loureiro, S., Martins, M. A.S., Panzacchi, P., Prasad, M., Prodana, M., Puga, A.P., Ruysschaert, G., Sas-Paszt, L., Silva, F.C., Teixeira, W.G., Tonon, G., Delle Vedove, G., Zavalloni, C., Glaser, B., Verheijen, F.G.A., 2017. Biochars in soils: towards the required level of scientific understanding. J. Environ. Eng. Landsc. Manag. 25, 192–207. https://doi.org/10.3846/16486897.2016.1239582.

[40] Brown, R.C. The Role of Pyrolysis and Gasification in a Carbon Negative Economy. Processes 2021, 9, 882. https://doi.org/ 10.3390/pr9050882

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[41] Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017 Oct 16;114(44):11645–50. Available from: http://dx.doi.org/10.1073/pnas.1710465114

[42] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[43] European Biochar Industry (2021) European Biochar Market Report 2020. Accessed 10.05.2021. https://www.biochar-industry.com/wp-content/uploads/2021/02/Market-Overview_public_2021-02-17_V1.01.pdf

[44] European Biochar Industry (2021) European Biochar Market Report 2020. Accessed 10.05.2021. https://www.biochar-industry.com/wp-content/uploads/2021/02/Market-Overview_public_2021-02-17_V1.01.pdf

[45] The Royal Society and Royal Academy of Engineering (2018) Greenhouse Gas Removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[46] see e.g. Guyomard, H., Bureau J.-C. et al. (2020), Research for AGRI Committee – The Green Deal and the CAP: policy implications to adapt farming practices and to preserve the EU's natural resources. European Parliament, Policy Department for Structural and Cohesion Policies, Brussels. https://www.europarl.europa.eu/RegData/etudes/STUD/2020/629214/IPOL_STU(2020)629214_EN.pdf

[47] European Parliament and Council (2019), Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2, Brussels

[48] Verra (2021) Development of New Biochar Methodology Underway (webpage). Accessed 11.05.2021. https://verra.org/development-of-new-biochar-methodology-underway/

5.7 Fiche: Biomass in Buildings

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Solution name	**Biomass in buildings**

Introduction	**Brief description of the technology**
	- Use of sustainably produced biomass materials in buildings and construction as a means to extend the time of carbon storage compared to short-lived uses. Biomass can be sourced from sustainable models of forestry and cultivation, e.g. timber and bamboo for structural foundations, wood, cob, flax, linen, hemp and other forms of cellulose fibre for building envelope insulation. Using biomass in the built environment enables extending the longevity and security of carbon storage, generated through forestation and agriculture[1].
	GHGs targeted (and land use category, if appropriate)
	- Carbon Dioxide (CO_2)
	Examples of solutions already operational or in planning
	- Limited examples of biomass in building projects with various carbon removal claims (estimated using different methods), but a fast-growing activity. The landscape of Marked-Based Schemes to reduce the GHG emissions associated with the construction of buildings can be summarised as follows:
	  - A significant number of initiatives define and certify the overall sustainability performance of a building over its lifecycle. Among these, Level(s) is the recent EU-based and EU-sponsored holistic initiative, competing with the global, privately managed BREEAM scheme set up a decade earlier. In addition to these two trans-national initiatives, several have been developed at national level, such as HQE Bâtiment Durable in France, BES 6001 in the United Kingdom, Greencalc+ and GPR Gebouw in the Netherlands;
	  - Two initiatives (Label Bas-Carbone and BenchValue) focus on the quantitative evaluation and certification of the benefits in terms of saved GHG emissions of a broad range of actions (Label Bas-Carbone) and more specifically of the substitution of mineral-based construction materials with wood-based alternatives (BenchValue). These two schemes create the technical base for a market in carbon credits, but do not develop such a market;
	  - Two initiatives (Puro.Earth and Carbomark) have moved to the ultimate stage of establishing an exchange market for carbon credits, whereby they create a platform to match the supply of carbon credits by companies that remove GHG emissions with the demand by companies eager to compensate theirs.
	  - Brock Commons Tallwood House, construction management by Urban One Builders (Canada): 18-story mass timber hybrid residence at University of British Columbia, completed in 2017, wooden inputs (Cross Laminated Timber (CLT) and Glulam): 2,233 m3, avoided and sequestered CO_2 estimated using the Wood Carbon Calculator for Buildings: 679 tCO_2 avoided and 1,753 tCO_2 sequestered over the life cycle[1],[2],[3],[4].
	  - Oakwood Tower in London, Cambridge University's Department of Architecture, PLP Architecture, Smith and Wallwork (UK) - proposal: 80-story wooden building, wooden inputs: 65,000 m3 of structural timber (softwood), estimated sequestration of 50,000 tCO_2 (no indication on the method)[5],[6],[7].

Solution fiche template	
Section	Aspects covered
	• Dalston Works, Waugh Thistleton Architects, Ramboll, B&K Structures (UK): 10-story wooden building, largest CLT project globally, material inputs (CLT): approx. 3,850 m3, sequestered CO_2 estimated: 2,866 tCO_2 (no indication on the method)[8]. • Mjøstårnet, Brumunddal (Norway): 18-story wooden building, wooden inputs (CLT, Glulam, Trä8), Moelven subcontractor for structural timber components: Follows the Puro.earth methodology requirements, audited for carbon removals of 541 kg/m3 with a 10% safety buffer and permanence of 50 years [9],[10]. • The French Plan "Immeubles de Grande Hauteur en bois" (High-rise Timber Building Plan) plan aims to demonstrate the feasibility of high-rise timber buildings, in a very concrete way. It also aims to showcase the most appropriate technical solutions. The plan was implemented by the ADIVbois Association (Association for the Development of Wooden Buildings), a dedicated organisation created in 2016 in the context of the governmental initiative, "New Industrial France". The association's work made it possible to support demonstration projects through technical support, better structuring of the sector, the promotion of innovations for their normative and regulatory appropriation, and their industrialisation. ADIVbois is still continuing its work through the regrouping of major construction players in terms of high-rise timber construction and the production of guidelines, the financing of technical tests for the industrialisation of suitable construction systems, among other initiatives.
Potential	
Technology readiness level (TRL)	**Current TRL level** • TRL: 8-9 [11], [12] • Qualitative discussion of development (e.g. expected TRL level by 2030, 2050, development risks, uncertainties) • The solution is technically scalable, but supply and demand are uncertain[1]. • Recently, treatments have been developed to improve stability, durability as well as resistance to fungal decay and fire in wood for construction[1]. • Recent years have shown an uptake in timber building and increasingly ambitious projects. In North America and Scandinavia timber constructions are widespread[1]. • 60% of infrastructure required in 2030 not constructed yet, which could be an opportunity for carbon storage through biomass in buildings if the right incentives are introduced[1].
Potential carbon removals	**Technical and/or realistic potential** (i.e. t CO_2-e removals, Europe-wide, annual – now, future) and total potential removal **Global removal potential** estimate reported in several sources (but lack of information on estimation method): 0.5 to 1 $GtCO_2$/year. • Global CO_2 utilisation potential in wood products in 2050: 70 to 1,100 $MtCO_2$/year[13]. • Building with biomass is widely used in construction and at commercial scales, but represents a small fraction compared to conventional construction with concrete and steel[14],[1]. • Uncertain cumulative carbon removal potential[12]. **EU-level:** • UK's national strategy incl. 0.4 $MtCO_2$/year by 2050[15].

Solution fiche template	
Section	Aspects covered
	- In a scenario based on strong increase in material wood use, additional removal potential to baseline scenario could result in carbon removal of 14 $MtCO_2$/year in 2021-2030[16] **Constraints/interaction effects and assumptions** (e.g. land use requirements, contingencies reg. other solutions) - Delivering the technical potential would require allocating a large share of the world's sustainable wood to be used in the built environment[1]. **Brief description of calculation method and uncertainties** - Global CO_2 utilisation potential in wood products in 2050 estimated as the share of volumes of CO_2 sequestered via afforestation/reforestation in 2050 that flow into industrial roundwood products; upper end estimate also includes the volumes of industrial roundwood products that are sustainably harvested from existing forests and plantations[13]. **System boundaries and lifecycle emissions considerations** - Energy demand for harvesting, treating, processing, and transporting biomass, which could reduce the carbon benefits[1]. - End-of-life management of wooden infrastructure: materials should be repurposed, reused or burnt with CCS to keep the carbon sequestered. This could prove challenging at large scale deployment[1], [17]. - Many LCAs of cradle-to-gate indicate that the manufacturing stage accounts for more carbon emissions than raw material extraction and transportation[17].
Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs (including energy demand) - Low cost, negligible additional costs in comparison with traditional building materials[18], [12]. - Breakeven cost (cost in 2015 USD/tCO_2 adjusted for revenues, by-products, and any CO_2 credits or fees, likely to underestimate the ability to achieve economies of scale): industrial roundwood products associated with a breakeven cost estimated: − 40 USD to 10 USD/tCO_2[13]. **Projected future costs** - Lack of understanding of potential cost reductions but expected to decrease with more investment and market growth[18].
Duration of removals / permanence	**Duration of removals & risks of reversibility** - Carbon storage throughout the lifespan of a building: 50-100 years[12], [13], [17], [18]. - Lifespan depends on the specific materials and application e.g. timber and bamboo for structural foundations and hemp and other forms of cellulose fibre for insulation[1]. - High likelihood of release due to disturbance, combustion, or decomposition[13]. - Risk of reversibility at end-of-life depending on how the building is decommissioned. If materials remain in use or burned with CCS, continued storage is likely[1], [18]. **Conditions for permanence & options to manage impermanence** - Reversal can be countered by several end-of-life options: reuse, repurpose, combustion with CCS or conversion to biochar[1], [12], [17], [18].

Solution fiche template	
Section	Aspects covered
Practical barriers	**Other barriers** that would limit the wide-scale uptake/ implementability of this solution (e.g. legal, land area requirements, public acceptance, ownership, economic considerations etc.) - Low demand for wooden building products in some countries[1], [11], [14]. - Limited and slow build-up of skills and expertise with timber building along the whole value chain[1], [14]. - Lack of sawmill equipment - Need to correct biased regulation, which favours fossil-fuel based materials: heterogeneity of fire safety legislation, - Difficult access to biomass from demolition sites - Need for regulatory support, building standards for wood constructions and modification of building requirements to ensure fire safety and quality assurance[1], [14] - Need for incentives for redirecting biomass currently used by other industries, biomass currently not recycled and redirecting exports towards domestic production - Need for afforestation incentives and sustainable forest management due to shortages of sustainable biomass supply[1], [111]. - Issues of public pre-conceived notions about wooden building (durability, fire hazard and moisture) in countries where building with biomass is not commonplace, mostly related to fire risk; but new treatments and solutions being developed that reduce or remove this barrier[1], [12], [5]. - Need for cooperation between business and government for further deployment and to avoid and reduce obstacles in the construction industry[1]
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** - Carbon removals from biomass in buildings connected to biogenic storage function of harvested wood products, for which the IPCC GL and EU LULUCF set accounting approaches. The IPCC GL lists different approaches which treat differently the long-term biogenic carbon storage function of wood products. The EU LULUCF directive requires Member States to account for emissions and removals resulting from changes in the pool of harvested wood products (paper, wood panels and sawn wood) using the first order decay function and specific default half-life values (25 years for wood panels and 35 years for sawn wood) [16], [19], [20], [21]. - **MRV rules** for embodied carbon emissions and biogenic carbon storage in wood products currently investigated in a DG CLIMA project, entitled “Evaluation of the climate benefits of the use of harvested wood products in the construction sector and assessment of remuneration schemes” - Puro Earth methodology for wooden building elements: net carbon storage of wood construction products calculated by subtracting embodied emissions (from raw materials, production and transport) from biogenic carbon storage (LCA or EPD approach)[22] - Research on improving the biogenic carbon accounting of the forestry phase[23] **Baseline setting methods** (including existing baseline data options)

Solution fiche template	
Section	Aspects covered
	- In many cases the carbon emission impact of long-lived wood products are calculated and documented on the basis of LCA, which shows a reduced carbon emission impact resulting in lower net carbon emissions of wood products compared to the non-wood counterparts. The climate benefit of wood products consists of carbon storage as well as avoided emissions by replacing non-wood products and the associated fossil CO_2 emissions[17]. **Key references** - EN15804:A2 - Core rules for the product category of construction products and the complimentary specification - EN16485 - Product category rules for wood and wood-based products for use in construction - EN16449:2014 - Calculation of the biogenic carbon content of wood and conversion to carbon dioxide

Co-benefits and negative externalities/leakage risks	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts)
	- **Positive:**
	  - Biomass for construction materials can replace carbon-intensive building materials such as steel and concrete[1], [12], [14]. Substitution probably has a higher effect on the GHG profile of buildings than on the storage potential[12], [14].
	  - Mass timber production from small-diameter or non-merchantable logs could be beneficial for wildfire prevention and forest restoration[18].
	  - Potential to improve recovery of post-consumer wood and encourage cascade use (circular economy)[16]
	- **Negative:**
	  - Competition for biomass with other sectors, which could lead to deforestation, poorly managed forests, land use changes and impacts on biodiversity[1], [18].
	  - Understanding of side effects/leakage risks
	  - Governance practices are essential to ensure sustainable biomass production and avoid negative externalities such as deforestation and poorly managed forests[14].

Governance aspects	**Actors involved**
	- Forest industry (e.g. Stora Enso[24]), construction industry (e.g. Tewo, Ekovilla, Moelven), architects (e.g. Voll Arkitekter, PLP architects)
	Scale/size of projects
	- Manufacturers participating in the Puro Earth certification mechanism deliver net carbon removals at a rate of 29 $kgCO_2/m3$ of product (TEWO's timber construction materials), 541 $kgCO_2/m3$ of product (Moelven's glulam beam) and 1,102 tCO_2/t of product (Ekovilla's cellulose fibre insulation)[25]
	- Linkage to existing policies and measures/strategies/funding schemes (e.g. CAP)
	- **IPCC GL** (Volume 4) on harvested wood products
	- **LULUCF Regulation** (EU): Member States must include in their LULUCF accounts changes in the carbon pool of harvested wood products.
	- **EU policies:**
	  - Initiative on green claims
	  - The Products Environmental Footprint
	  - The review of the Construct Product Regulation

Solution fiche template	
Section	Aspects covered
	- The Renovation Wave - The New European Bauhaus - Finnish Wood Building Programme (2016–2021) - French RE2020 regulation

Existing certification mechanisms	- Puro Earth – methodology for wooden building elements
	- Past experience from CARBOMARK project 2009-2011. Emission credits trading platform (voluntary carbon market). Italy (regional: Veneto, Friuli Venezia Giulia). At the end of the project, 21 private companies and 27 public forest owners had joined the CARBOMARK market and three buying contracts had been signed. According to these contracts, 350 tonnes of carbon have been stocked.
	- Examples of existing wood-focused or wood-including schemes:
	  - FSC – Forest Stewardship Council
	  - PEFC – Programme for the Endorsement of Forest Certification
	  - SFI – Sustainable Forestry Initiative
	  - Nordic Swan ecolabel criteria – e.g. for product category “Construction and façade panels”
	  - German ecolabel “Blue Angel” criteria – e.g. for product category “Low-emission composite wood panels”
	  - EU Ecolabel (Flower) criteria – e.g. for product category “Wooden floor coverings”
	  - HQE Bâtiment Durable (France) and label “Bâtiment biosourcé”
	  - Greencalc+ (Netherlands)
	- Red lists for e.g. certain tree species (e.g. CITES listing) or non-sustainable forestry (e.g. from countries/regions with high corruption)
	- European building schemes
	  - Level(s)
	  - Product environmental footprint (PEF), including PEF4Building
	- International building certification schemes, such as:
	  - LEED (Leadership in Energy & Environmental Design),
	  - BREEAM (Building Research Establishment Environmental Assessment Method)
	  - DGNB (German Sustainable Building Council)

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[1] Royal Society & Royal Academy of Engineering (2018), Greenhouse gas removal (link)

[2] Forestry Innovation Investment (2021), Introduction to Brock Commons Tallwood House: UBC Tall Wood Building (link)

[3] Forestry Innovation Investment (2017), BROCK COMMONS TALLWOOD HOUSE (link)

[4] Sathre, R. & O’Connor, J. (2010), A Synthesis of Research on Wood Products and Greenhouse Gas Impacts *(*link*)*

[5] Ecofys (2017), CCC indicators to track progress in developing greenhouse gas removal options (link)

[6] urbanNext (2021), Oakwood Timber Tower: Timber towers could transform London’s skyline (link)

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[7] Ramboll Group (2017), Dalston Works (link)

[8] Architect Magazine (2018), Dalston Works, the largest CLT Building in the World (link)

[9] Internationales Holzbau-Forum (2017), Mjøstårnet - Construction of an 81 m tall timber building (link)

[10] Puro Earth (2021), Moelven - Leading Scandinavian Timber producer (link)

[11] Joint Research Centre (2020), Negative emissions technologies

[12] Oxfam discussion papers (2020), Remove carbon now (link)

[13] Hepburn et al. (2019), The technological and economic prospects for CO_2 utilization and removal (link)

[14] American University (2021), What is Mass Timber Construction? (link)

[15] NEGEM (2021), Stocktaking of scenarios with negative emission technologies and practices (link)

[16] Rüter et al. (2016), ClimWood 2030 ‚Climate benefits of material substitution by forest biomass and harvested wood products: Perspective 2030' Final report (link)

[17] Bergman et al. (2014), The Carbon Impacts of Wood Products (link)

[18] The Economist benchmark (2020), CDR Benchmark (link)

[19] Geng et al. (2017), Review of carbon storage function of harvested wood products and the potential of wood substitution in greenhouse gas mitigation (link)

[20] Sato, A. & Nojiri, Y. (2019) Assessing the contribution of harvested wood products under greenhouse gas estimation: accounting under the Paris Agreement and the potential for double-counting among the choice of approaches (link)

[21] Official Journal of the European Union (2013), DECISION No 529/2013/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL (link)

[22] Puro Earth (2020) Puro.earth CO_2 Removal Marketplace (link)

[23] Head, M. (2019), IMPROVEMENT OF BIOGENIC CARBON ACCOUNTING IN THE LIFE CYCLE OF WOOD USED IN CONSTRUCTION IN CANADA (link)

[24] Stora Enso (n.d.), Building concepts (link)

[25] Puro Earth (2021), Puro.earth Carbon Removals (link)

5.8 Fiche: Direct Air Capture and Carbon Storage (DACCS)

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Solution name	**Direct Air Capture and Carbon Storage (DACCS)**

Introduction	**Brief description of the technology**
	● Direct Air Capture (DAC) uses chemical engineering processes relying on chemical capture to remove carbon dioxide (CO_2) directly from the atmosphere into a separating agent that is regenerated with heat, water, or both. The CO_2 is subsequently desorbed from the agent and released as a high purity stream. This CO_2 can be stored[40] into geological reservoirs (saline formations, depleted oil and gas fields) via e.g. pipelines transfers, stored in solid formation via carbon mineralisation or utilised by chemical conversion in various products[1].
	● There are two main methods to capture CO_2 from the air:
	  ○ Liquid systems: the air passes through chemical solutions (e.g. a hydroxide solution), which removes the CO_2 and returns the rest of the air to the environment[2], [3].
	  ○ Solid system: the air passes through filters composed of solid sorbents which chemically bind with CO_2[2], [3].
	  ○ Other nascent technologies include e.g. electrochemical methods whereby a specialised battery, whose electrodes have affinity for CO_2, absorbs CO_2 from the air when charging and releases it when discharging[4].
	GHGs targeted (and land use category, if appropriate)
	● Carbon dioxide (CO_2)
	Examples of solutions already operational or in planning
	● Existing DAC plants are small, global capture capacity of approx. 9000 tCO_2/year, CO_2 is mainly utilised in industrial processes (e.g. carbonating drinks, Power-to-X, greenhouse fertilisation) rather than permanently stored[1], [3].
	● Climeworks (Switzerland): operational since 2017, capture capacity: 900 tCO_2/year, technology based on adsorption-desorption process, captured CO_2 used to fertilise greenhouses[1], [5].
	● Climeworks and CarbFix project (Iceland): operational since 2017, capture capacity: 50t CO_2/year, technology based on an adsorption-desorption process, CO_2 capture injected underground in basalt rock formations for storage via carbon mineralisation, located near a geothermal power plant for access to renewable energy[3], [5].
	● Carbon Engineering and Occidental Petroleum (USA): expected to be operational in 2023, capture capacity: up to 1 $MtCO_2$ (first large-scale plant being developed), based on aqueous sodium hydroxide absorption, provision of CO_2 for enhanced oil recovery[3].
	● Orca project – another collaboration between Climeworks and Carbfix (Iceland): expected to be operational in spring 2021, capture capacity: 4000t CO_2/year, running on renewable energy, CO_2 storage via mineralisation[6].

Potential	

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[40] Information on geological storage will be found in the fiche on Carbon Capture and Storage (CCS), information on carbon mineralisation will be found in fiche on "carbon mineralisation" and information on utilisation will be found in the fiches on "Carbon Capture and Utilisation (CCU).

Solution fiche template	
Section	Aspects covered
Technology readiness level (TRL)	**Current TRL level** - Various stages of technology readiness depending on technology, ranging between prototype demonstration, pilot plant development, and commercialisation[1], [5], [7], .[8], [9], [10]. - TRL = 5-7 **Qualitative discussion of development** (e.g. expected TRL level by 2030, 2050, development risks, uncertainties) - Early developments expected by 2030, larger-scale developments expected by 2050 but more large-scale demonstrations needed to refine technology and reduce capture costs[1], [7], [11], [12], [13], [3].

Potential carbon removals	**Technical and/or realistic potential** (i.e. t CO_2-e removals, Europe-wide, annual – now, future) and total potential removal
	- **Global:**
	  - With current technology, no potential for removals at cost < 100 USD/tCO_2[2]
	  - Larger carbon removal potential expected by 2050 rather than in near term[12],[14]
	  - IEA global forecast: 1 MtCO_2/year in 2023 (Sustainable Development Scenarios)[3]
	  - Capacity expectation from technology developers: Climeworks has the goal to capture approx. 1% of global emissions by 2025 (equivalent to 225 MtCO_2/year, in comparison, current capacity is below 2,000 tCO_2/year (2020))[15], [16]
	  - 0.5–5 GtCO_2/year by 2050 with constraints (i.e. carbon storage, low-carbon energy availability, unexpected environmental side-effects, and land demand to a lower extent), up to 40 GtCO_2 by 2100 without constraints but large uncertainties in available potential estimates[17], [2], [18]
	- **EU:**
	  - Carbon capture by DAC in EU Clean Planet for All scenarios: 83-264 MtCO_2/year by 2050[11].
	  - Estimated removal potentials for EU Member States (+UK):[19]
	  - Netherlands: 34-158 MtCO_2/year in 2100
	  - UK: 1-25 MtCO_2/year in 2050
	  - Ireland: 6-24 MtCO_2/year in 2100
	  - Constraints/interaction effects and assumptions (e.g. land use requirements, contingencies reg. other solutions)
	  - Competition for low-carbon energy supply with other mitigation methods.
	  - Competition for storage capacity with other carbon removal methods (CCS, BECCS).
	Brief description of calculation method and uncertainties
	- Uncertain potential due to lack of available studies, realistic potential depending on constraints (storage capacity, cost and low-carbon energy availability, land demand to a lower extent)[17].
	System boundaries and lifecycle emissions considerations
	- Energy usage to operate capture, transport and storage.
	- Intensive infrastructure development and some land change impacts required for large-scale deployment.
	- Commercial DAC plants operated by Climeworks in Hinwil and Hellisheiði achieve negative CO_2 emissions with carbon capture efficiencies > 85%, but DAC is dependent on low-carbon energy to deliver net carbon removals over the life cycle [5], [20].

Solution fiche template	
Section	Aspects covered
Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs (including energy demand)) • Large variations in capture costs (incl. compression, excl. transport, injection and storage) reported in literature, ranging 100-1000 USD/tCO_2 depending on technology design choices and post-capture routes of CO_2. (incl. whether compression at high-pressure is needed or the CO_2 stream is used at low pressure) [3]. • Capture costs driven by capital investment, energy costs of capture and operation, energy costs of regeneration, and maintenance. Post-capture costs driven by CO_2 compression (in the case of geological storage or carbon mineralisation), transportation and storage[17] **Projected future costs** • Capture costs on a decreasing trend but uncertainties (lack of large-scale operations and early stage of technology) [1], [3], [17], [8],[21], [22] • Projected capture costs (incl. compression, excl. transport, injection and storage): DAC, excluding transport and storage: 600-1000 USD/tCO_2 for a first-of-a-kind plant, 94-300 USD/tCO_2 for nth plant 124-235 USD/tCO_2 for first state-of-the-art mega-tonne scale DAC plant, 40-400 USD/tCO_2 (at scale) [17], [5], [17], [22], [23] **Energy demand** • Minimum work to capture CO_2 : 19-21 kJ/mol CO_2 (i.e. 0.4 GJ/tCO_2)[24]: • Energy demand (capture): Solid sorbent technologies: 3.95-8.4 GJ/tCO_2; liquid sorbent technologies: 5.9-11.8 GJ/tCO_2; novel electrochemical technology: 1-2 GJ/tCO_2 [2], [3], [4] • Additional energy demand due to compression required for transport and storage (approx. 2.5 Mtoe/MtCO_2 , i.e. 1 GJ/tCO_2)[5]
Duration of removals / permanence	**Duration of removals & risks of reversibility** • > 100 years, for carbon storage in geological reservoirs or via mineralisation (cf. CCS and carbon mineralisation fiches) • 0-50 years, for carbon utilisation in different products (see CCU fiche) **Conditions for permanence & option to manage impermanence** • See CCS, Carbon Mineralisation, and CCU fiches
Practical barriers	Are there **other barriers** that would limit the wide-scale uptake/ implementability of this solution (e.g. legal, land area requirements, public acceptance, ownership, economic considerations etc.) • High energy or heat demand [7] • Requires abundant supply of and colocation with low-carbon energy[25] • High infrastructure demand and need for capital[9] • Current small-scale production of amines for the adsorbent[20]
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** • DAC is not covered in IPCC GL, nor in the EU ETS • CO_2 captured is directly measurable and energy usage easily traceable[2] • For MRV information reg. CO_2 storage, see CCS, Carbon Mineralisation, and CCU fiches **Baseline setting methods** (including existing baseline data options) • Financial additionality of DAC systems as 100% used for removing CO_2 from the atmosphere[18] • Accounting baseline set at 0 (and accounting for life cycle emissions, i.e. energy and infrastructure) [18]

Solution fiche template	
Section	Aspects covered
Co-benefits and negative externalities/leakage risks	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts) • Positive aspects: ◦ Limited land demand, can be located on land non-suitable for agriculture[7], [3], [11] ◦ Possibility of locating plants close to suitable storage or utilisation sites, reducing long-distance CO_2 transport and enabling access to low-carbon energy (e.g. renewable energy, waste heat from other industries) [1], [3] ◦ Perceived more benign than CCS, as fossil fuels not involved [26] ◦ Low negative externalities on human health and environment [9], [27] • Negative aspects (in bold, main negative aspects): ◦ No sustainability co-benefits[8], [18], [27] ◦ Potential effects of low CO_2 concentrations on nearby vegetation although likely to be local and highly uncertain [1] ◦ High power and heat demand[3], [17] ◦ High water demand to replace evaporation (for liquid sorbent methods) [1], [2], [8] ◦ Land and resource demand for large-scale deployment [1], [8] ◦ Understanding of side effects/leakage risks ◦ No issue related to potential displacement of emissions[10]
Governance aspects	**Actors involved** • Limited number of small entrepreneurial firms (e.g. Climeworks, Global Thermostat, Carbon Engineering, Verdox, Infinitree LLC and Skytree)[5], [26], [10] **Scale/size of projects** • Capacity of currently operating DAC facilities: 3-4000 tCO_2/year, median capacity: 50 tCO_2/year (15 facilities worldwide)[5] **Linkage to existing policies and measures/strategies/funding schemes** (e.g. CAP) • There is currently no EU legislation on DAC[28]
Existing certification mechanisms	• California Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard • US 45Q tax credit system

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[1] EASAC (2018), Negative Emission Technologies: What role in meeting Paris Agreements targets? (link)

[2] National Academy of Sciences, Engineering, and Medicine (2019), Negative Emissions Technologies and Reliable Sequestration. A Research Agenda (link)

[3] IEA (2021), Direct Air Capture (link)

[4] Voskian, S. & Hatton, T. A. (2019), Faradaic electro-swing reactive adsorption for CO_2 capture (link)

[5] IEA (2020), Energy Technology Perspectives 2020 (link)

[6] Climeworks (2020), The rapid construction of Climeworks' new direct air capture and storage plant Orca has started (link)

[7] Royal Society & Royal Academy of Engineering (2018), Greenhouse gas removal (link)

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[8] Climate Advisers (2018) Creating Negative Emissions: The Role of Natural and Technological Carbon Dioxide Removal Strategies (link)

[9] Ecofys (2017), CCC indicators to track progress in developing greenhouse gas removal options (link)

[10] NewClimate Institute (2020), Options for supporting Carbon Dioxide Removal (link)

[11] European Commission (2018), In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (link)

[12] Joint Research Centre (2019), Direct Air Capture (link)

[13] Joint Research Centre (2020), Negative emissions technologies

[14] Minx et al. (2018), Negative emissions—Part 1: Research landscape and synthesis (link)

[15] Climeworks (2018), Climeworks raises USD 30.8 million to commercialize carbon dioxide removal technology (link)

[16] CarbonBrief (2017), The Swiss company hoping to capture 1% of global CO_2 emissions by 2025 (link)

[17] Fuss et al. (2018), Negative emissions—Part 2: Costs, potentials and side effects (link)

[18] Oxfam discussion papers (2020), Remove carbon now (link)

[19] NEGEM (2021), Stocktaking of scenarios with negative emission technologies and practices (link)

[20] Deutz, S. & Bardow, A. (2021), Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption (link)

[21] IOGP (2019), The Potential for CCS and CCU in Europe (link)

[22] Rhodium Group (2019), Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology (link)

[23] Goldman Sachs (2019), Carbonomics. The Future of Energy in the Age of Climate Change (link)

[24] Bui et al. (2018), Carbon Capture and Storage (CCS): the way forward (link)

[25] EASAC (2019), Forest bioenergy, carbon capture and storage, and carbon dioxide removal: an update (link)

[26] Nemet et al. (2018), Negative emissions—Part 3: Innovation and upscaling (link)

[27] The Economist (n.d.) Investing in Carbon Removal: Demystifying Existing Approaches (link)

[28] European Parliament (2021), Carbon dioxide removal: Nature-based and technological solutions (link)

5.9 Fiche: Bioenergy with carbon capture and storage (BECCS)

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Solution name	**Bioenergy with carbon capture and storage (BECCS)**
Introduction	**Brief description of the technology** • Atmospheric CO$_2$ extraction by plant biomass for use as fuel (combusted or converted), with subsequent sequestration (injection into geological formations) of CO$_2$ from the biomass to energy process. Feedstocks include dedicated bioenergy crops, residual products and forest biomass, and being tested municipal waste (Waste-to-Energy) and algae[1], [2]. **GHGs targeted** (and land use category, if appropriate) • Carbon dioxide (CO$_2$) **Land use categories for biomass feedstock:** forests, croplands, (in addition, algae cultivation or municipal organic solid waste has been proposed as alternatives)[3] **Examples of solutions already operational or in planning** • Currently, more than 10 facilities, most involving the capture of fermentation CO$_2$ from ethanol plants and only one large-scale[2], [4], [5]: • Kansas Arkalon (USA), operational since 2009, capacity of 0.29 Mt CO$_2$/year for EOR. • Lantmännen Agroetanol (Sweden), operational since 2015, capacity of 0.2 Mt CO$_2$/year for use. • AlcoBioFuel bio-refinery CO$_2$ recovery plant (Belgium), operational since 2016, capacity of 0.1 Mt CO$_2$/year for use. • Illinois Industrial Carbon Capture and Storage, implemented by Archer Daniels Midland and funded by the Department of Energy (US): operational since 2017, capture capacity: 1Mt CO$_2$/year, CO$_2$ captured from ethanol production and stored into the Mt. Simon Sandstone saline aquifer in the Illinois Basin[6], [7] • Drax BECCS plant (UK), operational since 2019, pilot project. Drax power station converted from coal-fired to biomass. Plan to capture 4 MtCO$_2$/year at one of the power station units with storage in the North Sea oil field, with a start date in 2027. Plan to CCS on all four bioenergy power units by mid-2030s[4] • Twence WtE plant (Netherlands): uses Aker's Just Catch modular carbon capture plant to capture CO$_2$ will be captured from flue gas, commissionning expected in 2021, CO$_2$ capture capacity: 100,000 tCO$_2$/year[4] • Klemetsrud WtE plant (Norway): expected to be operational in 2023/2024 (if approved for investment), planned CO$_2$ capture capacity: 400,000 tCO$_2$/year (from both fossil and biological materials)[2], [8], [9].
Potential	
Technology readiness level (TRL)	**TRL level depending on technology**: TRL is assessed 3-7 for BECCS in power industry, 7-9 for BECCS in bioenergy industry[10] [12] [1] **Qualitative discussion of development** (e.g. expected TRL level by 2030, 2050, development risks, uncertainties) • BECCS is the most developed technological approach for carbon removal. It is not deployed at scale yet, but readiness is moderate for deployment as there are examples of solutions in operation and commercialisation[11,12,5].

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BECCS application in bioethanol production is most commercially-attractive, as the technology is already mature and the potential to decarbonise the transport sector[2]
Expected to reach max. potential before 2050, will likely decline after 2050 as other approaches such as DACCS will be more effective and cheaper[11]
Deployment at scale expected beyond 2020s/2030s[1]

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<td>Potential carbon removals</td>
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<p>Technical and/or realistic potential (i.e. t CO_2-e removals, Europe-wide, annual – now, future) and total potential removal</p>
<p>Global potential estimate by 2050: 0.5-5 $GtCO_2$/year[3], [11], [13], [14], [15], [16]. Below 2.1 $GtCO_2$/year, when incl. only readily available agricultural and forestry residues, but losses during transport and conversion could divide this potential by 2[11]</p>

Cumulative global potential by 2100 estimated 100-1,170 $GtCO_2$[5], [17].
BECCS is valued as one of the most promising solutions to achieve climate neutrality in the medium-long term[18]. IPCC scenarios (1.5°C) include removals from BECCS in three scenarios with annual CDR rates of global deployment ranging from 0-1, 0-8, and 0-16 $GtCO_2$/year removed in 2030, 2050 and 2100 respectively, and cumulative global CDR removals by 2100 of 151-1,191 $GtCO_2$[15], [19],

<p>EU-level:</p>

Carbon capture from biomass in EU Clean Planet for All scenarios: 5-276 $MtCO_2$/year by 2050 (assuming most of the biomass produced domestically, only 4 to 6% imported by 2050)[20]
Estimated potentials of Negative Emission Technologies and Practices by EU Member States (+UK), where available [18]

France: 10 $MtCO_2$/year in 2050
Finland: 14 $MtCO_2$/year in 2050
Netherlands: 17-55 $MtCO_2$/year) in 2050
UK: 51-83 $MtCO_2$/year) in 2050
Ireland: 6-44$MtCO_2$/year in 2100.

EU biogenic carbon removal potential (excl. dedicated bioenergy plantations): 200 $MtCO_2$/year (incl. 2/3 from pulp and paper, biomass co-fired, WtE, and wastewater treatment facilities; 1/3 from crop residues organic food waste, and livestock manure)[21]
EU biogenic CO_2 capture potential from WtE in EU assuming applying carbon capture technologies at all EU WtE plants: 80 $MtCO_2$/year (incl. min. 90% capture efficiency and average biogenic content 56%). Biogenic CO_2 capture potential of which negative emissions: 40-47 $MtCO_2$/year[22]
The forest resources in the EU have increased steadily since the 90's and in 2020 amounted to a total forest area of 159 Mha[25]
1 EJ of biomass typically yields approx. 0.02–0.05 $GtCO_2$ worth of negative emissions[14]. In 2016, the bioenergy consumption in the EU was 4.8 EJ [23], whereas EU potential of sustainable biomass can reach 17 EJ in 2050.[24]
On the storage and use side: See CCS and CCU fiches

<p>Constraints/interaction effects and assumptions (e.g. land use requirements, contingencies reg. other solutions)</p>

High requirements of land for BECCS to power generation (biomass as feedstock for power plant): 0.03-0.16 ha/tCO_2/year [32].
Competition with other land-use such as food production and overlap with reforestation / afforestation.
Competition for biomass, water, fertilizer (in some cases), and carbon storage sites (CCS, DACCS).

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	- Climate change will affect soil dynamics for carbon storage and crop production[25]. **Brief description of calculation method and uncertainties** - Overall, the global CO_2 removal potential estimates in the sources are derived based on bioenergy, geological storage potentials and sustainability safeguards as limiting factors and also consider costs and additional aspects from the literature on the entire BECCS chain. However, the methodology remains unclear - EU biogenic carbon removal potential derived from assessment of biogenic CO_2 content and biogenic carbon removal efficiencies for point sources and distributed sources, and factoring in CO_2 transport and injection losses[21] - Potential expressed in "tonnes avoided" includes energy penalty associated with capture/transport/storage compared to an unabated bioenergy plant. **System boundaries and lifecycle emissions considerations** - Key factors to determine BECCS' efficiency in removing CO_2 from the atmosphere includes: 1) emissions from bio-crop production, 2) emissions from crop processing, 3) effects on land carbon stocks from land use change[19]. - Former LCA studies have shown that carbon emissions in the full life cycle could result in 50% or less carbon efficiency[19]. - Negative emissions are typically not delivered from year 1. Recent research has shown that over much of global land area, purpose grown bioenergy crops for BECCS electricity generation would actually have a positive emissions factor when assessed over a timeframe of 30 years, and only providing true negative emissions when deployed over much longer time frames (~80 years)[15].

Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs (including energy demand)
	- 30-400 USD/tCO_2 globally, depending on specific feedstock source, access to biomass, cost of biomass, combustion or conversion approach, distance and transport of biomass, electricity price, plant lifetime and efficiency[26], [11], [16], [19], [14].
	- CO_2 avoided costs (costs for implementing BECCS in US$/t$CO_2$ avoided) for different technologies globally[4] [2]:
	  - Ethanol production: 20-175 USD/tCO_2
	  - Biomass gasification: 30-76 USD/tCO_2
	  - Pulp and paper mills: 20-70 USD/tCO_2
	  - Combustion: 88-288 USD/tCO_2
	- CO_2 capture costs for different technologies globally:
	  - Ethanol production: 15-30 USD/tCO_2[5]
	- Fuel transformation processes (e.g. bioethanol production from sugar or starch cane) or biomass gasification[27]: 15-30 USD/tCO_2 [5], 22-24 USD/tCO_2 for CCS from high CO_2 concentration stream vs 27-66 USD/tCO_2 if CCS extended to flue gas streams
	- On the storage and use side: See CCS and CCU fiches
	Projected future costs
	- Capture and storage costs will likely decline, but biomass costs will likely increase, if deployed at large scale[14], [28].

Duration of removals / permanence	**Duration of removals & risks of reversibility** - Permanence depends on sequestration method: Low reversibility risk in geological storage and building materials (see CCS fiche), and for CCU, permanence depends on applications and end-of-life management (see CCU fiche)[29], [30]. **Conditions for permanence & option to manage impermanence** - See CCS and CCU fiches

Practical barriers	Are there **other barriers** that would limit the wide-scale uptake/ implementability of this solution (e.g. legal, land area requirements, public acceptance, ownership, economic considerations etc.)[31] • Biomass supply incl. availability of land, water and fertiliser[4] • High requirements of infrastructure include equipment and facilities to process biomass as well as infrastructure for capture, storage and CO_2 transportation[11], [26], [13]. • Need for economic small-scale capture plants for deploying BECCS at WtE facilities relatively small • Distance between biomass sources, power stations and storage sites, unfavourable in the EU context[14], [19], [21]. • Limited level of public acceptance[14], [1], [18], [15], [16] • Availability of storage and suitable facilities [14], [19], [151]
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** • IPCC GL ensure all agriculture/land use emissions are accounted for, combustion as well if not already covered. Removal upon storage can be reported as well. Negative emissions from BECCS can be recorded in national GHG inventories, by applying a zero-emission factor to biomass combustion and subtracting captured and stored CO_2 from respective sectors totals • At project level: any fossil emissions (co-firing) are covered by EU ETS/ESR, but biomass is zero-emissions rated but negative emissions are not recognised • In order for biomass to be zero-rated in the EU ETS, the RED II sustainability criteria have to be met for biofuels and bioliquids and, as of 2022, also for gaseous and solid biomass fuels* (which "should" ensure that the emissions under 1) are not only accounted for but exhibit GHG savings above certain threshold). The RED II also provides a link between the 3 IPCC sectors under which biomass-related emissions and removals are reported (land-use, agri, combustion) • Key elements where effective monitoring at project-level is required: 1) GHG emissions and environmental impacts across value chain including feedstock production, 2) integrity of CO_2 storage. An option to manage the first is using certification schemes similarly to those of other bio-based products e.g. bioenergy, forestry products, palm oil[26]. • Emissions from bioenergy production vary between geographies, feedstocks, and timeframe. These variables represent significant challenges for tracking and reporting of progress, designing incentives and for designing a credible market-based approach[15]. • A standard by the European Committee for Standardisation (CEN) is underway for verification and auditing of biomass-for-energy supply chains[32]. **Baseline setting methods** (including existing baseline data options) • In a regional cap-and-trade scheme the baseline setting accounts for the substitution of fossil fuel for biomass meaning that capturing and storing the CO_2 from a biomass plant only recognises negative emissions from storage and not the benefit from zero-emissions biomass.[33] E.g. for CCS methodologies, the baseline can be set according to actual measured CO_2 captured and injected from the project. • Whereas, project-based schemes (e.g. CDM) can demonstrate that the baseline is a higher emission technology (e.g. unabated coal-fired plants) so that both zero-emissions biomass and negative emissions from storage can be recognised.[33] **Key references** • 2006 IPCC Guidelines for National Greenhouse Gas Inventories[15]

Co-benefits and negative externalities/leakage risks	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts) • Positive: ◦ Generation of energy, energy independence, bio-energy pathways[12, 1, 14] ◦ Potential to increase and diversify rural income[14] • Negative: ◦ Potential impact on food prices and food security due to land use competition[29, 16, 15, 14] ◦ Biodiversity loss[29, 16, 15, 14, 19, 25] ◦ Direct and indirect emissions from land use change[29, 16, 15, 14] ◦ Pressure on water resources and risk of water pollution [29, 16, 15, 14] ◦ Deforestation and forest degradation[14, 25] ◦ Albedo change[19]. ◦ Understanding of side effects/leakage risks ◦ Challenges in identifying and quantifying GHG emission effects of human induced direct and indirect land use changes (dLUC/iLUC) driven by increasing demand for bioenergy[33] ◦ Existing qualitative and quantitative approaches to mitigate leakage risks based on restricting biomass supply that is eligible for a zero-emissions rating or requiring full life cycle GHG emissions assessments (incl. dLUC/iLUC) [33]
Governance aspects	**Actors involved** • On the capture side: forestry sector, crop sector, energy sector, and technology developers ◦ 455 WtE facilities in EU[2] ◦ On the storage and use side: See CCS and CCU fiches **Scale/size of projects** • Ethanol production: 90,000 tCO_2/year (Husky Energy Injection, Canada); 1$MtCO_2$/year (Illinois Industrial Carbon Cpature and Storage, USA) • Power generation: 180,000 tCO_2/year (Mikawa post combustion capture plant, Japan); 4$MtCO_2$/year (DRAX, UK)[5] • WtE: 3,000 tCO_2/year (Saga City waste incineration plant, Japan); 100,000 tCO_2/year (Twence WtE facility, Netherlands); 400,000 tCO_2/year (Klemetsrud WtE plant, Norway) [2, 8, 9] **Linkage to existing policies and measures/strategies/funding schemes** (e.g. CAP) • Regulation 2018/1999/EU on the Governance of the Energy Union and Climate Action[25] • EU Renewable Energy Directive 2018/2001/EU[25] • The CCS Directive 2009/31/EC: framework for the safe selection of storage sites[25] • Industrial Emissions Directive 2010/75/EU[25] • Forest Europe declarations: safeguarding the sustainability of forest management[25] • EU CCS Directive
Existing certification mechanisms	• N/a

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[1] Joint Research Centre (2020), Negative emissions technologies

[2] Global CCS Institute (2019), Bioenergy and Carbon Capture and Storage (link)

[3] National Academy of Sciences, Engineering, and Medicine (2019), Negative Emissions Technologies and Reliable Sequestration. A Research Agenda (link)

[4] Global CCS Institute (2020), Global Status of CCS 2020 (link)

---

[5] IEA (2020), Energy Technology Perspectives 2020 (link)

[6] The Midwest Center for Investigative Reporting (2020), Despite hundreds of millions in tax dollars, ADM's carbon capture program still hasn't met promised goals (link)

[7] Illinois Industrial Carbon Capture & Storage (2017), Eliminating CO_2 Emissions from the Production of Bio Fuels - A 'Green' Carbon Process (link)

[8] The City of Oslo, (n.d.), Carbon Capture and Storage at Klemetsrud (link)

[9] Fortum (2021), A full-scale carbon capture and storage (CCS) project initiated in Norway (link)

[10] NewClimate Institute (2020), Options for supporting Carbon Dioxide Removal (link)

[11] The Economist benchmark (2020), CDR Benchmark (link)

[12] Climate Advisers (2018) Creating Negative Emissions: The Role of Natural and Technological Carbon Dioxide Removal Strategies (link)

[13] EASAC (2018), Negative Emission Technologies: What role in meeting Paris Agreements targets? (link)

[14] Fuss et al. (2018), Negative emissions—Part 2: Costs, potentials and side effects (link)

[15] Climate Analytics and C2G (2021), Governing large-scale carbon dioxide removal: are we ready? - an update (link)

[16] European Parliament (2021), Carbon dioxide removal. Nature-based and technological solutions (link)

[17] Rueda et al. (2021), Negative-emissions technology portfolios to meet the 1.5 °C target (link)

[18] NEGEM (2021), Stocktaking of scenarios with negative emission technologies and practices (link)

[19] EASAC (2019), Forest bioenergy, carbon capture and storage, and carbon dioxide removal: an update (link)

[20] European Commission (2018), In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (link)

[21] Rosa et al. (2021) Assessment of carbon dioxide removal potential *via* BECCS in a carbon-neutral Europe (link)

[22] Endrava (2021), The CCS potential for Waste-to-Energy plants (link)

[23] European Commission (2019), Brief on biomass for energy in the European Union (link)

[24] Faaij (2019) Securing sustainable resource availability of biomass for energy applications in Europe; Review of recent literature (link)

[25] Joint Research Centre (2021), The use of woody biomass for energy production in the EU (link)

[26] Royal Society & Royal Academy of Engineering (2018), Greenhouse gas removal (link)

[27] IEA Greenhouse Gas R&D Programme (IEAGHG) (2021), IEAGHG Technical Report: 2021-01 Biorefineries with CCS (link)

[28] Reid et al. (2019), The future of bioenergy (link)

[29] National Academy of Sciences, Engineering, and Medicine (2019), Negative Emissions Technologies and Reliable Sequestration. A Research Agenda (link)

[30] National Academy of Sciences, Engineering, and Medicine (2019), Gaseous Carbon Waste Streams Utilization: Status and Research Needs (link)

[31] Nemet et al. (2018), Negative emissions—Part 3: Innovation and upscaling (link)

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[32] Ecofys (2017), CCC indicators to track progress in developing greenhouse gas removal options (link)

[33] IEA Greenhouse Gas R&D Programme (IEAGHG) (2014), Biomass and CCS-guidance for accounting for negative emissions (link)

5.10 Fiche: Enhanced rock weathering

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Solution name	**Enhanced rock weathering (EW)**
Introduction	**Brief description of the technology** • Enhancement of geochemical processes that naturally absorb CO_2 from the atmosphere. Enhancement spreads fine-grained silicate rocks containing calcium or magnesium on land (e.g. cropland) which react with CO_2 by forming carbonate minerals and hence remove CO_2 from the atmosphere [1][2]. The method is also applied to open ocean and coastal zones [3] **GHGs targeted (**and land use category, if appropriate) • Carbon Dioxide (CO_2) **Examples of solutions already operational or in planning** • Silicate-rich slag has been used as a fertiliser for over a century in the USA, resulting in small scale application of enhanced weathering [1] • greenSand (Netherlands): Offers carbon credits to customers from applying crushed olivine as replacement for sand and gravel in construction or landscaping projects (credits sold 42 EUR/tCO_2) [4][5]. The company has since 2007 scattered 45,452 tonnes of greenSand Olivine and claims to have removed 3,284 tonnes CO_2 [5] • Working Lands Innovation Center: EW demonstration experiment in coastal California, the Central Valley, and Imperial Valley. The project is in partnership with farmers, ranchers, government, mining industry, and Native American tribes. It tests the GHG removal effect of rock dust and compost amendments from soil, including other aspects such as crop yields and plant and microbial health. The project supports the commercialisation of soil amendment technologies [6][7] • University of Sheffield - Leverhulme Centre for Climate Change Mitigation, 10-year programme established in 2016: Large-scale field trials to measure rates of rock weathering in agricultural soils under natural conditions and how nutrient release and pH change may increase crop productivity. The project utilises basalt rock dust as a by-product meaning there are no additional CO_2 emissions from mining and grinding. The project aims to estimate carbon removals based on field studies [8]
Potential	
Technology readiness level (TRL)	**Current TRL level** • Low maturity - R&D stage, TRL: 1-5 [2][4][9] • The technical processes involved in terrestrial enhanced weathering are well established, in the sense of that application of granular fertilisers and various forms of line is practiced in agricultural sector at small scale.[1][10] • Immature technology in the sense of carbon removal solution, requiring further research, development, and demonstration across a range of crops, soil types, etc. More research on its efficacy, permanency, monitoring and reporting.[1] **Qualitative discussion of development** (e.g. expected TRL level by 2030, 2050, development risks, uncertainties) • Limited efforts focusing on EW [11]. Considered one of the least promising removal solutions by 2030 and 2050 [10], and low current deployment priority [2] • Deployment at scale by or beyond 2050[2]

Solution fiche template	
Section	Aspects covered
Potential carbon removals	**Technical and/or realistic potential** (i.e. t CO_2-e removals, Europe-wide, annual – now, future) and total potential removal • Global sequestration potential: 1-4 $GtCO_2$/year by 2050 [2,10,4,12,13] ◦ Cumulative global potential by 2100: 100 $GtCO_2$ [14] ◦ Global silicate mining waste (9-17 Gt mineral/year) could be used to sequester 0.7-1.2 tCO_2 /year [1] ◦ Maximum carbon capture potential: 0.3 tCO_2 per tonne of basalt [1] • EU countries (+UK) incl. EW demand in their carbon removal scenarios: Netherlands (1.4 $MtCO_2$/year by 2050), UK (76 $MtCO_2$/year by 2050) [11] ◦ Carbon removal potential in France, Germany, Italy, Spain and Poland where TEW is deployed to approx. 10% of croplands: 57 $GtCO_2$/year; between 17% and 25% of croplands: 103 $MtCO_2$/year; between 38% and 57% of croplands: 206 $MtCO_2$/year[10] • Relative lower potential in EU countries than globally due to less agricultural land area [10] • Constraints/interaction effects and assumptions (e.g. land use requirements, contingencies reg. other solutions) • Low land and water requirements for application (approx. 0.01 ha/tCO_2e), however large scale application could require increase in mining activities and results in competition with other land use types and deforestation [4,9,11]Deployment of carbon sequestation by EW can be enhanced through co-deployment with feedstock crops for BECCS and biochar [10] **Brief description of calculation method and uncertainties** • Sequestration potential estimates based on models and lab experiments and vary greatly depending on grain size, water pH, temperature and local conditions [9,12] • Estimates do not include sequestration potential of organic biomass increase due to geogenic nutrient fertilisation and improved soil conditions [12] • Uncertainties in how fast the minerals weather and capture carbon [9] **System boundaries and lifecycle emissions considerations** • Emissions from mining, rock grinding processes and transport make it challenging for EW to be carbon-negative across the lifecycle. It also means that it can take decades before the net effect of an EW project becomes carbon-negative [9,14] • Carbon removal efficiency losses can occur depending on grounding size, use of renewable energy and length of transportation [9] • Improving the energy efficiency of rock grinding processes could improve the likelihood of EW being carbon-negative across the lifecycle. Experiments show 40% energy-savings through optimisation of the applied pressure and modification of feed size distribution [14]
Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs (including energy demand) • Uncertain and varying, some sources point out 23-578 USD/tCO_2 [11,9,3,12,10] • Recent study[10] indicating for EU countries costs between and 157 USD/tCO_2 and 194 USD/tCO_2 • Costs depend on rock type, e.g. 60 USD/tCO_2 for dunite, and 200 USD/tCO_2 for basalt [12] • Costs depend on rock origin, rock grinding technology and transport of materials [12] • Costs may be partially offset by gains in crop productivity and reduced requirements for lime, fertiliser, pesticide and fungicide applications [1] **Projected future costs** • Likely to decline with technology and market developments [10]

Solution fiche template	
Section	Aspects covered
	• Cost reduction levers include energy-efficient rock grinding and co-deployment with afforestation/reforestation projects or agroforestry [10] • Costs in fast-growing nations are 50% lower than Europe, USA and Canada. Main differences are driven by costs of labour, diesel and electricity [10] **Energy demand** • 0.08-0.2 GJ/tCO_2, but upstream processing and transporting large amounts of rock could increase life-cycle energy demand to 12.5 GJ/tCO_2 [11]
Duration of removals / permanence	**Duration of removals & risks of reversibility** • Duration of removals expected from months to geological time scale [12]. • Potential effect of soil saturation [1] [12] • CO_2 can be sequestered by EW in different pools, first it remains as dissolved inorganic carbon (or alkalinity) in the soil pore solution or groundwater. If it gets supersaturated, carbon minerals can precipitate in the soil and be stored in 106 years or more. If it does not precipitate on land, it is transported to the ocean and will be stored as ocean alkalinity [12]. **Conditions for permanence/options to manage impermanence** • n/a
Practical barriers	Are there **other barriers** that would limit the wide-scale uptake/ implementability of this solution (e.g. legal, land area requirements, public acceptance, ownership, economic considerations etc.) • Increase in mining, processing, and safe treatment of tailings to produce large volumes of minerals for large scale deployment of EW [9] [2] • Demand for energy, infrastructure [9] [3], availability of suitable land and finite solubility of silicic acid are significant shortcomings [2] • There are strict rules on applying materials to the soil: the use of ground silicates or silicate wastes might require new regulations and standards. It would also require communication with the public and land owners [14] [1] • Realizing the potential will depend on governance aspects such as commitment of farmers and governments, implementation of the right policy frameworks and wider public acceptance [10] • Low awareness of EW as an option for carbon removal [13]
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** • Methodological uncertainties and high complexity related to monitoring, reporting and verification [4] • Audited field scale assessments including environmental monitoring as well as evaluation of the efficacy of CO_2 capture are required [1] • Not included in any carbon accounting agreements (e.g. not included in IPCC GL), this leaves potential difficulties with quantifying removals[2]. • Establishment of MRV guidelines and processes are needed [1] [15] • To verify carbon sequestration rates of EW will require collection, processing and analysing of soil samples, with a frequency that depends on the measurement of interest [7]

Solution fiche template	
Section	Aspects covered
	• GHG measurements are done in three ways: 1) manually using static flux chambers where measurements are taken weekly or bi-weekly, 2) using automated chambers that allow data to be collected hourly, or 3) using Eddy Covariance monitoring methods. In the Working Lands Innovation Center project they used a combination of these approaches [7] **Baseline setting methods** (including existing baseline data options) • It has been suggested that a carbon price incentive would likely be the only way to make EW economically interesting for operators in most situations however additionality should account for co-benefits (current usage as fertiliser) [9]
Co-benefits and negative externalities/leakage risks	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts) • Positive: ◦ Unlikely to cause major public concerns unless large-scale deployment causes impacts on ecosystems [1] ◦ Can help reverse negative impacts of agriculture and make the land more productive with an increase in crop yields, improved plant nutrition and soil fertility, which can reduce or replace the need for synthetic fertilizers [11,12,14,10] ◦ Can be co-deployed and connected to other land-based methods in order to increase sequestration potential, increase biomass production or increase yields [1,11,12] ◦ It may be possible to safeguard against increased mining by exploiting underutilized by-products, stockpiles of crushed basalt, from the aggregate industry or waste products from mining and industrial processes [1,10] • Negative: ◦ Upscaling may require additional mining of new rocks, which requires significant energy for rock extraction, grinding and transportation and create additional CO_2 emissions and environmental impacts [1] ◦ Potential impacts on human health in case of particles of respirable size and potential impacts on groundwater when particles are washed away [1,3,9,12,4,3] ◦ Potential release of heavy metals, changes in soil hydraulic properties, soil contamination and disturbed ecosystems [4,3,12] ◦ Potential impacts on marine ecosystems due to release of mineral products[16] **Understanding of side effects/leakage risks** • Uncertainties about environmental risks versus environmental benefits, as risks depend on the soil and specific minerals used [14] • If mining is required to source rocks, there are potential risks such as deforestation. The potential risks and negative environmental impacts are especially prevalent if mining is linked to tropical deforestation [1,4]
Governance aspects	**Actors involved** • Farmers, Governments, Mining and aggregate industry **Scale/size of projects** • Lack of project examples to provide indication of scale/size, but one relevant indicator is land intensity of EW projects, estimated below 0.01 ha/tCeq/year [11] **Linkage to existing policies and measures/strategies/funding schemes** (e.g. CAP) • No EU legislation that specifically concerns EW [3]

Solution fiche template	
Section	Aspects covered
Existing certification mechanisms	- greenSand sells credits in the form of 'Cleanup Certificates', which is not described further on their website and neither is the certification mechanism. They are affiliated with NL Greenlabel, an organisation that develops a form of ecolabelling [5]

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[1] Royal Society & Royal Academy of Engineering (2018), Greenhouse gas removal (link)

[2] Joint Research Centre (2020), Negative emissions technologies

[3] EU Parliament (2021), Carbon dioxide removal: Nature-based and technological solutions (link)

[4] New Climate Institute (2020), Options for supporting Carbon Dioxide Removal (link)

[5] grenSand (link)

[6] Houlton (2021), Enhanced Weathering: crushed rocks spread on farmland can capture billions of tons of CO_2/year (link)

[7] Working Lands Innovation Center (link)

[8] Leverhulme Centre for Climate Change Mitigation (link)

[9] Oxfam discussion papers (2020), Remove carbon now (link)

[10] Beerling et al. (2020), Potential for large-scale CO_2 removal via enhanced rock weathering with croplands (link)

[11] Climate Advisors (2018), Creating negative emissions: The Role of NBS and TBS Strategies (link)

[12] Fuss et al (2018), Negative emissions - Part 2: Costs, potentials and side effects (link)

[13] NEGEM (2021), Stocktaking of scenarios with negative emission technologies and practices (link)

[14] Ecofys (2017), CCC indicators to track progress in developing greenhouse gas removal options (link)

[15] Energy Futures Initiative (2020), Rock Solid. Harnessing Mineralisation for Large-Scale Carbon Management (link)

[16] Bach et al. (2019), CO_2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems (link)

5.11 Fiche: Carbon Capture and Storage (CCS)

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Scheme name	**Carbon Capture & Storage (CCS)**
Introduction	• Brief description of the technology • Integrated chain of technologies that enables capturing CO_2 from the exhausts of power stations or other industrial sources, compressing & transporting CO_2, and storing the CO_2[1]. • The most advanced and widely adopted capture technologies are chemical absorption and physical separation; other technologies include membranes and looping cycles such as chemical looping or calcium looping. Industrial sources include chemicals production, iron & steel production, cement production, fuels production. Applicable CO_2 capture technological options differ depending on the CO_2 source[2]. • Transport can be performed via existing steel pipelines, shipping, or in road/rail tankers[1] • Storage includes a set of possibilities for injection of CO_2 in dense or liquid form into deep geological formations (i.e. saline formations or depleted oil & gas reservoirs)[1]. Enhanced oil recovery (EOR) is a technique which entails injecting CO_2 in oilfields to enhance production, while some or all of the injected CO_2 remain stored in the reservoir (applied since the 1970s in the US, and to a limited extent in other non-EU countries)[2]. Injection in basalt rocks is also considered more recently based on experience of Carbfix project in Iceland. This is called in situ mineral carbonation or carbon mineralisation, which is an alternative to conventional geological storage and consists in injecting concentrated CO_2 streams into suitable geological formation where it mineralises in the pores.[3] In basalt and peridotite formations, carbon mineralisation rates are highest and 90% of the CO_2 may be mineralized in a few months to decades. The concentrated CO_2 streams can e.g. be obtained from coupling with carbon capture at industrial sources.[4] • GHGs targeted (and land use category, if appropriate) • Carbon dioxide (CO_2) • Examples of solutions already operational or in planning (as of early 2021) • 26 commercial CCS facilities currently operational worldwide, incl. 16 for EOR, and 37 under development or construction. Also, development of CCS hubs targeting economies of scale[5], [6]. • Only 2 operational facilities in Europe, but at least 11 projects in development in France, Ireland, UK, Norway, Belgium, the Netherlands and Sweden, with a combined capacity of approx. 30 $MtCO_2$/year [2,7] • Sleipner CO_2 project, operated by Equinor (Norway): operational since 1996, capture capacity: 1$MtCO_2$/year, CO_2 captured from natural gas processing and stored in the Utsira sandstone formation (saline aquifer formation)[8], [9] • Snohvit CO_2 storage project, operated by Equinor (Norway): operational since 2008, capture capacity: 0.7Mt CO_2/year, CO_2 captured from natural gas processing and stored into the Tubåen sandstone formation (saline aquifer formation)[10] • Boundary Dam CCS (Canada): operational since 2014, capture capacity: 1Mt CO_2/year, CO_2 captured from coal-based power generation and stored via EOR • Air Products steam methane reformer (US): operational since 2013, capture capacity: 1Mt CO_2/year, CO_2 captured from hydrogen production and stored via EOR • Abu Dhabi CCS (UEA): operational since 2016, capture capacity: 0.8Mt CO_2/year, CO_2 captured from iron & steel production and stored via EOR

Solution fiche template	
Section	Aspects covered
	- Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 stream (Canada): operational since 2020, capture capacity: 0.3-0.6 $MtCO_2$/year, CO_2 captured from fertilizer production and stored via EOR - Northern Lights Project, developed by Equinor, Shell and Total (Norway): CCS hub aggregating CO_2 streams (starting with WtE and cement plants) for compression et liquefaction of CO_2 before transport by dedicated ship to a project site in the North Sea, commissioning expected in 2024, combined capacity of 0.8 $MtCO_2$/year[5]. - Net Zero Teesside, developed by BP, ENI, Equinor, Shell and Total (UK): CCS hub where CO_2 from the power station, and a diverse cluster of biomass power, hydrogen production and carbon intensive industry, will be transported via common pipeline network to permanent geological storage in the North Sea, expected to become operational within the decade, expected combined capacity of 10 $MtCO_2$/year[5]. - CarbFix experiment conducted Reykjavik Energy (geothermal power plant), together with a consortium of research scientists (Iceland): started in 2014, capacity: 10–20 $ktCO_2$/year, co-mineralisation of CO_2 and sulphur, alternated injections of CO_2 and water to ensure that CO_2 entirely dissolves in water at depth. CarbFix approach currently deployed at 4 new geothermal systems sites in Italy, Turkey, Iceland and Germany (EU funded GECO project). - Wallula Project in Washington State (USA): 977 tCO_2 were injected between 838 and 886 meters in depth over 25 days during the summer for the purpose of CO_2 storage through carbon mineralisation.
Potential	

Technology readiness level (TRL)	**Current TRL level**
	- CO_2 capture: TRL depends on technology, e.g.:
	  - Post-combustion chemical absorption using amine solutions, cryogenic-based CO_2 capture: TRL = 9[11], [12]
	  - Pre-combustion Integrated Gasification Combined Cycle-CCS, Post-combustion adsorption, membrane CO_2 capture, oxy-combustion: TRL = 7[11], [12]
	  - Post-combustion biphasic solvents, chemical looping combustion: TRL = 6
	  - Post-combustion ionic liquids: TRL = 3
	  - The TRL also varies depending on the industrial process considered[2], e.g. CCS is more mature in the power generation sector and chemical industry with concentrated CO_2 streams than in the cement and steel industry (see Figure 3.1 in source for the full detail)
	- CO_2 transport:
	  - Pipeline: TRL = 9[2], [11]
	  - Shipping: TRL = 7-9[2], [11]
	  - CO_2 storage by injection in deep geological formations[6], [13]:
	  - Saline formation (salt cavern or saline aquifer): TRL = 8-9[11]
	  - Depleted oil & gas reservoirs: TRL = 7
	  - Enhanced oil recovery (onshore): TRL = 9[11]
	  - In-situ carbon mineralisation at lab- and pilot-scales: TRL = 3-5
	Qualitative discussion of development (e.g. expected TRL level by 2030, 2050, development risks, uncertainties)

Solution fiche template	
Section	Aspects covered
	- Mature technology for several industrial c but lack of progress in CCS development and demonstration projects within the EU reported incl. project cancellations, due to lack of financial incentives/business model[14] - Low technical barriers for the deployment of CCS, cost is the most significant barrier in the short to medium term[15] - CCS was expected to be deployed first in the power sector, while large-scale commercial application of CCS to emissions from industrial installations (e.g. steel or cement) expected to follow from 2030 onwards[16] However, with advancement of renewables, application of CCS in industry is the priority in the EU - Ongoing research on cost-effective improvements in CO_2 separation and capture technologies based on new materials (e.g., non-aqueous solvents, advanced cryogenic process, and polymeric membranes)[17] - In-situ carbon mineralisation requires further exploration at the scale of $MtCO_2$/year[12] and optimal capacity will likely not be realised before 2050[3], [4]. It is an understudied, high-risk, high-reward opportunity solution[12].

Potential carbon removals	**Technical and/or realistic potential** (i.e. t CO_2-e removals, Europe-wide, annual – now, future) and total potential removal
	- Carbon capture in industry and power sector (excl. from biomass) in EU Clean Planet for All scenarios: 47-120 $MtCO_2$/year by 2050[18]
	- Source-side (incl. biogenic sources): large industrial hubs in EU (+ UK) candidate for CO_2 capture – total of approx. 175 $MtCO_2$/year[2]: North Rhine-Westphalia/Ruhr (35 $MtCO_2$/year), Fos-Berre/Marseille (31 $MtCO_2$/year), Rotterdam (28 $MtCO_2$/year), Antwerp (20 $MtCO_2$/year), Le Havre (14 $MtCO_2$/year)), Skagerrak/Kattegat (14 $MtCO_2$/year), Humberside (12.4 $MtCO_2$/year), South Wales (8.2 $MtCO_2$/year), Grangemouth/Firth of Forth (4.3 $MtCO_2$/year), Teesside (3.1 $MtCO_2$/year), Merseyside (2.6 $MtCO_2$/year), Southampton (2.6 $MtCO_2$/year)
	- Storage-side:
	  - High-level estimation of EU (incl. UK and Norway) cumulative storage capacity in geological formation (depleted oil & gas reservoirs and saline aquifers): 302-2120 $GtCO_2$ incl. onshore (161-1129 $GtCO_2$) and practically accessible offshore, mostly in the North Sea (141-991 $GtCO_2$), down to 134 $GtCO_2$ when national storage restrictions are considered[1], [19].
	  - Cumulative storage potential in major oil & gas fields in EU, UK, and Norway: 28.5 $GtCO_2$[5]
	  - CO_2StoP: dataset of geological parameters that enables the assessment of potential geological CO_2 storage capacity in EU Member States
	Large theoretical storage potential for carbon mineralisation: theoretical potential is effectively limitless due to the large quantities of suitable silicates but there is a lack of actual potential estimates[4], [12], [20]. Potential reservoirs include flood basalts, pillow lavas, ultramafic rocks (e.g., peridotite), serpentinites and ophiolites.
	Constraints/interaction effects and assumptions (e.g. land use requirements, contingencies reg. other solutions)
	- CCS compete with CCU solutions
	- CCS competes with other low-carbon solutions such as renewables in the power sector or hydrogen in steel industry.

Solution fiche template	
Section	Aspects covered
	- Possible feedback limitations due to changes in the rock structure (porosity, fractures) induced by in situ mineralisation[4]. **Brief description of calculation method and uncertainties** - Storage potential: derived assuming proportionality with sedimentary formation volume, and sedimentary formation volume estimated using existing data on worldwide sedimentary basins and compiled map of sediment thickness; offshore storage considered practical if water depth less than 300 meters, within 200 miles of a major landmass, and outside of Arctic or Antarctic regions[19] **System boundaries and lifecycle emissions considerations** - Infrastructure deployment and process energy

Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs (CAPEX), running costs (OPEX))
	- Costs vary depending on capture costs (depending on percentage volume of CO_2 in the flue gas) and distance for transport and storage[1]
	- CO_2 capture (incl. compression, US):
	  - Power generation: 36-87 USD/tCO_2 [2], [12]
	  - Cement: 60-120 USD/tCO_2 [2]
	  - Iron & steel: 40-100 USD/tCO_2 [2]
	  - Hydrogen production: 50-80 USD/tCO_2 [2]
	  - Ammonia: 25-35 USD/tCO_2 [2]
	  - Natural gas processing: 15-25 USD/tCO_2 [2]
	- CO_2 transport:
	  - CO_2 compression: 19-25 USD/tCO_2
	  - Offshore/onshore pipeline (250km, capacity: 10MtCO_2:/year): 3.7-5.2 USD/tCO_2 (offshore), 2.4-4.0 USD/tCO_2.250km (onshore) – costs decrease with capacity[21]
	  - Offshore pipeline/shipping - shipping costs are less dependent on capacity than offshore pipeline costs[22]
	  - 1000 km and capacity: 1MtCO_2:/year: 46 USD/tCO_2 (offshore pipeline), 29 USD/tCO_2 (shipping)
	  - 1000 km and capacity: 10MtCO_2:/year: 11 USD/tCO_2 (offshore pipeline), 24 USD/tCO_2 (shipping)
	- CO_2 storage by injection in deep geological formations:
	  - Costs vary significantly; from 1-7 EUR/tCO_2 for onshore depleted oil & gas fields to 2-20 EU/ tCO_2 for offshore storage in mature CCS industry[23], [24].
	  - In the US: EOR: - 28 USD/ tCO_2 (negative storage cost because CO_2 cost is purchased for EOR, US)[25]
	  - 20-30 USD/tCO_2 for storage in basalt, and 10-30 USD/tCO_2 for storage in peridotite – costs depend on temperature and pressure. Uncertainties due to lack of fundamental understanding of processes and engineering systems required for effective sequestration[12]. Storage costs likely higher than for conventional geological storage, but long-term monitoring costs may be avoided as CO_2 stored in permanent solid form[12], [4].
	Energy demand
	- Energy: capture work for a coal power plant[12]
	  - Post-combustion: 1.0-2.6 GJ/t CO_2
	  - Pre-combustion: 1.1-1.6 GJ/t CO_2

Solution fiche template	
Section	Aspects covered
	- Oxy-combustion: 1.3-1.7 GJ/t CO_2 - Chemical looping: 2.1 GJ/t CO_2 **Projected future costs** - CAPEX cost expected to decrease with increasing deployment of CCS, e.g. expected economies of scale with CCS hub development[5], [26] - Advanced solvents with reduced degradation are necessary to reduce capture cost, but must be demonstrated at scales large enough for power plant applications[17] - CCS for a new-build coal- or gas-fired power plants located at a generic site in Northern Europe expected to be cost-competitive with other sources of low-carbon power, including on-/offshore wind, solar power and nuclear in the early 2020s[27] - Moderate cost reduction expected for carbon mineralisation[12].
Duration of removals / permanence	**Duration of removals & risks of reversibility** - IPCC indicates that appropriately selected rock formations are very likely to retain 99% of injected CO_2 over 1000 years[28] - For a typical offshore North Sea storage site, both likelihood & potential volumes of released CO_2 in a theoretic incident very low and decrease with time, expected that 99.99% of the injected CO_2 remains in the subsurface[29] - Permanent containment has not yet been fully demonstrated at a large scale in the EU[30], [31] - Established high likelihood of permanency for carbon mineralisation as carbonate minerals are inert[32], Permanence for carbon mineralisation expected to be very high for mineralisation of basalt or peridotite[12]. Experience of CarbFix: over 95% of the CO_2 injected into the CarbFix site in Iceland was mineralized to carbonate minerals in less than 2 years. **Conditions for permanence & options to manage impermanence** - Appropriate site selection, e.g. the EU CCS directive requires development of computer models and simulations of CO_2 injection, risk assessment, and identification of all potential hazards, especially leakage of CO_2[16] - Monitoring in place must be capable of detecting leakages, acceptable maximum leakage rates of 0.001-0.01%/year suggested in literature[30] - Existing corrective techniques to reduce or prevent further leakage or to try to correct and remediate the leakage itself, and any impacts at surface[33]. Techniques depend on leak location (i.e. geological or well) and can be e.g. reduction of CO_2 injection pressure or peripheral extraction of formation water or other fluids. None of these techniques have yet been used in CO_2 storage applications or environments, but are routinely used in oil & gas industry. - For carbon mineralisation permanence depends on geological formation, technique used and on the pre-, mid- and post-injection operation and management of the storage facility[32]. CarbFix implemented a solution trapping technique (where CO_2 is first dissolved in water and trapped at depth) in order to prevent CO_2 leakage in the absence of an impermeable caprock at the mineralisation site[12].
Practical barriers	Are there **other barriers** that would limit the wide-scale uptake/ implementability of this solution (e.g. legal, land area requirements, public acceptance, ownership, economic considerations etc.) - Solvent degradation[5] - Increased demand for thermal energy[5]

Solution fiche template	
Section	Aspects covered
	• Lack of widespread CCS infrastructure but possibility to reuse existing infrastructure/equipment used in Oil & Gas industry and possibility to use existing steel pipeline with limited infrastructure upgrade[30], [34] • Cross-chain risks (i.e. interdependence among parties) and associated lack of incentives for storing CO_2[5] • Long term liabilities[5] • Legal restrictions at national level, e.g. onshore storage prohibited in UK, Norway and the Netherlands, no storage allowed in five federal states in Germany, Latvia and Austria. Most EU governments are either positive or neutral reg. deployment of CCS[1], [2]. • Issue reg. public acceptance, e.g. public opposition against onshore storage in Germany, but established body of research giving insight in the factors influencing social acceptance for CCS [2], [35], [36], [37] • Little public awareness specifically for carbon mineralisation[38]. • Scalability dependent on identification of suitable storage reservoirs with close proximity to the CO_2 source and reservoir development (drilling and building a storage infrastructure)[4].
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** • MRV of CO_2 capture at energy and industrial facilities is well established, e.g. IPCC GL (volume 2 & 3), EU CCS Directive, EU ETS • Sophisticated MRV techniques needed for the storage part e.g. seismic imaging, measuring pressure in and above sequestration reservoir, routine measurements of well integrity, aerial imagery, gravity field monitoring, marine and seabed surveys – requirements laid out in the EU CCS directive and IPCC GL (Volume 2 – Chapter 5)[16] • Significant research on monitoring & verification of storage, and on both leak detection and remediation[39]. • EU ETS MRG require amount of emissions leaked from the storage complex to be quantified for each leakage event with max. overall uncertainty over the reporting period of ±7.5%[33]. • Limited experience with different methods for monitoring CO_2 storage, particularly in relation to the wide range of geological and site conditions and storage options across Europe[33] • Choice of monitoring technologies on a site-by-site basis (IPCC GL (Volume 2 – Chapter 5) • Limitations to monitoring plan in the areas of quantification, accuracy, resolution and the time sampling of specific monitoring in the overall storage life cycle[33] • Reducing MRV costs is needed for large-scale project deployment[40] • Current lack of MRV guidelines for carbon mineralisation specifically. Uncertain and high complexity of MRV methods[32]. • For carbon mineralisation, the CarbFix project uses SF6 and 14C tracers to assess the fate of CO_2 in the basalt-hosted aquifer, whereas in the Wallula project, extensive surface studies and borehole observations were used to detect potential leakage of CO_2[12]. • Carbon mineralisation may not require long-term monitoring (in comparison with conventional geological storage)[4]. **Baseline setting methods** (including existing baseline data options)

Solution fiche template	
Section	Aspects covered
	- EU ETS: fossil-based CO_2 captured from installation and transferred to storage site regulated by EU CCS directive subtracted from installation inventory, counted as avoided emissions[41] - EU/EEA Innovation Fund: Reference GHG emissions based on CO_2 releases that would occur in the absence of the project **Key references** - EU ETS directive and Monitoring and Reporting Guidelines - EU: CCS Directive 2009/31/EC and guideline documents provides the legal framework for the safe selection of storage sites and regulates the concession of storage permits[42] - Industrial Emissions Directive 2010/75/EU, regarding transport aspects - IPCC Guidelines – Volumes 2 (Chapter 5) on carbon transport, injection and geological storage, Volumes 2 & 3 on carbon capture from fuel combustion (under "Energy") or process-related (under "Industrial Processes and Product Use") - CDM procedures to manage a range of physical and accounting risks, including risks and liability - US 45Q tax credit system – MRV guidance on the tax credit requirements

Co-benefits and negative externalities/leakage risks	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts)
	- Co-benefits:
	  - Reuse of existing Oil & Gas infrastructure
	- Negative externalities:
	  - Risk of carbon lock-in on fossil fuel infrastructure
	  - Fossil-based CO_2 compete for storage against biogenic CO_2
	  - Potential risk of water pollution due to overpressure[39], [42]
	  - Potential risk of enhanced seismic activity [39], [42]
	  - CO_2 leakage, even at very low rate, could have negative local health & environmental impacts, but these are expected to be limited [30], [39], [42], [29]
	Understanding of side effects/leakage risks
	- n/a

Governance aspects	**Actors involved** - Large CO_2-emitting industrial installations: cement, steel & iron, hydrogen, fertiliser - Oil & gas industry (Equinor, Shell, E-Gas) - Technology developers (e.g. Siemens, CarbFix)[43] - Research institutes - Energy company (e.g. Reykjavik Energy) **Project scale/size** - Large-scale projects (capacity of existing projects: 0.3-8.4Mt CO_2/year)[2] **Linkage to existing policies and measures/strategies/funding schemes** (applicable in the EU) - EU/national funding, e.g. EU Innovation Fund, EU Just Transition Fund, Recovery and resiliency facility, CCS Infrastructure Fund in the UK, Sustainable Energy Transition subsidy scheme in the Netherlands

Solution fiche template	
Section	Aspects covered
Existing certification mechanisms	- CDM - but no CCS projects have ever been approved under the CDM[44] - EU CCS directive - US 45Q tax credit system - California Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard - Climeworks sells CO_2 removed via DAC + in-situ carbon mineralisation by their partners CarbFix, but there is no formal certification process

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[1] IOGP (2019), The Potential for CCS and CCU in Europe (link)

[2] IEA (2020) Energy Technology Perspectives 2020. Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions (link)

[3] Joint Research Centre (2020), Negative emissions technologies

[4] Royal Society & Royal Academy of Engineering (2018), Greenhouse gas removal (link)

[5] Global CCS Institute (2020), Global Status of CCS 2020 (link)

[6] IEA (2020), Energy Technology Perspectives 2020 (link)

[7] Global CCS Institute (n.d.), Facilities database (link)

[8] Equinor (2019), Sleipner partnership releases CO_2 storage data (link)

[9] Institution of Civil Engineers (2017), Sleipner carbon capture and storage project (link)

[10] Zero Emission Resource Organisation (n.d.), Snøhvit (link)

[11] Ramboll Group (2020), CCS/CCU catalogue

[12] National Academy of Sciences, Engineering, and Medicine (2019), Negative Emissions Technologies and Reliable Sequestration. A Research Agenda (link)

[13] Bui et al. (2018), Carbon Capture and Storage (CCS): the way forward (link)

[14] EASAC (2018), Negative Emission Technologies: What role in meeting Paris Agreements targets? (link)

[15] Budinis et al. (2018), An assessment of CCS costs, barriers, and potential (link)

[16] European Commission (2012), Ensuring safe use of carbon capture and storage in Europe (link)

[17] Office of Fossil Energy (n.d.), Post-Combustion Carbon Capture Research (link)

[18] European Commission (2018), In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (link)

[19] Kearns et al. (2017), Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide (link)

[20] EASAC (2019), Forest bioenergy, carbon capture and storage, and carbon dioxide removal - an update (link)

[21] IEA (2020), Indicative unit CO_2 pipeline transport costs, onshore (link)

[22] IEA (2020), Shipping and offshore pipeline transportation costs of CO_2 by distance (link)

[23] European Technology Platform for Zero Emission Fossil Fuel Power Plants (n.d.), The Costs of CO_2 Storage. Post-demonstration CCS in the EU (link)

---

[24] European Technology Platform for Zero Emission Fossil Fuel Power Plants (2019), The cost of subsurface storage of CO_2 (link)

[25] Núñez-López, V. and Moskal, E. (2019), Potential of CO_2-EOR for Near-Term Decarbonization (link)

[26] Global CCS Institute (2020), Is CCS Expensive? Decarbonisation costs in the net-zero context (link)

[27] European Technology Platform for Zero Emission Fossil Fuel Power Plants (n.d.), Post 2020, CCS will be cost-competitive with other low-carbon energy technologies (link)

[28] Benson et al. (2005), Chapter 5 - Underground geological storage (link)

[29] European Technology Platform for Zero Emission Fossil Fuel Power Plants (2019), CO_2 Storage Safety in the North Sea: Implications of the CO_2 Storage Directive (link)

[30] Ecofys (2017), CCC indicators to track progress in developing greenhouse gas removal options (link)

[31] European Commission (2015), Study to support the review and evaluation of Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive) (link)

[32] NewClimate Institute (2020), Options for supporting Carbon Dioxide Removal (link)

[33] European Commission (2011), Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide (link)

[34] Joint Research Centre (2019), Direct Air Capture (link)

[35] Siego et al. (2014), Public perception of carbon capture and storage (CCS): A review (link)

[36] Gough et al. (2018), Understanding key elements in establishing a social license for CCS: An empirical approach (link)

[37] d'Amore et la. (2020), Introducing social acceptance into the design of CCS supply chains: A case study at a European level (link)

[38] NEGEM (2021), Stocktaking of scenarios with negative emission technologies and practices (link)

[39] Fuss et al. (2018), Negative emissions—Part 2: Costs, potentials and side effects (link)

[40] Orr, F.M. (2018), Carbon Capture, Utilization, and Storage: An Update (link)

[41] IEA Greenhouse Gas R&D Programme (IEAGHG) (2014), Biomass and CCS-guidance for accounting for negative emissions (link)

[42] European Parliament (2021), Carbon dioxide removal: Nature-based and technological solutions (link)

[43] Siemens (2010), Siemens Post-Combustion CO_2 Capture Technology for combined cycle and steam power plant applications (link)

[44] Climate Analytics and C2G (2021), Governing large-scale carbon dioxide removal: are we ready? - an update (link)

5.12 Fiche: Carbon Capture and Utilisation (CCU)

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Solution name	**Carbon Capture & Utilisation (CCU)**

Introduction	**Brief description of the technology**
	- Set of technologies involving the utilisation of CO_2 from various sources (e.g. air, biogenic, fossil) in diverse production processes. Some applications include direct use of CO_2 such as in soft drinks production, greenhouses, and in enhanced oil recovery (EOR) where it is used as a working fluid or solvent – these are not further addressed in this fiche, and EOR is addressed in the CCS fiche. Other applications use CO_2 as a feedstock in chemical or biological technologies to convert it into value-added products which then retain CO_2 for different time periods, mainly [1], [2], [3]:
	  - Fuels: carbon in CO_2 used to convert hydrogen into a synthetic hydrocarbon fuel that can be used as gaseous or liquid fossil fuel
	  - Chemical building blocks: carbon in CO_2 used as an alternative to fossil fuels in the production of chemicals that require carbon to provide their structure and properties, e.g. polymers and primary chemicals such as ethylene and methanol, which are building blocks to produce a range of end-use chemicals
	  - Building materials: CO_2 can be used in the production of building materials as feedstock in its constituents (i.e. cement and construction aggregates) via reaction between CO_2 and minerals or waste streams (e.g. concrete waste) to form carbonates. Another way that CO_2 can be used in building materials consists in adding CO_2 to concrete during curing, CO_2 emissions originating from calcination of carbonate rocks during the manufacture of cement (excl. energy-related emissions) can to a certain extent be taken up in the concrete by carbonation depending on availability of CO_2, moisture factors and exposure surface[2], [3]. This technique also reduces the quantity of cement needed to reach similar product strength requirements.
	  - Other pathways include e.g. biological production of fuels and chemicals from algae feeding on CO_2
	GHGs targeted (and land use category, if appropriate)
	- Carbon dioxide (CO_2)
	Examples of solutions already operational or in planning
	- 9 operational pilot/commercial projects referenced as operational/ongoing on Smart CO_2 Transformation platform[4]
	- George Olah facility owned by Carbon Recycling International (CRI) and jointly operated by HS Orka and CRI (Iceland)[1], [5]: operational since 2012, capacity: approx. 5,600 tCO_2/year, first commercial plant based on the ETL technology, produces methanol from CO_2 captured from the Svartsengi geothermal power station which also supplies power for electrolysis of water to produce hydrogen[6]. CRI offers a standard plant design with a nominal production capacity of 50,000-100,000 tonne methanol per year[7].
	- Covestro facility in Dormagen (Germany)[1]: operational since 2016, produces around 5,000 t/year of polyether polycarbonate polyol (cardyon®) where CO_2 substitutes up to 20% of fossil feedstock normally used in the process (TRL = 6-7). The polyol can be converted into flexible polyurethane foam.

Solution fiche template	
Section	Aspects covered
	• CarbonCure (US & Canada): has developed four curing technologies (for ready mix concrete, reclaimed water, recast and recycled aggregates), operates approx. 300 CO_2-curing concrete facilities, and aims to utilise approx. 166 $MtCO_2$/year by 2030 for application to building materials[1], [8]. • Carbon8 (UK): developed the “Accelerated Carbonation Technology”, currently operating two commercial plants using CO_2 to convert waste residues into lightweight aggregates as a component of building materials, capacity: 5,000 tCO_2/year to convert approx. 60 kt/year of APC residues, aims to have six other plants in 2021[6]
Potential	

Technology readiness level (TRL)	Current TRL level
	• For TRL of carbon capture technologies, see “CCS” fiche. On the application side, many technologies are at early stage of development[1]
	• TRL depending on products & pathways:
	  ◦ CO_2 to fuels via chemical pathways (synthetic methane, methanol, ammonia, synthetic liquid hydrocarbon, DME, Fischer-Tropsch diesel): wide range – near commercial to early stage R&D [2]; TRL = 4-9 for [9], [10]
	  ◦ CO_2 to chemical building blocks via chemical pathways (OME1, ethylene, PP, propylene, PU, and PE): wide range – near commercial to early R&D [2], TRL: 7-9 [9]
	  ◦ CO_2 to building materials via mineralisation (calcium and sodium carbonates): commercial/near commercial [2], TRL = 6-8 [9]
	  ◦ Algae-based CO_2 products (proteins, ethanol, methane): commercial/near commercial[2], TRL = 5-8 [9]
	Qualitative discussion of development (e.g. expected TRL level by 2030, 2050, development risks, uncertainties)
	• CCU technology developers & researchers mostly active in production of chemical intermediates, fuels and building materials, and in processes such as mineralisation, catalytic conversion, and in electrochemical processes[11]
	• R&D needs for CCU to fuels and chemical products: catalyst development, low carbon, low cost hydrogen; electrochemical process development; photocatalytic processes; LCA development[2]
	• Commercial deployment opportunity: near-term (3-10 year) for building materials, near-to medium term (5-20 years) for chemical commodities[12]

Potential carbon removals	**Technical and/or realistic potential** (i.e. t CO_2-e removals, Europe-wide, annual – now, future) and total potential removal
	• Current global market for CO_2 estimated at 0.08-0.18 $GtCO_2$/year[13], [14]
	• Difficult to estimate potential of CO_2-based products due to immature technologies, market expected to remain small in the short term, but could grow rapidly in the longer term[1]
	• Wide range of global potential estimates:
	  ◦ 1-2 $GtCO_2$/year in by 2050[13]
	  ◦ Very optimistic (with strategic actions implemented e.g. R&D to reduce costs and infrastructure development): 7 $GtCO_2$/year by 2030[11], [6]
	Global CO_2 use potential of carbon-based products industry:
	• Fuels: 0.07-2.1 $GtCO_2$/year by 2030[2], [11], 1-4.2 $GtCO_2$/year by 2050[15]
	• Building materials: 0.9-5 $GtCO_2$/year by 2030[11], 0.1-1.4 $GtCO_2$/year by 2050[15]

Solution fiche template	
Section	Aspects covered
	• Methanol: 5-50 MtCO_2/year by 2030[11] • Polymers: 0.1-2 MtCO_2/year by 2030[11] • Chemicals: 0.3-0.6 GtCO_2/year by 2050[15] • Algae-based products: up to 3 GtCO_2/year by 2030[2], 0.2-0.9 GtCO_2/year by 2050[15] • EU-level CO_2 use potential in products • Synthetic fuels: 150-275 MtCO_2/year by 2050 (Clean Planet scenario)[16] • Max. removal potential per product and route provided, for example: ◦ Methane (via CO methanation over a nickel catalyst or Gas fermentation of syngas by the anaerobic bacterium Clostridium sp.): 1008-1862 MtCO_2/year[9], [17] ◦ Synthetic fuel (via high temp. electrolysis and inverse CO-shift of CO_2 followed by Fischer Tropsch synthesis to Cn hydrocarbon): 525-1206 MtCO_2/year[9], [17] ◦ Calcium/magnesium carbonates - construction aggregates (via Single-step direct aqueous mineralisation of calcium/magnesium silicates or two-step mineralisation to improve mineral dissolution and carbonate formation): 115-412 MtCO_2/year [9] ◦ Concrete product (via CO_2 injected into concrete to form calcium carbonate nanoparticles within the concrete): 332 MtCO_2/year[17] ◦ Ethylene (via Direct using modified F-T catalysis, Direct electrochemical reduction of CO_2, or methanol to olefin (MTO) process - condensation of CO_2-derived methanol to DME followed by conversion to olefin): 56-77 MtCO_2/year[9], [17] ◦ Propylene (via methanol to olefin (MTO) process - methanol plus ethylene or methanol to olefin (MTO) process - condensation of CO_2-derived methanol to DME followed by conversion to olefin): 41-85 MtCO_2/year [9], [17] ◦ Proteins from microalgae: 36 MtCO_2/year [9] ◦ Ethanol (via electrochemical reduction, Electrochemical conversion using copper nanoparticle n-doped graphene electrode, or gas fermentation of syngas produced from CO_2 by the anaerobic bacterium Clostridium autoethanogenum): 10-11 MtCO_2/year[9], [17] ◦ Across 43 CCU products: 1,000 tCO_2/year - 2 GtCO_2/year[17] [17] ◦ Theoretical total annual CO_2 binding volume of 15 shortlisted products amounts to 2Gt CO_2/year[9] • Natural concrete curing process: ◦ Tier 1 value suggested to account for total CO_2 uptake in the use stage and end-of life stage of concrete buildings at national level: 23% of the national calcination emission. For EU-28, this would be: 22.5 MtCO_2/year (78 MtCO_2 from cement production and 20 MtCO_2 cement production from lime production in 2018)[18] **Constraints/interaction effects and assumptions (**e.g. land use requirements, contingencies reg. other solutions) • CCU compete with other low-carbon solutions dependent on renewable electricity, e.g. transport electrification[19] **Brief description of calculation method and uncertainties** • Estimates provided by ICEF[11] derived from estimated market size in 2015, estimated compounded annual growth rates (CAGR), and estimated market penetration of CCU technologies depending in a scenario where strategic actions are implemented, and in a scenario where status quo is maintained

Solution fiche template	
Section	Aspects covered
	• Max. CO_2 utilisation potential into each product determined by multiplying tonnes of CO_2 used per tonne of product by the quantity of product demand. Product demand derived from Eurostat databases (2016) to obtain the quantities of conventionally produced chemicals produced within + imported into, the EU28 countries[17]. **System boundaries and life cycle emissions considerations** • CCU can have climate benefits over their life cycle if they rely on low-carbon energy and displace a product with higher life cycle emissions, but climate benefit quantification is challenging, and improved methodologies are needed to inform future policy and investment decisions[6] • Current LCA methods not designed to distinguish between various temporary carbon retention times, several approaches proposed to address this challenge but current lack of consensus among experts[6]
Costs	**Current costs** (i.e. overall €/t CO_2-e, set-up costs, ongoing costs) • CO_2-based products likely to be much more expensive than conventional and alternative low-carbon products due to high-energy intensity, apart from building materials[1] • Break-even cost (cost in 2015 USD/tCO_2 adjusted for revenues, by-products, and any CO_2 credits or fees, likely to underestimate the ability to achieve economies of scale)[15] ◦ Fuels: 0-670 USD/tCO_2 ◦ Concrete building materials: -30-70 USD/tCO_2 ◦ Chemicals: -80-300 USD/tCO_2 ◦ Algae-based products: 230-920 USD/tCO_2 • EU-level costs of CO_2 use (based on production costs and CO_2 binding)[9] ◦ Synthetic fuel (via high temp. electrolysis and inverse CO-shift of CO_2 followed by Fischer Tropsch synthesis to Cn hydrocarbon): 470 EUR/tCO_2 ◦ Methanol (direct hydrogenation): 489 EUR/tCO_2 ◦ Methane (hydrogenation or methanation): 730-1277 EUR/tCO_2 ◦ Ethylene (via Methanol to Olefin and DME as intermediate): 219-468 EUR/tCO_2 ◦ Calcium carbonate/sodium carbonate: 136 – 227 EUR/tCO_2 ◦ Proteins from micro-algae (animal feed): 1,111-11,111 EUR/tCO_2 **Projected future costs** • Ability to maintain security in the supply of fuels and commodity chemicals that have traditionally relied on petrochemical feedstocks is a key driver for future investment in CCU[19] **Energy demand** • Fuels: highly energy-intensive, and most economically viable where both low-cost renewable energy and CO_2 are available[1] • Chemical building blocks: energy demand varies significantly according to the pathway[1], low energy demand for polymers[6] • Building materials: less energy-intensive than for fuels and chemicals CCU pathways[1], mineralisation of building waste can be performed in lower temperature and pressure conditions than mineralisation of silicate rocks and hence is less energy-demanding, but depends on carbonation process and transport distances for materials[6], [20]
Duration of removals / permanence	Duration of removals & risks of reversibility

Solution fiche template	
Section	Aspects covered
	- The retention of CO_2 in CCU products depends highly on the application. It is temporary for fuels and chemicals building blocks (less than 1 year for fuels, up to 10 years for most chemical intermediates, up to hundreds of years for polymers), while it can be permanent for building materials[1], [6], [9] **Conditions for permanence and options to manage impermanence** - Permanence of CO_2 removals associated with CCU products that temporary retain CO_2 depends on the end-of-life pathway, e.g. plastics may be recycled, incinerated or landfilled[6] - Experts advocate LCA to address impermanence issues in accounting, but no consensus on the methodology[21]
Practical barriers	Are there **other barriers** that would limit the wide-scale uptake/ implementability of this solution (e.g. legal, land area requirements, public acceptance, ownership, economic considerations etc.) - Large-scale deployment of CO_2-based chemicals and fuels dependent on large-scale supply of renewable electricity[1], [6] and access to low-cost hydrogen[11] - Large-scale deployment of CCU to building materials requires increased availability of alkaline materials to provide needed calcium and/or magnesium[2], 1.6-3.7t of the carbonatable materials to fix 1 tCO_2[20] - Fuels, building products and commodity chemicals are highly standardized & regulated and established markets difficult to penetrate with new products[2] - Lack of governmental priorities on R&D for CCU[11], although recent developments in e.g. Germany and France - Lack of value chain integrating conversion, hydrogen generation and carbon capture[11] - Need for R&D on catalysts to reduce energy required in conversion processes[11]
Suitability	
MRV	**Qualitative discussion and critical assessment of MRV, and uncertainties** - CO_2 inputs and product outputs can be measured with high level of accuracy e.g. in CCU to methanol and building materials[21] - Complexity to design an MRV framework because of the wide range of products operating in different markets and risk of double counting or leakage in case the MRV system is not well-designed (e.g. emission monetised in one sector but emitted in another sector without capturing in the MRV system) [6] - No existing carbon pricing systems in force today cover CO_2 emissions across all sectors[6] - The MRV framework would have to recognise whether or not the carbon is permanently stored in the product and including downstream emissions in the MRV framework should not interfere with legislation already tackling downstream emissions, e.g. transport fuel directives[6]. - Blacklisting CCU processes based on LCA results has been suggested to introduce CCU into the EU ETS, to avoid deductibility of emissions in the case of environmentally disadvantageous CCU processes[22] - Other suggested indicators to compare CCU processes include Carbon to Atmosphere Factor (indicating whether the process leads to net emissions or net removal of CO_2 to/from the atmosphere) and Net Energy Factor (indicating how much extra energy is needed for the CCU and CCS technologies per tonne of CO_2 abated)[23].

Solution fiche template	
Section	Aspects covered
	• EU/EEA Innovation Fund requires from participants a monitoring plan incl. source of data, measurement methods and procedures, monitoring frequency, quality assurance and control procedures, responsibility for collection and archiving. Uncertainties dealt with e.g. by using conservative estimates and measures. But also, if there is no guarantee that the CO_2 will not be emitted in use or end of life, such as in CCU methanol or CCU ethanol, the combustion emissions are added to the calculation of GHG emission avoidance • CCU to fuels[24]: EU RED II directive will establish in delegated acts (2021) 1) methodology for assessing GHG emissions savings from recycled carbon fuels, which shall ensure that credit for avoided emissions is not given for CO_2 the capture of which has already received an emission credit under other provisions of law, and 2) minimum thresholds for GHG emissions savings of recycled carbon fuels through LCAs **Baseline setting methods (**including existing baseline data options) • 45Q tax credit: CO_2 eligible for crediting would have otherwise been released into the air[6] • EU/EEA Innovation Fund: Reference GHG emissions based on EU ETS benchmark(s) or 2030/2050 forecasts for the power mix **Key references** • ZEP (2020) A method to calculate the positive effects of CCS and CCU on climate change • EU/EEA Innovation Fund (2020) Methodology for calculation of GHG emission avoidance • US 45Q tax credit system – MRV guidance on the tax credit requirements
Co-benefits and negative externalities/leakage risks	**Co-benefits** (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts) • Positive ◦ Public acceptance is generally higher for CCU than for CCS, which provides an opportunity to build trust among parties and then transfer it to the CCS by increasing synergy between CCU and CCS[19] ◦ Fostering circular use of carbon ◦ Use of existing infrastructure (power to gas/liquids) ◦ Solution for energy storage (Power to gas/fuels) • Negative • High energy demand for CCU pathways (e.g. chemicals and fuels) • Understanding of side effects/leakage risks • Effective accounting system must be in place to ensure that subsequent release of CO_2 retained in CCU products is taken into account[21]
Governance aspects	**Actors involved** • 180 global developers include start-ups, mid-sized companies, corporations, consortia, and research institutes[11] • Building materials: Carbon8, Solidia Technologies and CarbonCure • Polymers: Covestro, Novomer and Asahi Kasei • Fuels: Carbon Recycling International (CRI), Miracles **Scale/size of projects** • CCU to fuel (example from CRI): 5,600 tCO_2/year • CCU to building aggregates (example from Carbon8): 5,000 tCO_2/year CCU to concrete curing (example of CarbonCure Ready Mix)[8]: CO_2 added at a rate of 0.15% by weight of cement to ready mix concrete, example of Iowa City Ready Mix with 2.7 tCO_2 utilised in 5 months at one plant using CarbonCure Ready Mix (equivalent to 6.5 tCO_2/year)[25].

Solution fiche template	
Section	Aspects covered
	Linkage to existing policies and measures/strategies/funding schemes (e.g. CAP) • R&D funding: Mission Innovation, EU's Horizon 2020 programme, EU/EEA innovation fund, US DOE's Carbon Use and Reuse R&D portfolio, National Key R&D programmes on CO_2 use in the Chinese 13th Five-Year Plan • Public procurement: in Canada and the Netherlands, that favour material inputs with low-carbon footprints for construction projects • Mandates: EU Renewable Energy Directive (RED II) and Low Carbon Fuel Standard in California, favouring low-carbon transport fuels including recycled carbon (CO_2-derived) fuels
Existing certification mechanisms	• Puro Earth methodology on carbonated building elements • VCS methodology for CO_2 Utilisation in Concrete Production (in development) • VCS methodology for Greenhouse Gas Capture and Utilisation in Plastic Materials (v1.0) • US 45Q tax credit system – MRV guidance on the tax credit requirements

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[1] IEA (2020), Energy Technology Perspectives 2020 (link)

[2] C2ES (2019), Carbon utilization: A vital and effective pathway for decarbonization (link)

[3] Stripple et al. (2018), CO_2 uptake in cementcontaining products Background and calculation models for IPCC implementation (link)

[4] European Commission (n.d.), CO_2 utilisation projects (link)

[5] Offshore Technology, (n.d.)

[6] IEA (2019), Putting CO_2 to use (link)

[7] Carbon Recycling International (n.d.), Technology and Services (link)

[8] Carbon Cure (n.d.), CarbonCure's 500 Megatonne CO_2 Reduction Technical Roadmap (link)

[9] European Commission (2019), Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects (link)

[10] Ramboll Group (2020), CCS/CCU catalogue

[11] Innovation for Cool Earth Forum (2016), Global Roadmap for Implementing CO_2 Utilization (link)

[12] Innovation for Cool Earth Forum (2017), Carbon Dioxide Utilisation (CO_2U). ICEF Roadmap 2.0 (link)

[13] European Commission (2018), Novel carbon capture and utilisation technologies (link)

[14] Orr, F.M. (2018), Carbon Capture, Utilization, and Storage: An Update (link)

[15] Hepburn et al. (2019), The technological and economic prospects for CO_2 utilization and removal (link)

[16] European Commission (2018), In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (link)

[17] Carbon Next project (2017). Deliverable 2.1: Report on fully integrated and intensified value chain concepts for process selection (link)

[18] Eurostat. (2021) Title: Greenhouse gas emissions by source sector (source: EEA), Code: env_air_gge

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[19] Joint Research Centre (2020), Negative emissions technologies

[20] Skocek et al. (2020) Carbon capture and utilization by mineralisation of cement pastesderived from recycled concrete (link)

[21] IEA Greenhouse Gas R&D Programme (IEAGHG) (2018), 2018-TR01C GREENHOUSE GAS EMISSIONS ACCOUNTING FOR CARBON DIOXIDE CAPTURE AND UTILISATION (CCU) TECHNOLOGIES - SYNTHESIS OF RESEARCH FINDINGS (link)

[22] German Environment Agency (2019), Support for the revision of the Monitoring and Reporting Regulation for the 4th trading period (focus: Carbon Capture and Utilisation (CCU)) (link)

[23] European Zero Emission Technology and Innovation Platform (2020), A method to calculate the positive effects of CCS and CCU on climate change (link)

[24] Official Journal of the European Union (2018), DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (link)

[25] Carbon Cure (n.d.), Iowa City Ready Mix & CarbonCure: A Success Story. Blazing a trail with greener concrete (link)

6 ANNEX 2 - SOLUTION FICHE TEMPLATE

Table 4 Solution fiche template

Solution fiche template	
Section	Aspects covered
Descriptive/context	
Solution name	**Name**
Introduction	• Brief description of the technology • GHGs targeted (and land use category, if appropriate) • Examples of solutions already operational or in planning
Potential	
Technology readiness level (TRL)	• Current TRL level • Qualitative discussion of development (e.g. expected TRL level by 2030, 2050, development risks, uncertainties)
Carbon removal potential	• Technical and/or realistic potential (i.e. t CO_2-e removals, global, Europe-wide, annual – now, future) and total potential removal • Constraints/interaction effects and assumptions (e.g. land use requirements, contingencies reg. other solutions) • Brief description of calculation method and uncertainties • System boundaries and lifecycle emissions considerations
Costs	• Current costs (i.e. overall €/t CO_2-e including CAPEX and OPEX costs) • Projected future costs • Energy demand
Duration of removals / permanence	• Duration of removals & risks of reversibility • Conditions for permanence and options to manage impermanence
Practical barriers	• Are there other barriers that would limit the wide-scale uptake/ implementability of this solution (e.g. legal, land area requirements, public acceptance, ownership, economic considerations etc.)
Suitability	
MRV	• Qualitative discussion and critical assessment of MRV, and uncertainties • Baseline setting methods (including existing baseline data options) • Key references (to existing MRV frameworks)
Co-benefits and negative externalities/leakage risks	• Co-benefits (e.g. downstream productivity benefits) and negative externalities (e.g. biodiversity impacts, water quality/quantity impacts), • Understanding of side effects/leakage risks
Governance aspects	• Actors involved (i.e. sectors and if available, examples of organisations) • Scale/size of projects • Linkage to existing policies and measures/strategies/funding schemes (e.g. CAP)
Existing certification mechanisms	• Is this technology already applied under existing certification mechanisms? Reference to fiche, or short description.

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The European Commission is developing a certification mechanism for nature-based (NBS) and technology-based carbon removal solutions (TBS). To support its development, this report reviews twelve existing NBS and TBS regarding their potential to remove carbon and their suitability for deployment within Europe. Each solution is described with their maturity, estimates of carbon removal potential (tCO_2-e), costs, practical challenges and permanence aspects. By documenting different key characteristics the report supports the development of a robust and effective system to incentivise uptake of carbon removals within Europe.

This report is published alongside a second, related report, “Certification of carbon removals - Part 2: A review of carbon removal certification mechanisms and methodologies”.

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