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GLOBAL GOVERNANCE OF NEGATIVE EMISSION TECHNOLOGIES AND PLATFORMS- GLOBAL SUPPLY CHAINS AND COHERENT ACCOUNTING

BELLONA REPORT

DISCLAIMER

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NEGEM

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EXECUTIVE SUMMARY

Negative Emission Technologies and Practices (NETPs) are intricate systems which aim to reduce the amount of CO_2 present in the atmosphere and are an essential component to achieve the targets of the Paris Agreement. For NETPs to achieve their intended purposes, they must demonstrably remove more CO_2 than they emit greenhouse gas (GHGs) in the process of doing so. However, proving the realisation of this objective is complicated by their temporal and spatial nature. For all NETPs, the quantification of their overall net impact on the climate system presents a challenge because of their varying energy and material inputs, as well as the inherent difficulty of monitoring storage over extended periods of time. Moreover, NETPs which cross jurisdictional boundaries present an additional challenge due to the nature of existing GHGs accounting frameworks, which attribute responsibility for emissions and removals on a territorial basis.

Projects that cross territorial boundaries may therefore fail to fully account for the net climate impact due to unharmonized standards and monitoring. At the same time, countries only report part of the overall NETP system in their own national inventories. The superposition of difficult-to-quantify NETPs systems along with the truncated nature of global GHGs accounting will make it difficult to identify and quantify the real-life net removal of such projects.

POLICY RELEVANT MESSAGES:

Adopt a robust definition of carbon dioxide removal (CDR), including:

- physical extraction of CO_2 from the atmosphere, the permanent storage of that CO_2, and the accounting for all associated emissions in the extraction and storage processes and associated supply chains so that only *net* removal is considered CDR

- a definition of permanence that, at minimum, aligns with the physical lifespan of CO_2 in the atmosphere, 300-1000 years
- accurate and usable methodologies to measure and monitor greenhouse gas flows

Implement guardrails for NETP deployment, including:

- explicit CDR targets that sit on top of emission reduction targets
- strict sustainability criteria for biomass, energy, land, water, and other resources used in a NETP system
- near term, deploy NETP systems with short supply chains, that minimise geographic and temporal distance between extractions, storage, and associated emissions, as well as for NETP systems with geological storage that has a low risk of reversal

Address gaps in CDR life cycle accounting, including the need for**:**

- a mandate that only "cradle-to-grave" system boundaries are acceptable for LCA of NETP systems
- ensuring all carbon that enters the system is accounted for from source to sink—carbon balances should always close,
- separate accounting of emissions, extractions, removals, and avoided emissions
- separate accounting of CO_2 stored in biological sinks and CO_2 stored in geological sinks

Address gaps in territorial accounting, including the need for**:**

- explicit treatment of non-biological methods of extracting of CO_2 from the atmosphere
- explicit treatment of non-geological storage of CO_2
- explicit separation of reporting of emissions, extractions, and storage of CO_2, instead of reporting net changes in flows or stock

Maintain rigour when merging CDR life cycle accounting with territorial accounting:

- all associated emissions of the extraction and storage processes, including intermediate transport and conversion and upstream supply chains
- uniformly high quality of methodologies used for accounting extraction, storage, and associated emissions
- liability for reversals and leakage, regardless of when or where they occur
- minimum acceptable CDR efficiencies, to reduce the risk of "false CDR", where a CDR system, due to unexpected impacts, or incomplete accounting, leads to an increase in atmospheric greenhouse gas emissions

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INTRODUCTION

The urgency and scale of the climate crisis requires not only the rapid and immediate reduction of greenhouse gas emissions, but also the large-scale removal of greenhouse gases, specifically CO_2, from the atmosphere. The most recent IPCC report on climate change identifies three sequential roles of carbon dioxide removal in mitigating catastrophic climate change (Figure 1)

1. As a supplement to rapid and massive reductions in emissions, thus accelerating net reductions and decreasing the speed of global warming.
2. As a means to balance remaining emissions of fossil CO_2 and non-CO_2 greenhouse gases to maintain "net zero", thus stabilising the amount of greenhouse gases in the atmosphere.
3. As a means to achieve a "net negative" society, where the amount of greenhouse gases in the atmosphere decreases.

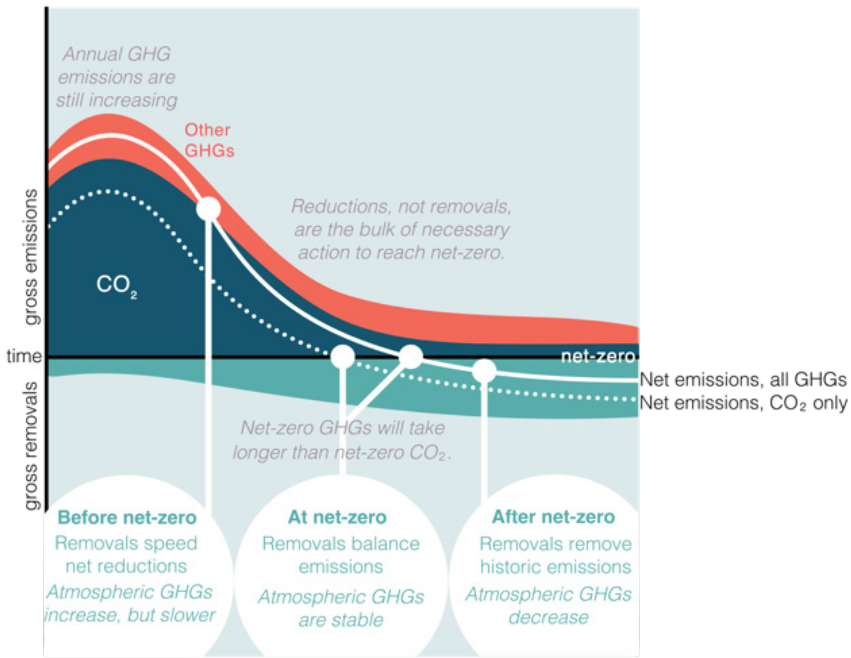

Figure 1. The three sequential roles of carbon dioxide removal in mitigating catastrophic climate change[1]

To generate carbon dioxide removal, also known as negative emissions, an activity must meet four minimum criteria, as summarized by Tanzer and Ramirez (2019) , namely:

Physical extraction: Physical greenhouse gases are removed from the atmosphere.

Permanent storage: The removed gases are stored out of the atmosphere in a manner intended to be permanent.

Complete accounting of associated emissions: Upstream and downstream greenhouse gas emissions associated with the removal and storage process, such as biomass origin, energy use, gas fate, and co-product fate, are comprehensively estimated and included in the emission balance.

Net removal: The total quantity of atmospheric greenhouse gases removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere.

There are many available pathways that could potentially result in negative emissions (Figure 2) by extracting and storing atmospheric carbon. However, large scale removal of carbon dioxide from the atmosphere is a complex task that currently has many uncertainties. A fundamental concern is "how much carbon dioxide removal can we accomplish, both annually and cumulatively?", which in turn informs what is the allowable quantity of residual emissions in a net-zero world. The future availability of negative emission technologies and practices (NETP) is dependent on groundwork laid now to ensure the technical availability of NETP system components such as sustainable biomass, renewable energy, CO_2 transport and storage; systems for physically monitoring and measuring the extraction, emission, and storage of greenhouse gases; accurate models that can be used to estimate the behaviour of NETPs over time and their interactions with the environment; and robust policies to incentivise NETP development and prevent the misuse of resources or incomplete accounting of when net removal occurs.

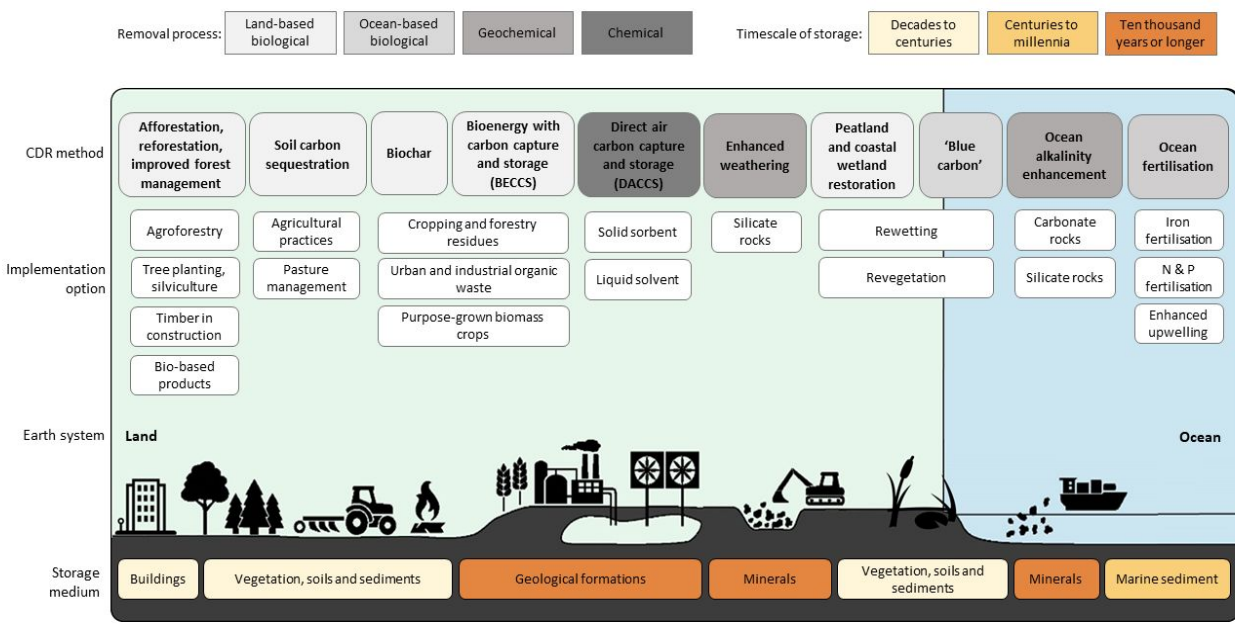

Figure 2. Carbon dioxide removal, or "negative emissions" is the physical, permanent, and net removal of greenhouse gases from the atmosphere.

A variety of options to remove and store atmospheric CO_2 are available but ensuring that these activities result in true CDR requires managing storage to prevent or compensate for any potential re-emissions, and to ensure that the quantification of CDR accounts for the greenhouse gas emissions in the removal and storage processes and their supply chains.

Source: IPCC AR6 WGIII, Chapter 12 (Box 8, Figure 1)

This paper is part of that basic research, conducted under the Horizon 2020 NEGEM project, whose goal is to assess the potential available scale of negative emissions possible with different NETPs and concerns relevant to their implementation at scale. A first complexity is that NETPs are diverse and often involve complex supply chains. Extraction, transport, and storage of CO_2 may occur in different jurisdictions, and production and transport of material and energy inputs may be further dispersed.

A second complexity, of critical policy concern, is the issue of greenhouse gas accounting.

For NETPs, accounting has a dual role: first, it must provide an accurate assessment of the flows of greenhouse gases entering and exiting the atmosphere, so as to assess whether and how much a NETP actually results in negative emissions; and second, its potential future role in long term climate plans assesses whether responsible parties, such as nation states, are fulfilling their obligations to reduce their climate impacts. Carbon accounting measures both physical flows of carbon (and other greenhouse gases) and actions actors take to discharge of responsibility to minimise their net greenhouse gas emissions. To do so accurately and fairly requires:

Clear definitions and metrics of what carbon/GHG flows and actions need to be measured and when a removal can be claimed to have occurred.

Clear methodologies with a scientifically-sound basis of how to measure physical flows of carbon and other greenhouse gases in the extraction and storage processes and in the associated supply chains, including those occurring in disperse locations, over time, such as in transboundary supply chains.

Clear jurisdiction that defines who is responsible for conducting and reporting the measurement.

Clear liability that defines who is responsible for removals and emissions that occur at different locations and timespans, such as in transboundary supply chains.

These accounting issues are particularly relevant in light of the proliferation of “net zero” greenhouse gas targets set by national actors, as “net zero” implies that some quantity of carbon dioxide removal will be used to balance out residual emissions and in fulfilment of international agreements, such as the nationally determined contributions (NDCs) of the Paris agreement. This then further requires international agreement on accounting standards for carbon dioxide removal. While existing accounting frameworks for territorial greenhouse gas emissions exist, such as the IPCC guidelines for national greenhouse gas inventories, there is no international or domestic comprehensive accounting framework for carbon dioxide removals, though there are increasingly urgent calls[3] for framework development and harmonisation. Furthermore, NETPs that involve the transboundary transport of biomass or CO_2 create additional complications, as the emissions and removals may be accounted for differently in different jurisdictions.

To understand the challenges of accounting and governance specific to the large-scale deployment of NETPs, we assess what must be accounted for across different NETPs supply chains; evaluate existing relevant accounting frameworks; provide special attention to existing regulation for transboundary accounting of biomass flows and CO_2 storage; and then illustrate how different NETPs would be accounted for under different frameworks and NETP-specific concerns. Finally, we provide a summary of identified accounting gaps and recommendations for next steps in research and policy development.

Note that this paper focuses on the accounting concerns of transboundary NETP governance. It is not the intention of this paper to evaluate whether and which NETPs are suitable for large scale deployment, and the inclusion of any technology here should not be interpreted as an endorsement or condemnation. Nor does this paper consider the many other non-accounting concerns of NETP governance such as ensuring environmental and social justice or optimising resource use. Finally, this paper does not consider the creation or trading of carbon credits between nations or non-state actors, for which a robust and harmonised accounting framework is also a prerequisite.

WHY NEGETIVE EMISSIONS SYSTEMS ARE COMPLICATED

Negative emissions require both the physical extraction of CO_2 from the atmosphere and permanent storage of that atmospheric CO_2. NETPs vary in how they achieve this (Table 1). Atmospheric CO_2 can be extracted biologically (e.g., the photosynthesis of biomass), geologically (e.g., the weathering or carbonation of rocks), or chemically (e.g., amines and other solvents and sorbents). Once extracted, that CO_2 can be stored geologically (e.g., in minerals, as dissolved minerals, or injected into underground formations) or biologically (e.g., in standing biomass, soil, or buried biomass).

To achieve their purpose of reducing the amount of greenhouse gases in the atmosphere, NETPs must permanently store more atmospheric CO_2 than greenhouse gases they emit in the process of extraction and storage and associated supply chains (e.g., transport, energy provision, material construction, etc.). It is only the net amount of atmospheric CO_2 removed—the amount stored that exceeds the associated emissions—that can be counted as a reduction of atmospheric GHGs.

Therefore, accurately accounting for the greenhouse gas flows in an NETP system requires tracing both:

- Flows of carbon extraction and storage, including
    - when and where the CO_2 is extracted from the atmosphere
    - losses of CO_2 that occur between extraction and storage, such as in transport or during conversion of the carbon from one form to another
    - when and where the extracted CO_2 is permanently stored
    - any movement or re-release of CO_2 after it has been stored
- All associated greenhouse gas emissions (Table 1), including
    - the emissions associated with the supply chains providing land, material, energy, service, and infrastructure inputs into the extraction, transportation, conversion, and storage processes
    - the emissions associated with monitoring and maintaining the CO_2 storage
    - emissions from indirect land use change and other indirect impacts

The accounting of CDR potential across the wide range of NETPs can be complex. In particular, the timing of associated emissions, the monitorability of removals and storage, and the overall “removal efficiency”—the ratio of CO_2 removed to greenhouse gases emitted—can vary widely, as summarized in TABLE. Robust and comprehensive accounting is needed to avoid overcounting extraction and storage, undercounting associated emissions, or discounting the risk of storage reversal, and thus risking an increase in global warming in the name of “negative emissions”. These issues further increase in complexity when NETP systems cross national boundaries and are subject to multiple jurisdictions and multiple accounting systems.

Table 1. Overview of selected NETPs

NETP	Atmospheric CO_2 is...		Timing of associated emissions[1]					Gap between extraction and storage	Monitorability of Storage	Risk of CO_2 re-release	Estimated removal efficiency over 1000 years (100 years [2]
	extracted via	**stored in**	**Before Extraction**	**During Extraction**	**Between Extraction and Storage**	**During Storage Process**	**After Initial Storage**				
BioCCS, in which CO_2 produced from the combustion or other use of biomass is captured and permanently stored, e.g., in a geological formation	Photosynthesis	Geologic Formations	Land preparation	Decomposition, maintenance, fertiliser use	Harvest, Transport, biomass processing CO_2 capture, compression, transport, losses, energy use	energy use, injection losses	Leakage (low risk)	Yes, requires transport and conversion of biomass and then transport and injection of CO_2	High	Low	78-87% (52-89%)
DACCS, The use of fans, chemicals, and energy to extract atmospheric CO_2 into a solvent or sorbent, after which it is transported and stored permanently, e.g., in a geological formation	Chemicals	Geologic formation		Fans, CO_2 capture	CO_2 capture, compression, energy use, transport, losses	energy use, injection losses	Leakage (low risk)	Yes, requires transport and injection of CO_2. Possibility of co-location near storage site.	High	Low	-5-100% (-5-100%)
Afforestation, The deliberate cultivation of long-term biomass stocks that are indefinitely maintained.	Photosynthesis	Standing biomass	Forest preparation	Forest maintenance, decomposition	n.a.	Maintenance, decomposition, monitoring	Re-release from dieback or mismanagement (high risk)	No	Medium	High	31-95% (63-99%)
Enhanced Weathering, Ground silicate minerals spread on large surfaces to increase their rate of CO_2 dissolution to a period of years or decades.	Weathering	Dissolved minerals	Mining, grinding, transport, spreading	n.a.	n.a.	n.a.		No, but speed of extraction is low	Low	Low, uncertain	51-92% (17-92%)
Biochar, Pyrolysed biomass, which is then buried or used as a soil amendment.	Photosynthesis	Pyrolysized biomass	Land preparation	Decomposition, maintenance, fertiliser use	Transport, biomass processing, pyrolysis, transport, losses, repurposing	Spreading, Decomposition	Decomposition,	Yes, requires transport and conversion of biomass and then transport and spreading of biochar	Low	Medium	-3-5% (20-39%)

1: Excluded for clarity: construction of infrastructure and associated land use change

2: Chiquier et al (2022) A comparative analysis of the efficiency, timing, and permanence of CO_2 removal pathways. Energy & Environmental Science. https://doi.org/10.1039/D2EE01021F

OVERVIEW OF RELEVANT ACCOUNTING PRACTICES

Greenhouse gas accounting serves a dual purpose. The first is to track physical flows of greenhouse gases as they move between human activity, the atmosphere, and terrestrial sinks. The second is to assign responsibility for managing these flows to competent entities such as governments, corporations, or individuals. By comparing changes in physical flows over time, it is possible to assess whether the assigned entities are fulfilling their responsibilities (e.g., meeting their stated climate change mitigation commitments).

3. 1 Greenhouse gas accounting for nations

There are multiple ways to allocate emissions between sovereign regions[4] (Figure 3). Some are:

- **Territorial accounting** (sometimes also called "production-based accounting") attributes to a nation or other sovereign region the greenhouse gas emissions that occur within the borders of a region for a given timeframe, such as annually or cumulatively.
- **Consumption-based accounting** attributes to a nation the emissions associated with the final consumption of goods and services by that nation's residents, regardless of where the emissions occurred. It also excludes domestic emissions from exported goods and services.
- Less commonly seen, **Production-based accounting** attributes to a nation the greenhouse gas emissions that occur due to the economic output of the nation's residents, both private and corporate. This includes both emissions that occur domestically, but also those that occur internationally due to the economic activity of the residents. It also excludes emissions occurring domestically due to the economic activity of non-residents.

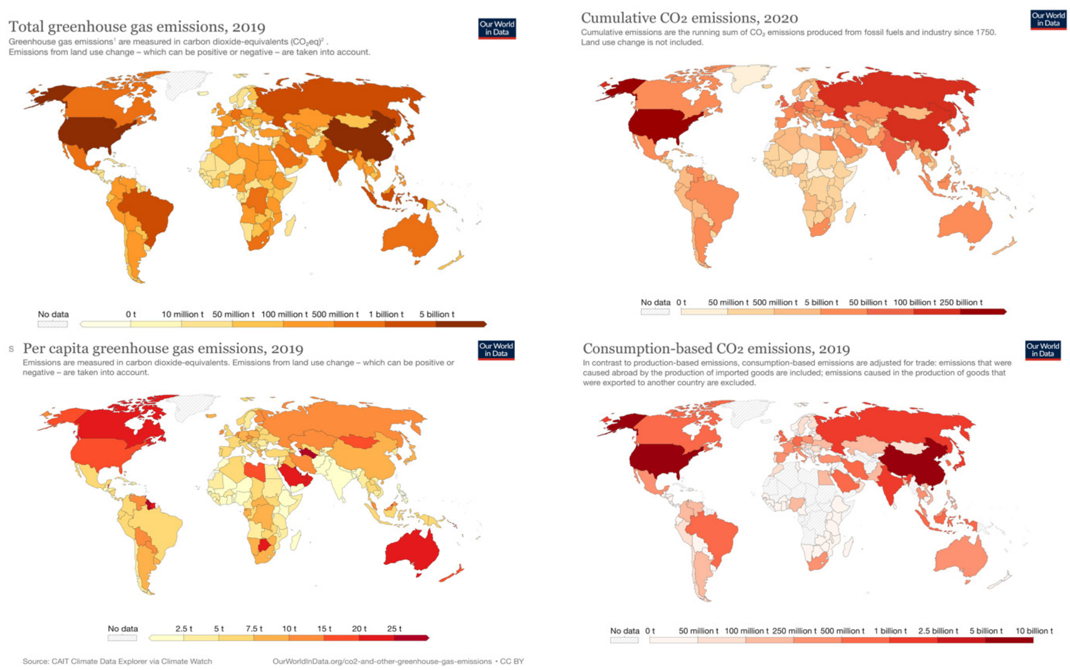

Figure 3. Different ways of accounting for a nation's emissions.[5]

Territorial accounting is the foundation of the national greenhouse gas inventories established by the UNFCCC that are used as the basis for international negotiation and commitments for climate change mitigation. The methodology for these inventories, the IPCC guidelines for national greenhouse gas inventories, was first established in 1994, with revisions in 1996, 2006 and most recently refined in 2019, covers emissions from energy production and transport, industrial processes and product use; agriculture, forestry; and waste, each divided into numerous subsectors. Emissions (and extractions) are accounted for by totalling emissions from each subsector.

The greenhouse gases accounted for include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride, trifluoromethyl sulphur pentafluoride, halogenated ethers, and other halocarbons[6]. Carbon dioxide, methane, and nitrous oxide are presented in their absolute emission quantity, whereas other gases are characterized by their "CO_2 equivalent" global warming potential.

The IPCC guidelines focus not on direct measurement of emissions, but uses indirect estimation calculated using standardised emission factors applied to data on fuel consumption; industrial, agricultural, and forestry production output; animal stocks; land use change; and population. Three levels of accounting are presented in the framework, to be used based both on the available resources a nation has to conduct the accounting as well as the perceived contribution of that sector's emissions to the overall emission balance. This in turn leads to differences in methodology used, and completeness of emissions from country to country.

The IPCC accounting system focuses on nation's domestic anthropogenic emissions, and has some explicit gaps, namely emissions from international sea and air transport (which are counted, but not assigned to a national inventory) or multilateral military operations (international emissions) and emissions from fires on unmanaged land (not considered anthropogenic), as well as non-GHG contributors to global warming (e.g., changes in albedo). It does have specific treatment of carbon extraction by biomass, as well as geologic storage of CO_2, both of which are components of multiple NETPs. These are discussed in further detail below.

3.2 Greenhouse gas accounting for NETP systems

Impacts or processes from all parts of a NETP system will not necessarily take place in a single nation or in a single year, and thus cannot whether or not a NETP system results in net removal cannot be clearly evaluated using the IPCC territorial accounting framework. NETPs requires **life cycle assessment** to fully account for the greenhouse gas emissions—and other environmental impacts—associated with the removal and storage processes and their supply chains, wherever and whenever they occur.

Life cycle assessment (LCA) is a "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040), from the extraction of resources used in the supply chains of energy, materials, and services used to produce a product or service; the use of that product itself; and the final fate of the product and any wastes produced. An inventory of the environmental flows is used to calculate environmental impacts. For GHG accounting for CDR, this focuses on greenhouse gases extracted from and emitted to the atmosphere. Two main types of LCA exist[7]:

> **Attributional** life cycle assessment seeks to answer the question of "Of all the global environmental impacts that occur, which can be attributed to this product/service?" Attributional LCA allocates to a product (or service) a fraction of global environmental impacts that are estimated to be associated with its production, use, and disposal. Attributional LCA assumes the world is static and typically makes use of average data (e.g., grid average emission intensity of energy production). For

processes that produce more than one product or service ("multi-functional processes"), attributional LCA must divide the associated impacts between the different outputs.

Consequential life cycle assessment seeks to answer the question of "If the demand for this product/services changes, what are the resulting changes in global environmental impacts? Consequential LCA estimates the *change* in global environmental impacts that would occur—both directly and indirectly—if a product (or service) is produced, used, and disposed. Consequential LCA there requires assuming a counterfactual baseline (i.e., what would have happened in the absence of a change). Typically, consequential LCA uses marginal data (e.g., the emission intensity of additional capacity for electricity production), and includes co-products and indirect impacts (e.g., changes in land use, demand, or production in other sectors).

All LCAs follow the same overarching framework, which is detailed in ISO14040:

Goal and Scope Definition, which defines the objective, reference flow, system boundaries, and the geographic, temporal, and technological scope of the study. Of particular concern for NETPs is the selection of system boundaries (Figure 4), which determines what processes of a system are accounted for. Inadequate boundary selection can lead to underestimation of associated impacts, incorrect estimation of net removal, or neglecting re-release of stored carbon. For NETP systems, the only appropriate system boundary choice is the broadest one "cradle-to-grave", that follows *all* flows from resource extraction to their final fate for all NETP processes and associated supply chains.

Inventory Analysis, which catalogues the economic and environmental flows in the product systems. Economic flows include the flows of material and energy between unit processes (e.g., electricity, steel, harvested biomass CO_2 to storage), whereas environmental flows are those between unit processes and land, water, or air (e.g., extraction of fossil fuels, nitrogen run off, emissions of CO_2 to air).

Impact Assessment, where the systems' environmental effects are evaluated using a framework of environmental impact harmonization and quantification. For life cycle accounting of greenhouse gas emissions, for example, the emissions flows are characterized into a their "CO_2 equivalent" global warming potential for a given timeframe (e.g., 100 years). Besides global warming, other impacts considered may be human toxicity, ecotoxicity, acidification, eutrophication, land use, water depletion, abiotic resource depletion, ozone depletion, among others. While greenhouse gas accounting for NETPs necessarily focuses on global warming, these other impact categories should also be considered and evaluated.

Interpretation, where the results of the impact assessment are analysed for consistency and completeness of data used, sensitivity to variation, and uncertainty. Due to the sheer data intensity of LCA, it always involves the use of some amount of estimated, incomplete, or extrapolated data. Assessing the quality of the data use and the sensitivity of the results to the uncertainties in the data or assumptions made by the researcher is an integral part of any LCA.

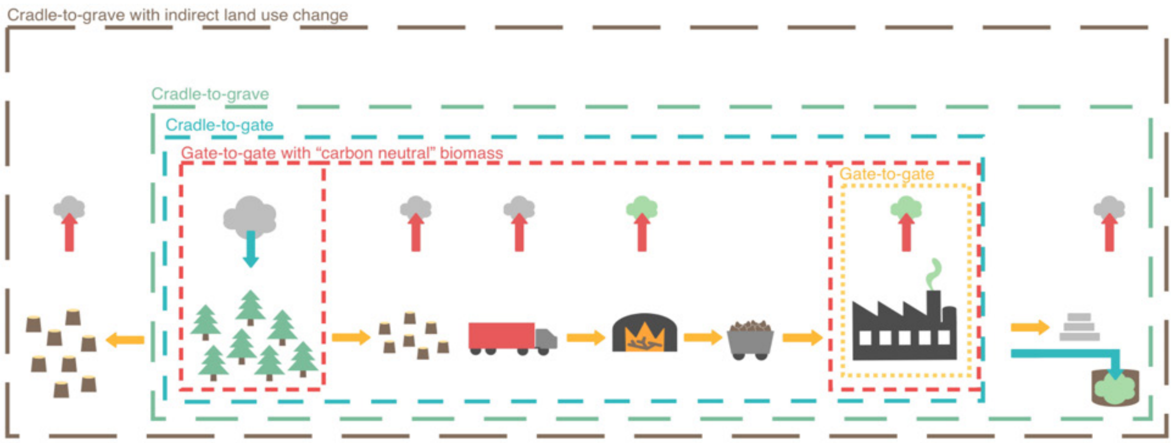

Figure 4. Different system boundaries used in life cycle assessment.[8]

System boundary selection can have a large impact on the perceived emission balance of an NETP system. Life cycle assessment of an NETP should have as broad a system boundary as possible, accounting for emissions in the extraction and permanent storage processes and all associated supply chains.

Some considerations particular to evaluating NETP systems using life cycle assessment[9] are:

- **availability of data.** Many uncertainties remain about implementing NETPs on a large-scale including, the material and energy inputs as technological learning progresses, the full extent of possible environmental impacts and indirect effects, as well as the overall response of the earth system from the increased extraction of CO_2 from the atmosphere.
- the **need to distinguish removals and avoided emissions**. When evaluating the "global warming potential" of a given system, it is common LCA practice to add together both estimated physical flows of greenhouse gas emissions and removals with "avoided emissions"—reductions in emissions that are assumed to happen in other sectors due to this new product (e.g., the displacement of other products or services), with both removals and avoided emissions having negative values. However, as avoided emissions are not physical removals but rather an assumed change, this practice can lead to a negative "global warming potential" without true negative emissions (net removal of greenhouse gases from the atmosphere).
- **temporality**. Standard LCA practice compresses all impacts of a system into a single metric, regardless of when those impacts occur. This obscures timing of extraction, storage, and associated emissions, which is particularly relevant for systems that involve CO_2 extraction that can occur over years or decades (e.g., afforestation, enhanced weathering). This delay can lead to a long "carbon payback period", which is the length of time it takes for the removals to compensate for the associated emissions of the NETP system.
- **risk of reversal and sink impermanence**, which represents another major temporal concern of LCA. Risk of impermanence requires explicit treatment in a NETP LCA's uncertainty assessment.

Issues of data availability are pertinent to all life cycle assessments and is a focal point in the uncertainty analysis conducted in the interpretation phase. Temporality is rarely treated in LCA, and the potential impermanence of CDR makes it a particularly critical issue for LCA of NETPs. TABLE summarises some options for integrating the need to treat temporality and also separation of removals and avoidance in NETP LCAs.

Table 2. Selected options for including CDR-specific issues into LCA.

	Goal and Scope	Inventory	Impact Assessment	Interpretation
Separation of removals and avoidance	Minimisation of multi-functional processes	Catalogue physical flows and avoidance flows separately	Use separate impact categories for physical emissions/extractions and avoided emissions	–
Temporality and impermanence	Establish explicit timeframe, large enough to account for permanence and reversal risks.	Catalogue when extraction, storage, and emissions occur; Explicit inclusion of potential reversals	Use of multiple GWP timeframes (e.g., 20-year, and 100-year); GWP factors for biogenic CO_2; graphing of GWP over time.	Sensitivity analysis on timing of emissions and on GWP timeframes; Sensitivity analysis on reversal rates and timing

TREATMENT OF NEGATIVE EMISSIONS SYSTEM COMPONENTS IN EU AND INTERNATIONAL ACCOUNTING FRAMEWORKS AND REGULATION

The extraction of atmospheric CO_2 by biomass and the storage of atmospheric and biogenic CO_2 in geological formations are two core components of multiple NETP systems. This section explores how both the capture and storage aspects of biogenic CO_2 are included in the UNFCCC accounting framework as well as in EU policy. While there will be other emissions associated with NETP value chains, this section focuses specifically on the path of the carbon removed from the atmosphere via biomass growth, captured and its final fate.

3.3 Regulation of biogenic CO_2 sources (and biomass)

There are several EU policies which regulate the accounting for biomass and the emissions resulting from its use. While biogenic CO_2 emitted under the EU ETS is not counted as an emission, other safeguards in the Renewable Energy Directive, the Effort Sharing Regulation and the Land Use, Land Use Change and Forestry (LULUCF) legislation are designed to record the change in carbon stocks of individual member states[10]. This policy design assumes that an alternative approach, where emissions would be counted in the energy sector, would make it very difficult to avoid double counting with the LULUCF sector. By focusing on the very start of the value chain, the complexity of the accounting is in theory reduced and potentially long supply chains do not need to be tracked until their final stage[11].

The climate impact of the harvesting of woody biomass is accounted for in the LULUCF Regulation (Article 7). The Regulation states that the emissions[12] resulting from changes in the pool of harvested wood products, including emissions from harvested wood products removed from its forests before 1 January 2013, should be reflected in the accounts of each member state. Harvested wood products resulting from deforestation, wood products stored in solid waste disposal sites and wood harvested for energy purposes shall be accounted for based on instantaneous emissions to the atmosphere (LULUCF Regulation). While the LULUCF regulatory framework tackles carbon stocks, the Renewable Energy Directive aims to outline sustainability, energy efficiency and greenhouse gas emissions saving criteria for the use of biomass as an energy source[13]. Minimising GHG emissions of biomass supply chains has also been on the policy agenda of the EU. In its 2010 Biomass Report, the Commission has developed a simplified methodology for the calculation of GHG performance of solid and gaseous biomass used for heating/cooling and electricity production[14]

The same approach is adopted by the UNFCCC and in the IPCC guidelines for national GHG inventories (IPCC 2006, 2019)[15]. According to the IPCC Guidelines, all carbon removed in wood and other biomass from forests is counted as emitted in the year of removal and in the country where the wood was harvested[16].

While the carbon accounting at source does in theory provide predictability and reduces complexity, the risks of double counting of the climate benefits of biomass aren't fully addressed by the current policies, particularly on a global level.

There are still many detrimental impacts of biomass use and loopholes in biogenic CO_2 accounting that are not fully recognised in the European or global policy framework. Key issues are detailed below.

4.1 The carbon neutrality and sustainability of biomass sources

Scientific studies, both from independent academia[17] and the Joint Research Centre of the EU[18], have demonstrated that some biomass sources, such as woody biomass, are not carbon neutral. Due to the time delay between the slow uptake of carbon by the biomass and the quick release upon combustion, there is a possibility that the claim of carbon neutrality is effectively the result of 'front-loading' the future removals necessary to balance out the emission pulse. The fundamental issue is that there is a mismatch between when CO_2 is captured and when it is emitted. However, this has not been reflected in the GHG accounting of biomass in the RED, where woody biomass and its by-products are still expected to significantly contribute to the renewable energy targets of the EU.[19]

4.3 Focus on the energy sector omits other potential sources of removals

According to Art. 29 of REDII, sustainability criteria for forest bioenergy are applied only to biomass utilised in installations producing electricity, heating and cooling or fuels with a total rated thermal input equal to or exceeding 20 MW (Member States may apply the sustainability criteria to installations with lower total rated thermal input).[20] However, cement and steel plants that may use biomass and are equipped with CCS could fall below this threshold and be exempt from the criteria.

4.2 Issues in Monitoring, Reporting and Verification

The fact that all countries trading biomass don't necessarily adhere to the same accounting rules (i.e., Annex 1 signatories versus non-Annex 1 signatories[21]) is a significant potential loophole in the biogenic CO_2 accounting system.

While emissions caused by harvesting woody biomass and its by-products should be reported in the land use sector of each country, monitoring and verifying such emissions on a global level is very difficult. Coordinating hundreds of different regulation mechanisms and creating additional ones where there is no credible monitoring and verification yet is a monumental task. The varying ability of countries to accurately monitor and report their emissions also contributes to this challenge.

4.4 Other biomass sources need to be regulated

While the double counting of woody biomass is, at least in theory, prevented by the existing regulatory framework, Carbon Dioxide Removal can be the result of permanent storage of other sources of biogenic CO_2. The move away from the use of first- and second-generation biomass requires a parallel effort in the development of regulations for more advanced types of biomass. While some of them may be accounted for to some extent, there is a need for a coherent policy approach that tackles the accounting of biogenic CO_2 at each step of the supply chain.

For example, the biogenic fraction of municipal solid and industrial waste is a potential avenue for achieving carbon removals.[22] However, these biogenic CO_2 sources are very heterogenous and accounting for their full climate impact is challenging.

The IPCC GHG accounting rules address the half-life of some products that might end up in the category of biogenic waste, such as paper, but offer several different methodologies to calculate their impact.[23] The multiple options presented could therefore lead to a lack of harmonisation across different jurisdictions.

Currently many accounting mechanisms assume that biogenic waste is carbon neutral (e.g., biogenic waste incineration), which doesn't take into account their origin and potential land-use change impact of the original product.

Table 3. Examples of biomass that could be relevant for NETP value chains and their corresponding relevant regulatory framework (non-exhaustive).

Examples of type of biomass	Relevant regulatory framework
Energy crops and residues	• Renewable Energy Directive
Woody biomass and by-products	• Renewable Energy Directive • LULUCF policy framework
Algae	• Renewable Energy Directive
Biogenic municipal waste	• Waste accounting rules IPCC • Waste Framework Directive
Wet biogenic waste (e.g., sewage sludge)	• Renewable Energy Directive • Waste accounting rules IPCC • Waste Framework Directive

In addition to newly produced biomass, there are a range of biogenic materials that are collected as wastes at the end of the life cycle of a given product. These materials include paper and cardboard waste, animal and mixed food waste, vegetal wastes (e.g., sludges from washing biomass), household waste, common sludges (e.g., water treatment waste) and wood and forestry wastes.[24] Since this type of biogenic CO_2 and carbon sources may end up in NETP value chains through processes such as municipal waste incineration with carbon capture and storage, it is crucial to attribute the correct climate impact to the biogenic component of the waste to establish whether or not net carbon removals are achieved.

Due to the variability in the type of product, use and lifetime, accounting for the climate impact of these wastes can only be properly done if their impact is accounted for every step of the way. For example, decades may pass between the harvesting of wood for paper and its final disposal – in the meantime, the room for error grows as policy and liability frameworks change. That is why policies that assume the instantaneous oxidation of products right away are useful, because they account for these emissions right at the start of the value chain.

When it comes to very heterogenous waste sources, such as biogenic municipal waste, it is important that any land use change impacts are accounted for earlier on in the supply chain to record the full impact of a given type of biomass (e.g., soy potentially causing deforestation and eventually ending up in the household waste in a different jurisdiction).

4.5 The issues of reversibility and biomass sink

The accounting for carbon storage in land sinks is regulated in the accounting rules on greenhouse gas emissions and removals resulting from activities relating to LULUCF. However, in case of reversals, Member States do not need to report emissions from natural disturbances (e.g., wildfires, insect and disease infestations, extreme weather events and geological disturbances) if they provide information demonstrating:[25]

- "that all land areas affected by natural disturbances in that particular reporting year have been identified, including their geographical location, year and types of natural disturbances;
- that no deforestation has occurred during the rest of the respective accounting period on lands that were affected by natural disturbances and in respect of which emissions were excluded from accounting;
- which verifiable methods and criteria will be used to identify deforestation on those lands in the subsequent years of the accounting period;
- where practicable, which measures the Member State undertook to manage or control the impact of those natural

disturbances;

- where possible, which measures the Member State undertook to rehabilitate the lands affected by those natural disturbances."

These exclusions are subject to specific conditions outlined in the LULUCF policy framework and depend on the calculation of the so called 'background levels' that are determined by several parameters described in Annex VI of the LULUCF Regulation.[26]

However, "if emissions in a particular year in the periods from 2021 to 2025 and from 2026 to 2030 exceed the background level plus a margin, the amount of emissions exceeding the background level may be excluded".[27] Consequently, in some cases, a part of the emissions resulting from natural disturbances would not be reported.

While there are some safeguards in the EU's LULUCF accounting rules ensuring that these sinks are no longer claimed as removals after natural disturbances occur,[28] this may not be the case for other jurisdictions across the globe from which biomass may be imported.

When it comes to products coming from the forestry and biomass sector, the carbon embedded in the product is still counted as emitted after the 'half-life' of a given biomass (i.e., 2 years for paper, 25 years for wood panels, 35 years for sawn wood). While long lived products are encouraged, the change in the 'carbon pool' in products needs to be reported under the LULUCF accounting methodology. Harvested wood products are one of the six 'carbon pool' categories included in the accounting for LULUCF (including above ground biomass, below ground biomass, litter, dead wood and soil organic carbon). However, for correct accounting for NETPs and carbon removal, it is crucial that the permanence of carbon storage is monitored – for products, even if they are long lived, this can be an insurmountable challenge in terms of monitoring, reporting and verific

ation.

4.6 Treatment of CO_2 transport and storage

Some NETPs, such as BioCCS or DACCS, will utilise CO_2 transport and storage networks to remove CO_2 from the atmosphere. Therefore, it is necessary to also analyse CO_2 transport and storage regulations globally to identify the potential gaps in the GHG accounting for NETPs. This section specifically addresses the transport and geological storage of gaseous CO_2 which is chemically captured from the air or from flue gases. Other forms of CO_2 storage are not addressed in this section.

The IPCC and the European Union already have guidelines and policy frameworks, respectively, which address the transport and storage of gaseous CO_2.

The IPCC special report on CCS[29] from 2005 considered two options for greenhouse gas accounting for CCS systems:

1. Reporting CO_2 that has been captured and permanently stored as an emission reduction in the sector where the capture initially took place (e.g., electricity generation, cement production). This method is however less transparent about overall carbon flows of a given supply chain. This GHG accounting system also mentioned the possibility to describe the carbon flows as additional information to increase transparency.
2. Reporting CO_2 that has been captured and permanently stored separately, as a CO_2 sink, and still counting the CO_2 as produced in its sector of origin.

The IPCC accounting framework[30] uses the first approach, which provides greater granularity of data on where CO_2 capture occurs, but less granularity on where and when the CO_2 is stored. Only CO_2 that goes to permanent geological storage or mineral carbonation is currently eligible to be counted as stored. The IPCC GHG inventory guidelines also explicitly mentions the geological sequestration of biogenic CO_2. The IPCC Guidelines note that "once captured, there is no differentiated treatment between biogenic carbon and fossil carbon: emissions and storage of both will be estimated and reported.[31] According to the methodology, both biogenic and fossil CO_2 captured from flue gases should not be added to the total emissions (i.e., net emissions should be reported).

Biomass combustion is not reported under the energy sector, on the basis that it is reported as emitted in the Land Use, Land-use Change and Forestry sector. Capturing and storing zero rated biogenic CO_2 emissions means that they are reported as carbon removals in the IPCC sector in which the capture takes place. It must be noted that this is not the case in the EU ETS, where biogenic emissions are out of scope.

4.7 CO_2 capture

According to the current IPCC guidelines, the CO_2 emissions captured from point sources, such as industrial or power plants, should be allocated to the sector where the CO_2 is generated. Additional energy emissions for the compression of CO_2 are also accounted under the capture category. However, the CO_2 generated does not need to be allocated to that sector if it can be shown that the CO_2 is stored in a properly monitored geological storage site.[32] In this case, the emission reduction is reported in the sector where the capture took place. If the captured CO_2 is used, it is assumed to be emitted in the sector where it was captured.[33] The fugitive emissions from the process of using the captured CO_2 are also included in this reporting and reported in the part of the supply chain where the CO_2 use happens.

The potential fugitive GHG emissions associated with the capture process (e.g., coming from the treatment of amines, etc.) are not explicitly mentioned and estimates are not available. Nevertheless, there is a reporting category specifically for fugitive emissions from CCS these emissions could be included in. While these emissions are likely to be negligible compared to CO_2 captured, they should still be included into the GHG accounting.

4.8 Transport of CO_2

The IPCC guidelines explicitly indicate that fugitive emissions from pipelines transporting the CO_2 should be allocated to the national territory of the pipeline, including offshore areas. This implies that emissions from one pipeline may be distributed between two or more countries. The IPCC Guidelines also indicate that, in the event of CO_2 leakages in pipelines crossing borders, the CO_2 leak should be accounted to the country where it occurs.

However, fugitive emissions resulting from other means of transport such as rail, ships or trucks, are not explicitly included in the IPCC Guidelines. Given that these means of CO2 transport will likely also be used in CCS projects, such as Klemetsrud (e.g., trucks to carry CO_2 to the port of Oslo), this lack of specific instructions might become an issue in the future. At the moment, the fossil fuel emissions from transport modes used (e.g., ships, trucks and rail) are covered under the category of mobile combustion and other relevant subcategories. Crucially, for international transport, these emissions are reported under 'international bunkers' and not allocated to any country.

4.9 Storage of CO_2

The IPCC Guidelines state that captured CO_2 does not have to be reported and counted in the sector where it was generated when it is permanently stored in a geological storage site or in the form of mineral carbonation. However, it is a requirement to account the CO_2 injected into the storage site. Emissions associated with the injection of the CO_2 into the geological storage site, and possible leakage, is meant to be closely monitored and is linked to the country in whose national jurisdiction or by whose international right the point of injection is located. This should include any emissions arising from leakage of CO_2 from a geological formation that crosses a national boundary but should be dealt with bilaterally between countries.

When it comes to CO_2 storage in terms of mineral carbonation, it is reported either in sector where capture took place, or in its own special category.

In the EU ETS, CO_2 storage is regulated by the CO_2 storage Directive.[34] The methodology in the Directive reflects the same rules present in the IPCC GHG accounting guidelines. Under the ETS Directive[35], CO_2 produced by an installation, and which is captured and geologically sequestered CO_2 does not require emission allowances to be surrendered if the geological storage site meets the requirements of the CO_2 Storage Directive. However, the CO_2 Storage Directive does not currently recognise the mineralisation of captured CO_2 as a way to avoid surrendering an emission allowance.

4.10 The need for robustness in rules for the GHG accounting of the use of CO_2

At the moment, the IPCC methodology for carbon or CO_2 stored in non-fuel products manufactured from fossil fuels or other non-biogenic sources of carbon considers emissions released from their production, use and destruction. Emissions are estimated at each stage, when and where they occur (e.g., in waste incineration).

This provision in the methodology is crucial, since if the product only results in temporary storage of carbon or CO_2 it should not be counted as a carbon sink. When it comes to long-term storage in products, the inventory methodology would need to be tailored and done on a case-by-case basis, but this would pose issues due to the potential diversity and heterogeneity of products on the market. To avoid this becoming a wild west of inventory accounting for various products, clear rules need to be established, recognising the need to verifiably trace the flow of carbon from the atmosphere to a permanent store, along with the emissions associated with the process.

4.11 Potential accounting issues related to CO_2 storage

Potential issues could arise when CCS GHG accounting is done for global supply chains. If the captured CO_2 is captured in one country but released in another, or at later times, the accounting becomes more complex and there are more moving pieces that need to be coordinated (e.g., multiple regulatory frameworks, timeframes and value chains). This accounting risk is particularly acute for emissions displaced in time and location, since the emission inventories are done by country and year. In other words, the yearly national GHG reporting accounting could easily fail to report emissions that are delayed in time, displaced to other countries or displaced to international waters.[36] In these cases, global GHG accounting methods must ensure that no double accounting of CO_2 storage occurs. While some regions already have coordination in place (e.g., within the European Economic Area), some examples will require further coordination (e.g., storage or capture of CO_2 to and from the EEA).

4/12 The London Convention and the London Protocol

The London Convention and the London Protocol are global agreements, under the auspices of the International Maritime Organisation (IMO), which manage and prevent the dumping of certain wastes, including CO_2, at sea. Prior to being amended, these agreements presented a legal barrier to geological storage of CO_2 as well as to the international 'export' of CO_2 intended to be geologically stored. In 2006 and 2009 respectively, amendments were drafted to address these legal barriers, on the condition that the relevant parties come to an 'arrangement' or 'agreement' with regards to issues such as permitting and that this be communicated to the IMO.

Despite these amendments, there is still broad confusion as to whether the international transport of CO_2 is permitted under the London Protocol, notably since the latest amendment is not yet globally in force, lacking the minimum number of ratifications. Parties which have ratified the amendments are deemed to be in compliance.

At the EU level, the European Commission issued a clarification in 2022[37] assuring that all its Member States and the members of the European Economic Area are already in compliance with the London Protocol on the basis that the CO_2 Storage Directive (or CCS Directive)[38] and the ETS Directive[39] already form a legal agreement which complies with the necessary requirements. Effectively, inside the European Economic Area, the London Protocol no longer presents a legal barrier. However, third countries seeking to either import or export CO_2 from the EEA do not benefit from this regulatory clarity.

In fact, under the ETS Directive, CO_2 produced by an installation and which is captured and geologically sequestered CO_2 does not require emission allowances to be surrendered, as long as the geological storage site meets the requirements of the CO_2 Storage Directive. Critically, the CO_2 Storage Directive only covers storage sites inside the EEA, meaning that CO_2 captured inside the EEA can only be transported and stored inside the EEA.

This is of particular relevance to the United Kingdom, in light of its exit from the EU and EEA. As it stands today, it is not legally possible to export CO_2 captured in the EEA to the UK, and vice versa. While the UK has substantial geological storage potential, only CO_2 captured in the UK can currently be stored there, making it more difficult for viable projects to materialise.

Finally, GHG accounting issues can also come up with countries or parties that do not accept liability for the transferred or stored CO_2. For example, while in the EU this is resolved by the CO_2 Storage directive, it is a possibility that two countries comply with the London Protocol and improperly handle the liability of CO_2 storage. Similarly, GHG accounting problems can arise if potential debits are transferred sufficiently far into the future, there could be little assurance that the systems and institutions of liability will still be in place if the CO_2 is released (IPCC 2005).

AN ILLUSTRATIVE EXAMPLE OF TRANSBOUNDARY ACCOUNTING IN CDR SUPPLY CHAINS: BIOCCS

5.1 The Supply Chain of BioCCS from a Life Cycle Accounting Perspective

A BioCCS system involves the extraction of atmospheric CO_2 via the photosynthesis of biomass and storage of CO_2 produced from the use of that biomass in secure geologic storage. In this illustrative example, we focus on greenhouse gas emissions for a BioCCS system and account for the CO_2 extracted from the atmosphere by biomass, as well as all greenhouse gases emitted during:

- the preparation and use of land for biomass cultivation
- the cultivation and harvesting of biomass
- transport of biomass
- the conversion of biomass into an intermediate product (e.g., pellets, charcoal, wood chips)
- biomass use (e.g., combustion of energy or conversion to final products)
- the capture of the CO_2 emissions from biomass use (and/or intermediate conversions) and associated energy use
- preparation and transport of captured biogenic CO_2
- the injection of CO_2 into secure geologic storage
- the indefinite monitoring of the stored CO_2
- the supply chains associated with the material, energy, and service inputs into the above processes
- infrastructure and machinery built for the extraction, transport, processing, or storage of biomass and CO_2
- biomass lost during cultivation, harvesting, transport, and conversion
- CO_2 lost during the capture, transport, and injection processes and storage leakages occurring after injection

The above list is meant to be illustrative, not exhaustive, and the processes and emissions in a BioCCS system will vary depending on the specific implementation. Figure 5 presents a highly simplified illustration of what these carbon flows might look like in a BioCCS case (not intending to be representative of actual flow quantities, which can vary widely depending on system configuration). Note that the extractions and emissions are counted regardless of where or when they occur, and the "net CDR" metric provides the amount of greenhouse gas emissions minus extractions over the whole life cycle of the BioCCS system. Also, the amount of CO_2 geologically stored is not explicitly accounted for in the life cycle greenhouse gas accounting, as it is neither an emission nor an extraction. Also note that, in attributional LCA, indirect impacts such as greenhouse gas emissions from indirect land use change resulting from a general increase for biomass demand or changes in the electricity mix from increased demand due to CO_2 capture energy use would not be accounted for[40]. However, these would be accounted for in a consequential LCA.

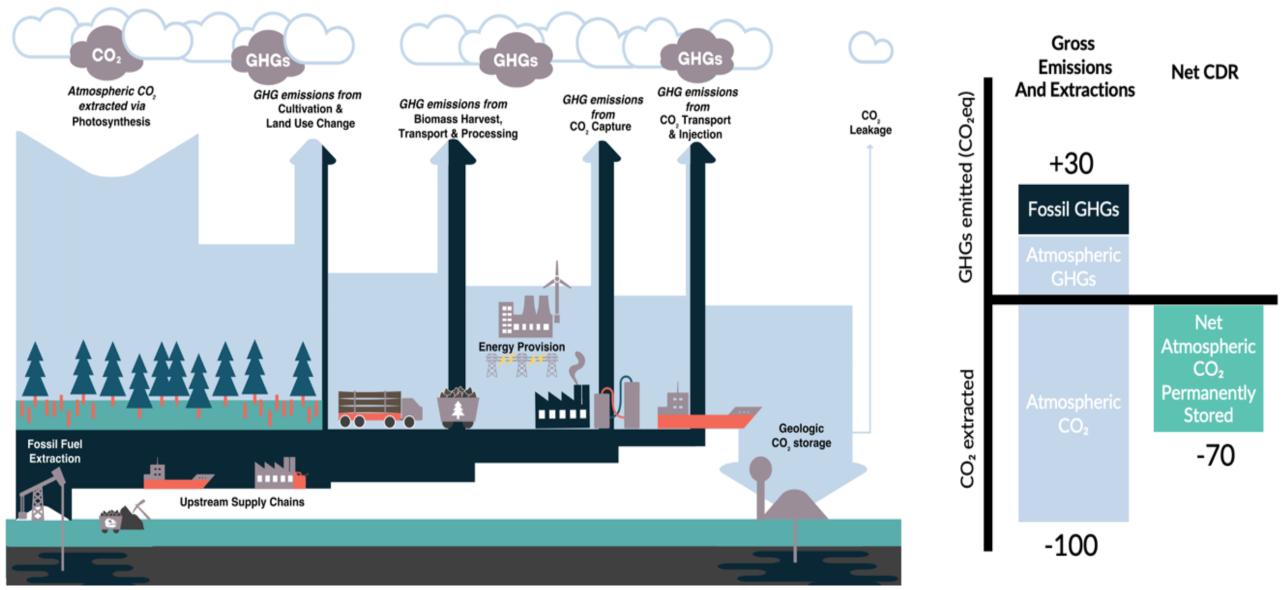

Figure 5. Stylised example of greenhouse gas flows in a bioCCS system.

5.2 Territorial Accounting of Transboundary CDR Supply Chains of BioCCS

In a territorial accounting framework, the intent is still to account for the same physical flows of emissions and extractions as in the LCA system, but they would be estimated and divided differently. If the greenhouse gas emissions for this BioCCS system were allocated using the IPCC accounting framework, they might be accounted for as shown in Figure 6. Where biomass is produced in nation A, used in nation B, and the resulting biogenic CO_2 transported to nation C for injection into geological storage, and a small CO_2 leak that occurs in the storage reservoir exits the ground in the territory of nation D.

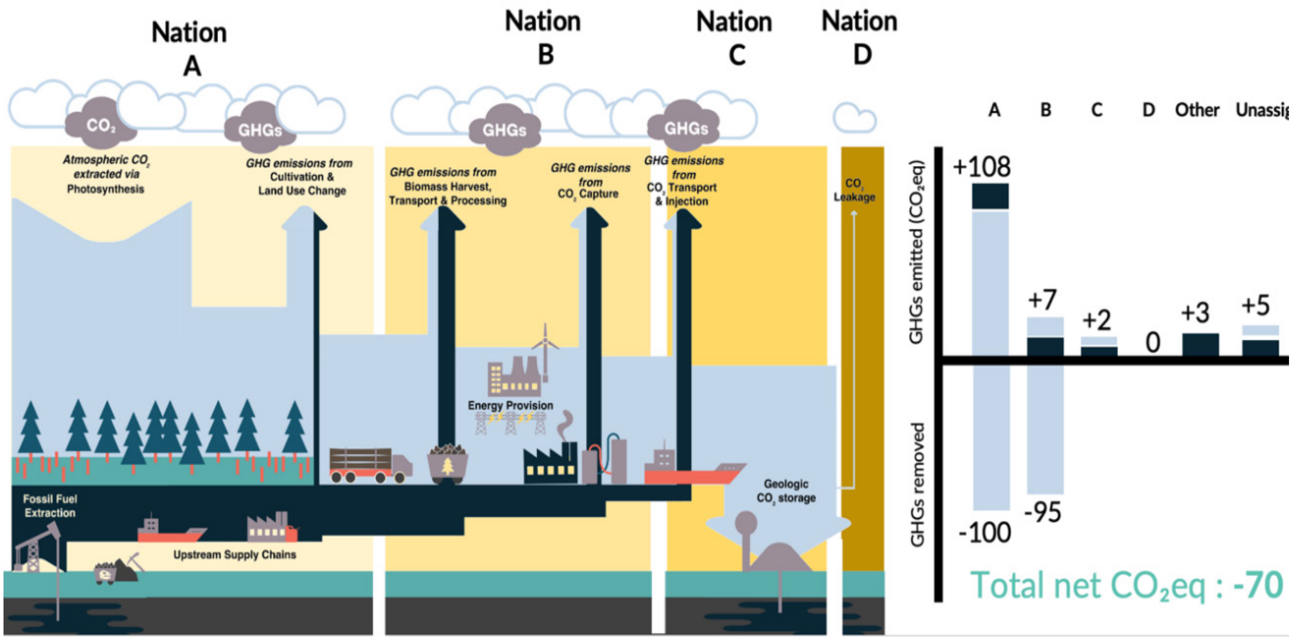

Figure 6. Stylised example of greenhouse gas flows and accounting in a transboundary bioCCS system.

Nation A, the biomass producer, counts the atmospheric CO_2 extracted by growing biomass as a "removal" (not net CDR). When that biomass is harvested, the carbon stored by the biomass is counted as emitted as CO_2. Because of this, any emissions of biogenic CO_2 from the harvested biomass, such as from combustion or losses, are not accounted for, though emissions of non-CO_2 biogenic greenhouse gases are counted. Nation A also accounts for any emissions of greenhouse gases resulting from land use change, biomass cultivation and harvest, road transport where the fuel was sold in Nation A, and any domestic waterway or rail transport of biomass.

Nation B, the biomass user, like Nation A, does not account for any emissions of biogenic CO_2 before that CO_2 is captured. When the biogenic CO_2 is captured intended for geological storage, the captured biogenic CO_2 is counted as a removal in the sector where the capture took place. This counteracts Nation A's accounting of the embodied emissions from harvested biomass and after the CO_2 is captured, any leaks or losses that take place in Nation B is counted as an emission. Nation B also accounts for domestic fossil and non-CO_2 biogenic greenhouse gas emissions from energy provision and industrial process emissions related to the conversion and use of biomass and CO_2 capture, as well as the domestic transport of biomass and CO_2.

Nation C, the CO_2 injector, accounts for CO_2 leakage that occurs in the transport and storage processes, CO_2 released during subsequent leakage, and the domestic fossil and non-CO_2 biogenic greenhouse gas emissions from energy provision and industrial process emissions related to transport and injection of that CO_2.

Nation D, where CO_2 leakage occurs, does not account for any emissions, as leakage occurring from geologic storage is accounted in the inventory of the injection site, regardless of where the leak surfaces. If, however, the leakage occurred from a pipeline within Nation D's territory, then it would be accounted for by Nation D.

The emissions resulting from the supply chains of fuels and materials used in the BioCCS system will also be accounted by the countries where those emissions occur. Emissions from the ship (or air) transport of biomass or CO_2 (and other materials in the associated supply chains) across international boundaries are part of a nation's estimate of emissions from fuel sold in international bunkers, but those emissions are not assigned to any nation's inventory.

IPCC greenhouse gas accounting is aggregated on the sector level, so these emissions and extractions would not be attributed to a "CDR" or "BioCCS" system, but rather added to the relevant sector total, such as "land converted to forest land", "fuel combustion", "solvent use", "domestic water-borne navigation", "transport of CO_2", etc. Emissions for each sector, and each nation, are aggregated into net values, so that, on paper, the emission balance for each nation in the direct BioCCS system would be:

- Nation A: +8
- Nation B: -88
- Nation C: +2
- Nation D: 0

Nation B, where biomass use and CO_2 capture occurred, is the only one with a net-negative balance (one that is 18 units greater than the total net removal of the BioCCS system), even though the extraction took place in nation A, and the storage in nation C. Furthermore, a fraction of the emissions is unaccounted for by the nations directly involved in BioCCS: emissions occurring in supply chains elsewhere are catalogued in disperse national inventories, and emissions from international ship and air transport are wholly unassigned to any actor. Indirect effects, such as land use change elsewhere from a general increase in biomass demand would be accounted for in the nations where they occur but would be wholly detached from any processes related to the BioCCS system.

5.3 Limitations & Other issues

One of the key limitations to the current accounting for biomass in the EU is the categorisation of all biomass sources as carbon neutral under the EU ETS[41]. This problem has been recognised by the EU policymakers and the current policy framework is being reformed to reflect the nuances of the recent scientific research outputs[42]. Under current accounting rules, the full climate impact of some sources of biomass is not fully reflected, which is why appropriate amendments need to be made to the relevant legislation.

In LCA accounting, the emissions and removals are assigned to the BioCCS system itself, thus allowing the total net removal to be estimated. However, a technology system is not a liable actor. In the territorial accounting, emissions and extractions are assigned to liable actors (nation states), however it is not possible from the annualised sectoral accounting to determine if a specific CDR system results in net removal and not all emissions from that CDR system may be assigned to a liable actor.

Life cycle accounting and territorial accounting handle time in ways that can distort perceptions of when emissions and removals occur. In territorial accounting, the emissions and extractions are accounted for in the year that they occur, with CO_2 embodied in biomass accounted for as a removal during its growth, an emission when it is harvested, and again as a removal when it is captured for the purposes of geologic storage. Furthermore, as emissions from land use are accounted for by the total change in carbon stocks in a given year, it is not possible to account for the specific growing time and carbon uptake speed of the biomass used in a BioCCS system. As the UNFCCC framework is focused on annual emission balances, if extractions/emissions from long-rotation biomass, or biomass that is harvested, used, and/or stored, or associated supply chains, occur in different years, there will not be a single inventory available that accounts for the total net emissions associated with the BioCCS system.

Life cycle accounting, in contrast, typically compresses into the single "net CO_2eq" metric, also obscuring any temporal delay. Emission factors for biomass that incorporate the global warming potential of the temporary residence of biogenic CO_2 in the atmosphere (until regrown by new biomass) have been proposed[43], but are not in widespread use, and still leaves the timing obscured.

Timing of extraction, emission, storage, and leakage is particularly relevant to the concepts of "carbon payback period" and the overall efficiency of the CDR system[44], which are not easily seen in the metrics used in life cycle or territorial accounting. The carbon payback period is length of time before a CDR system has permanently stored sufficient atmospheric CO_2 to compensate for the emissions in all its associated supply chains, particularly those of land use change. This delay also results in a "removal efficiency"—the ratio of net CO_2 removed to total CO_2 extracted—that can change over time. As illustrated in Figure 7, a BioCCS system that uses biomass from agricultural residues or energy crops grown on marginal agricultural land has a fast rotation period and no emissions associated with land use change can reach an equilibrium efficiency shortly after the system is operational, as it only has to payback emissions from infrastructure and other start-up activities. However, a BioCCS system that has to payback emissions from land use change may take years to "pay back" the initial emissions pulse, and decades to reach a CDR efficiency above 50%.

Finally, accounting for greenhouse gas emissions, even when done comprehensively, does not take into consideration the other issues relevant to biomass use, such as competing uses of biomass, land use change, water stress, eutrophication from fertiliser use, governance issues of importation, among others. Non-emission sustainability criteria are a fundamental concern for any use of biomass, though beyond the scope of this current report.

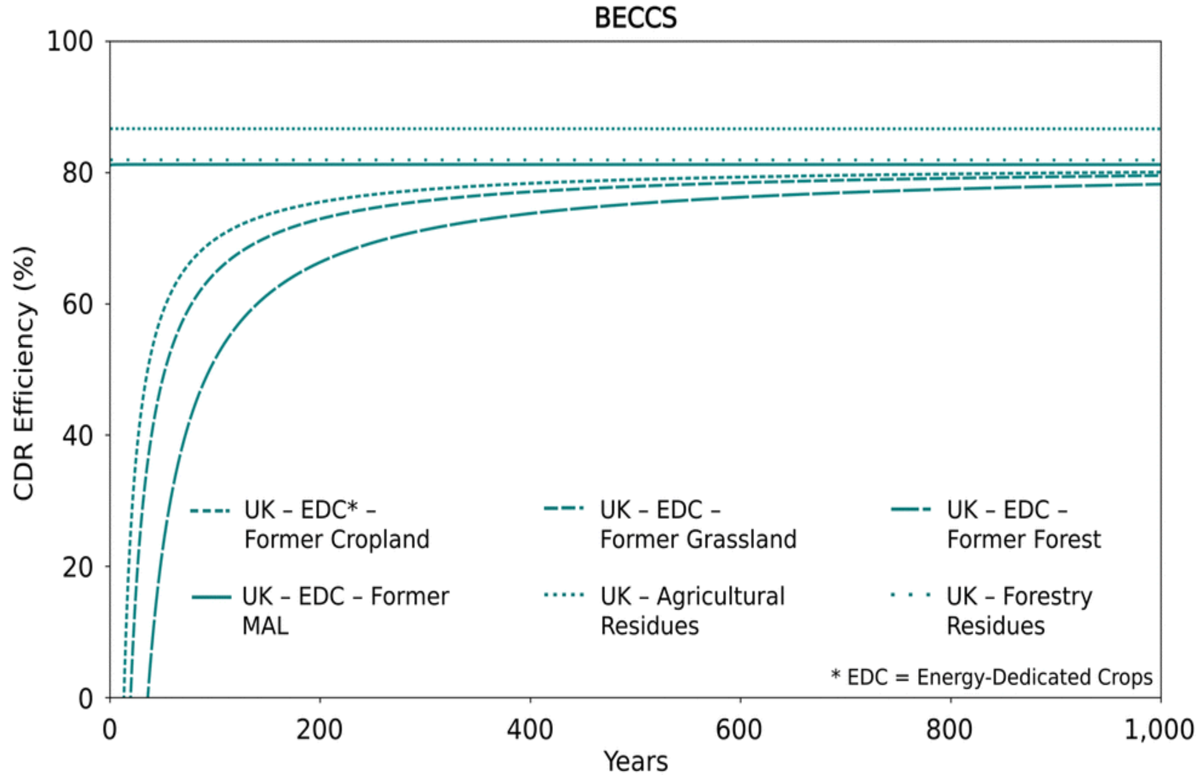

Figure 7. Figure 12 from Chiquier et al 2022 , "Evolution of the CO_2 removal efficiency of [BioCCS] over 1000 years for different types of biomass feedstock and land." [45]

The lines that do not start at year zero indicate systems with a "carbon payback period"—the time it takes for the greenhouse gas emissions of the BioCCS system

Accounting for emissions of a BioCCS system, or any system, is also dependent on the availability of accurate data about the system under study and the availability of resources to measure and report that data. Errors and uncertainties can arise from, e.g., insufficient system boundary choices; incorrect exclusion of a process within the system; inability to conduct measurements; inaccurate models used for emission estimation; lack of measurement or modelling technique; the use of unrepresentative data; measurement or modelling error; misreporting; or "unknown unknowns". In the case of territorial accounting, different nations may also use different estimation techniques or have differing quality of data or resources available for the estimation. While these issues are not specific to BioCCS or NETPs in general, the biggest risk specific to NETP systems is over-estimation of the net removal. This risk is worse for systems with low CDR efficiencies, as the risk becomes not only that less removal is happening than expected, but that the NETP systems results in a net *increase* in atmospheric CO_2.

TRANSBOUNDARY CONSIDERATIONS OF OTHER NETP SUPPLY CHAINS

The accounting considerations for transboundary bioCCS presented above are also concerns for other NETP supply chains involving biomass and CO_2 storage. However, each supply chain will have its own set of issues, depending on its specific complexities, some of which are summarized here for DACCS, biochar, enhanced weathering, ocean CDR, and storage of carbon in biomass.

6.1 Direct air carbon capture and storage

A DACCS system, Figure 8 involves the extraction of atmospheric CO_2 via the use of a chemical or physical solvent or sorbent, after which the captured CO_2 is sent to secure geologic storage.

An LCA focusing on greenhouse gas emissions for a CDR system would account for the CO_2 extracted from the atmosphere by direct air capture minus greenhouse gases emitted during

- the construction of the infrastructure and machinery used by the DAC plant and CO_2 transport and storage
- the energy provision for direct air capture, CO_2 preparation, and CO_2 transport
- the injection of CO_2 into secure geologic storage
- the indefinite monitoring of the stored CO_2
- the supply chains associated with the material, energy, and service inputs into the above processes
- CO_2 lost during the capture, transport, and injection processes and storage leakages occurring after injection

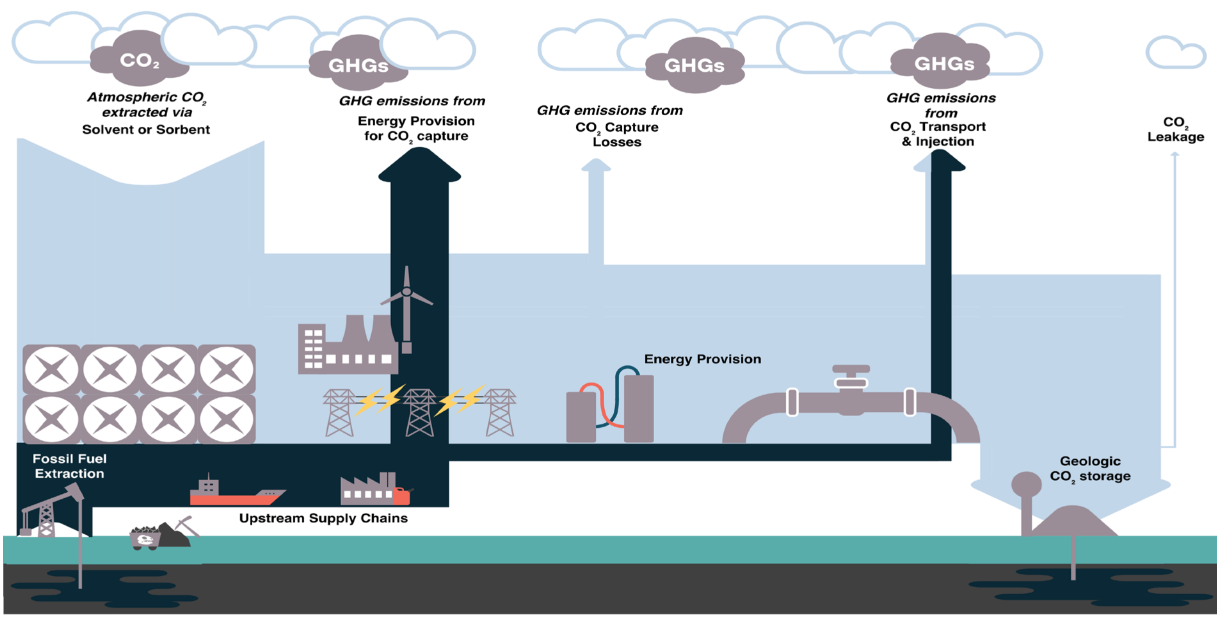

Figure 8. Stylised example of greenhouse gas flows in DACCS system

Direct air CO_2 capture has the same considerations for CO_2 transport, storage, and leakage as discussed for BioCCS. While CO_2 captured from the atmosphere via DAC is not explicitly considered in the IPCC accounting guidelines, all CO_2 captured for the purpose of geologic storage is treated the same. Geologically-destined CO_2 is counted negatively as a "removal" when it is captured and any subsequent re-release is counted as a positive emission[46]. Similarly, the same issues of supply chain accounting for the production of energy and materials apply.

Direct air capture is an energy intensive NETP, requiring between 8-12 GJ of electricity or thermal energy per tonne of CO_2 extracted. It is therefore essential to account for the exact energy mix used for a given DACCS system — and its exact carbon/GHG intensity. Crucially, the large-scale deployment of DACCS may also result into a higher overall energy demand, which in turn may have other indirect impacts. Ensuring that energy provision for DACCS is additional to existing energy production would decrease the risk of inducing indirect changes in energy provision elsewhere, such as may arise from competition with other demands for electricity or strain on grid transmission.

The international transmission of electricity and the international transport of captured CO_2 are the most likely points where transboundary emissions would occur in a DACCS system. However, DACCS systems have the potential to have operational supply chains that are short, in terms of geographic space between major processes; delay between extraction, storage, and associated emissions; and the number of inputs and conversion steps required. This reduces the risk of incomplete accounting, particularly if they are co-sited in areas with favourable energy resources and geological storage.

In terms of temporal issues, since extraction, energy provision, and storage can happen nearly simultaneously, the main risk for delayed emissions is the possibility of CO_2 leakage from geologic storage. However, if direct air capture plant uses grid electricity as its primary energy, or is accounted for using averaged electric or thermal energy provision emissions (e.g., as may be done in an attributional LCA), this can lead to the estimated emissions for the DACCS system having an overall removal efficiency that changes substantially over time, not due to carbon payback, but due to the increased efficiency of the energy provision system, as shown in Figure 14. In territorial accounting, this would be reflected in the decrease in energy emissions reported annually. In LCA, however, the emissions and extractions of the DACCS system are provided as a single net value, such as averaged over the expected operational lifetime of a plant, thus obscuring the impact of that change. The expected change in efficiency may even be lost entirely in attributional LCA, which typically uses static average data.

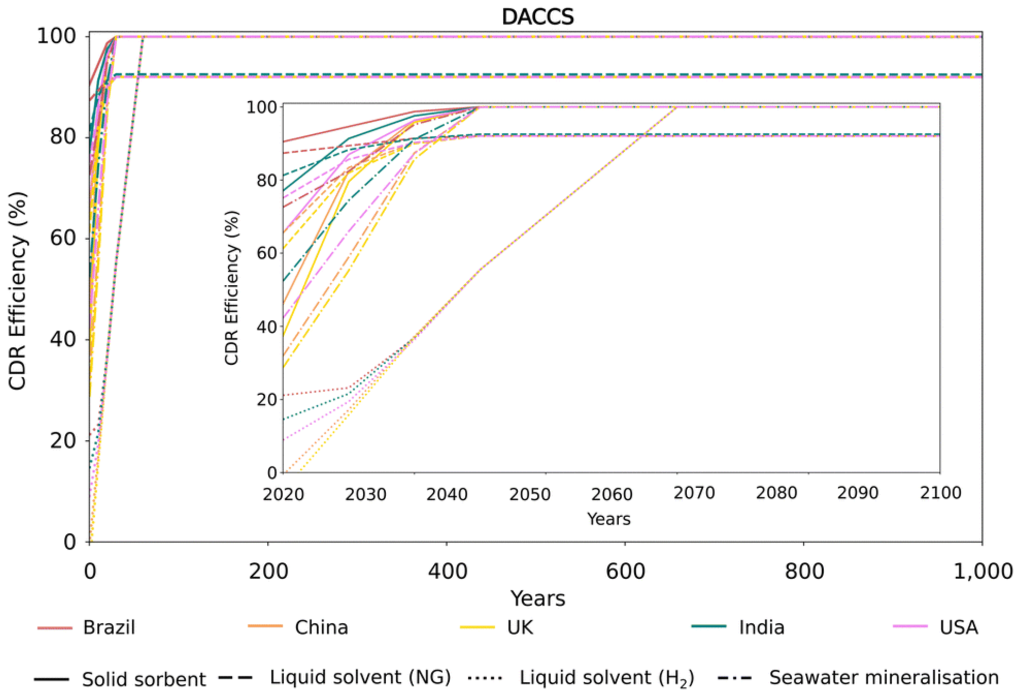

Figure 9. Figure 14 from Chiquier et al (2022). " Evolution of the CO_2 removal efficiency of DACCS over 1000 years for different regions and DACCS archetypes."[47]

6.2 Biochar

A biochar system (Figure 10) involves the extraction of atmospheric CO_2 via the photosynthesis of biomass, the conversion of that biomass into charcoal, and storage of that biochar either in concentrated form (e.g., biochar burial) or in disperse form (e.g., application to agricultural soils).

An LCA focusing on greenhouse gas emissions for a biochar system would account for the CO_2 extracted from the atmosphere by biomass minus greenhouse gases emitted during

- the preparation and use of land for biomass cultivation
- the cultivation and harvesting of biomass
- transport of biomass
- the preparation of biomass (e.g., chipping)
- the pyrolysis of biomass into biochar, including losses to biogas and biooil.
- the transport of biochar to its storage site
- the grinding and spreading of biochar, if in disperse soil storage
- changes in soil emissions (e.g., CH_4, N_2O) due to biochar application[48]
- the supply chains associated with the material, energy, and service inputs into the above processes
- infrastructure and machinery built for the extraction, transport, processing, and/or storage of biomass and CO_2
- biomass lost during cultivation, harvesting, transport, and conversion

the degradation of biochar

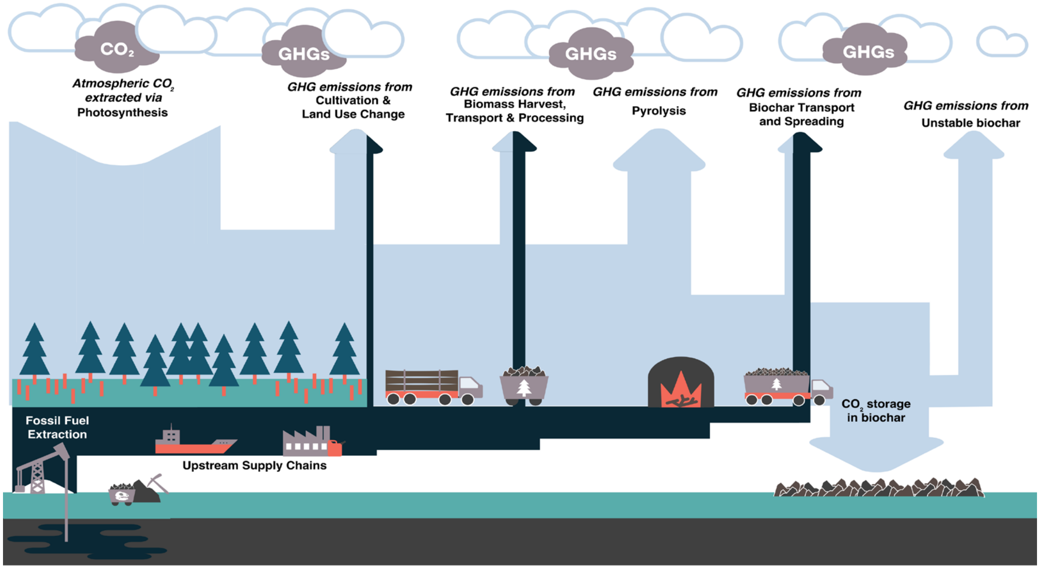

Figure 10. Stylised example of greenhouse gas flows in a biochar system

Biochar has the same accounting concerns for biomass production, harvesting, conversion, transport, and land use change as described in the BioCCS pathways. In particular, similar transboundary issues can occur if the biomass is grown in one region and the biochar is produced and/or used in another, and it is possible that a single production facility of biomass may not only import biomass from multiple regions, but also export biochar to multiple regions.

Biochar has a lower expected CDR efficiency (Figure 11) due to the carbon lost during the pyrolysis process and the decay of biochar. Pyrolysis efficiency can vary widely depending on biomass and pyrolysis conditions, with one review showing a range of 20-58% conversion of biomass to biochar[49], with the remaining lost to liquids and gas. The stability of the biochar also depends on the specific biomass and pyrolysis conditions used[50], as well as the specific soil it is applied to and climatic conditions it is exposed to.

Biochar is not currently considered an accountable form of CO_2 storage in the IPCC framework. Biochar decay (Figure 11) is a particular hurdle to is carbon accounting, since it leads to the eventual reversal of the removal, albeit potentially not full reversal for hundreds of years. For example, in the biochar modelling study by Woolf et al, biochar at the global mean soil temperature (14.9°C) lost 18-37% of its stored carbon over 100 years, 66-81% over 500 years, and 75-92% over 1000 years[51]. Since the decay occurs over time, rather than in an eventual pulse, a methodology is needed to assign liability for the reversal. For example, having a buffer of biochar so that the net removal accounted for represents an average CDR efficiency over a specified timeframe (e.g., 500 years) or having a liability to replace the decayed biochar overtime to maintain an average CDR efficiency.

The use of biochar as a soil amendment also introduces other complication into its accounting, namely issues of monitoring dispersed storage and albedo change. Applying biochar over a wide area increases the burden for monitoring its stability, particularly given the heterogeneity of potential biochar systems and limited available knowledge on biochar decay rates (NASEM, 2019). Secondly, the dark colour of biochar can decrease the albedo of the land to which it is applied. While not a greenhouse gas, changes in albedo can also have an indirect impact on global warming and is therefore relevant to achieving the end goal of NETP systems—reducing global warming—and should be accounted for.

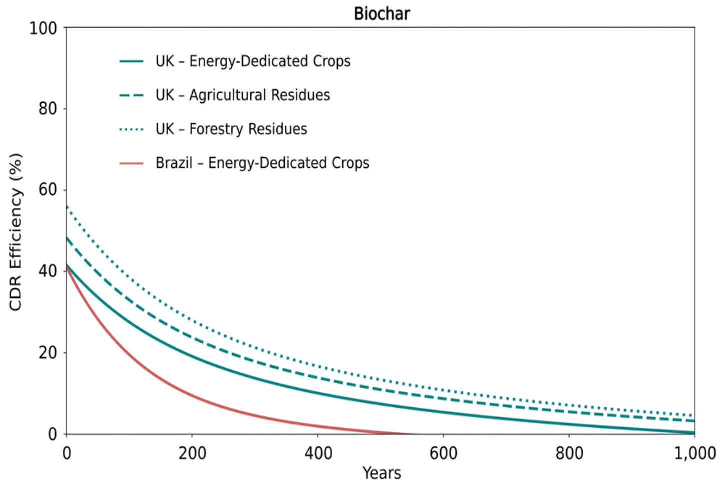

Figure 11 Figure 13. Figure 15 from Chiquier et al (2022), "Evolution of the CO_2 removal efficiency of EW over 1000 years for different alkaline rock characteristics (i.e., type, composition, or size) and different regions."53

6.3 Enhanced weathering

An enhanced weathering system involves speeding up the natural weathering of certain rocks, such as silicates, by mining, grinding, and spreading them over land to increase their exposed surface area. The rocks then react with CO_2 and moisture in the air over a period of years or decades, dissolving into carbonate molecules, which then leeches into soil and waterways.

An LCA focusing on greenhouse gas emissions of an enhanced weathering system would account for the CO_2 extracted from the atmosphere by the weathering process minus greenhouse gases emitted during

- the mining of minerals
- the crushing and grinding of the mined minerals
- the transport and application of mineral
- the monitoring of the CO_2 extraction by the minerals
- the supply chains associated with the material, energy, and service inputs into the above processes
- infrastructure and machinery built for the extraction, transport, or processing of the minerals

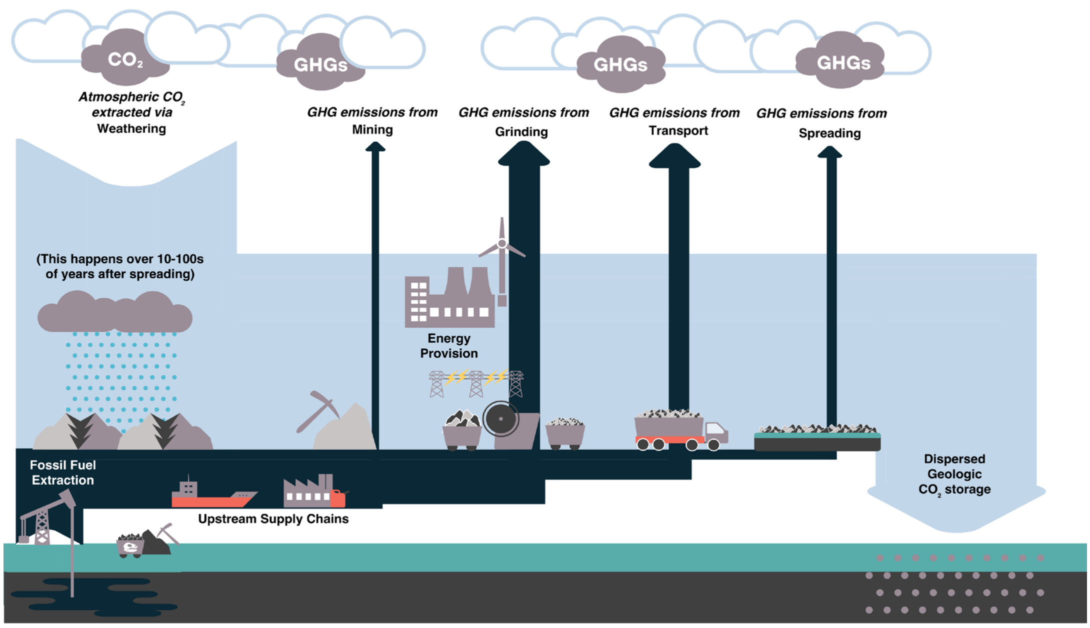

Figure 12. Stylised example of greenhouse gas flows in an enhanced weathering system

The extraction of atmospheric CO_2 by enhanced weathering is a process that can progressively take a few months to a few decades, and that usually after nearly all associated system emissions. This can result in "carbon payback period" of years or decades. Since the speed of weathering increases in warm, humid regions, yet 50% of the world's olivine—a silicate mineral commonly proposed for enhanced weathering—is produced in Europe (predominantly Norway)[52], this leads to the potential of minerals mined in temperate regions being transported to (sub-) tropical regions for spreading. Besides the impact on CDR efficiency due to emissions from transport, this also raises particular concerns relating to the attribution of emissions resulting from international transport.

Like biochar, enhanced weathering has to account for high upfront emissions, monitoring dispersed storage of extracted CO_2, possible changes in albedo, and uncertainty in timing of chemical reactions. For enhanced weathering, the rate of mineral dissolution is of critical concern and is dependent on the chosen mineral, the size of the ground mineral, and the climatic conditions that it is exposed to (Figure 13). Like DACCS, the primary source of emissions come from energy provision for the rock crushing process. And like biochar, there is no provision in the existing IPCC framework for the storage of atmospheric CO_2 in dispersed dissolved minerals.

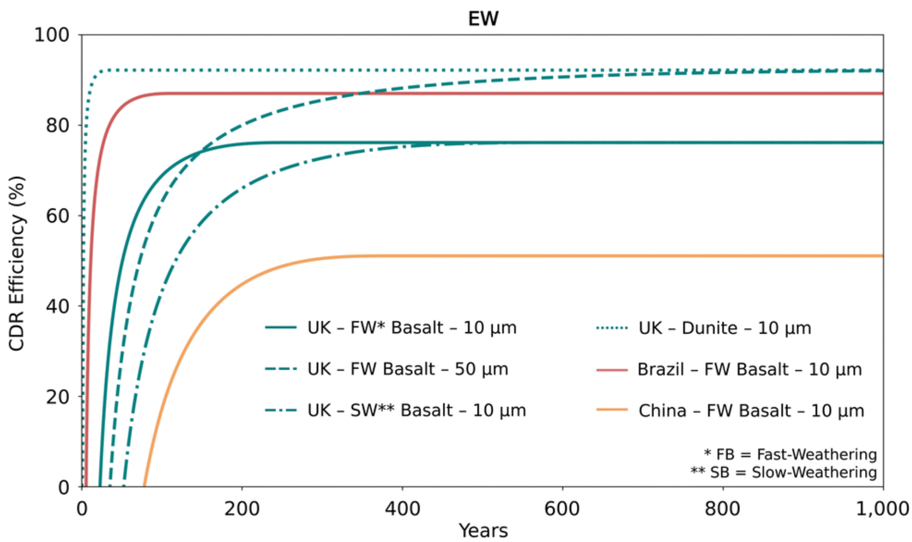

Figure 13. Figure 15 from Chiquier et al (2022), "Evolution of the CO_2 removal efficiency of EW over 1000 years for different alkaline rock characteristics (i.e., type, composition, or size) and different regions."[53]

6.4 Ocean NETPs

Ocean-based NETPs[54] present a significant challenge in identifying both the real-life impact of an ocean CDR system and accounting for the carbon flows at a jurisdictional level. It is important to note that the oceans already naturally remove and store a large fraction of annual CO_2 emissions. However according to the IPCC, only removals occurring as the direct result of human action can count as carbon dioxide removal. Separating natural removals to human-induced removals is one of the key challenges of accounting for ocean CDR.

Broadly, ocean-based removals entail the addition of nutrients, minerals or biomass in the oceans as a way to artificially enhance the rate at which CO_2 is converted into a more stable form of carbon or is more quickly brought into deeper layers of the ocean where the CO_2 is likely to remain for millennia.

These are still extremely nascent approaches to CDR, with most of the existing knowledge stemming only from academic or lab-scale scientific research. In fact, as a result of international agreements such as the Convention on Biological Diversity and the

London Convention it is currently only possible to deploy these methods of CDR in the context of controlled scientific research. Concurrently, due its relative nascency and rare real-life deployment, there is still high uncertainty on the impacts its deployment may have on both the climate and on the ecosystems involved.

At the project level, the quantification the climate effect of the whole deployment chain is difficult. The emissions associated with the overall process, such as mining, transport and the various energy inputs required are relatively easy to quantify. However, the fundamental challenge remains the ability to monitor how much CO_2 has been artificially removed and to reliably assert that it has been stored in a body of water which covers over two-thirds of the world's surface. Therefore, quantifying the net CO_2 impact of deploying ocean-based removal is already inherently complicated.

With jurisdictional accounting layered on top of the project-level accounting issues, the challenge becomes doubly complex. As it stands, there is no clear governance framework to regulate the deployment of ocean CDR, other than high-level agreements which effectively ban the process for non-scientific purposes. This issue is recognised, and a working group exists to further discuss this matter. Nevertheless, storing CO_2 in oceans will almost inevitably raise accounting issues across territorial waters, along with liability concerns with regards to possible environmental harm and reversal of storage.

One way to address this could be to ensure the country implementing the project remains liable for the damage while also claiming the benefit. However, the underlying physical challenges relating to potential side-effects and the reliable quantification of permanently removed carbon means accounting for ocean-based CDR is unlikely to be resolved in the near future in a manner compatible with existing frameworks or with 'per-tonne-of-CO_2' incentives.

6.5 CDR with storage in stationary biomass stocks

Afforestation and coastal blue carbon extract CO_2 from the atmosphere by the photosynthesis of biomass and the CO_2 is then stored in the above- and below-ground living biomass stocks (Figure 14). While by their stationary nature, the CO_2 does not travel geographically between extraction and storage, transboundary emissions may occur in the supply chains of fuel, fertilizer, and machinery inputs, or if increased afforestation leads to indirect land use change elsewhere.

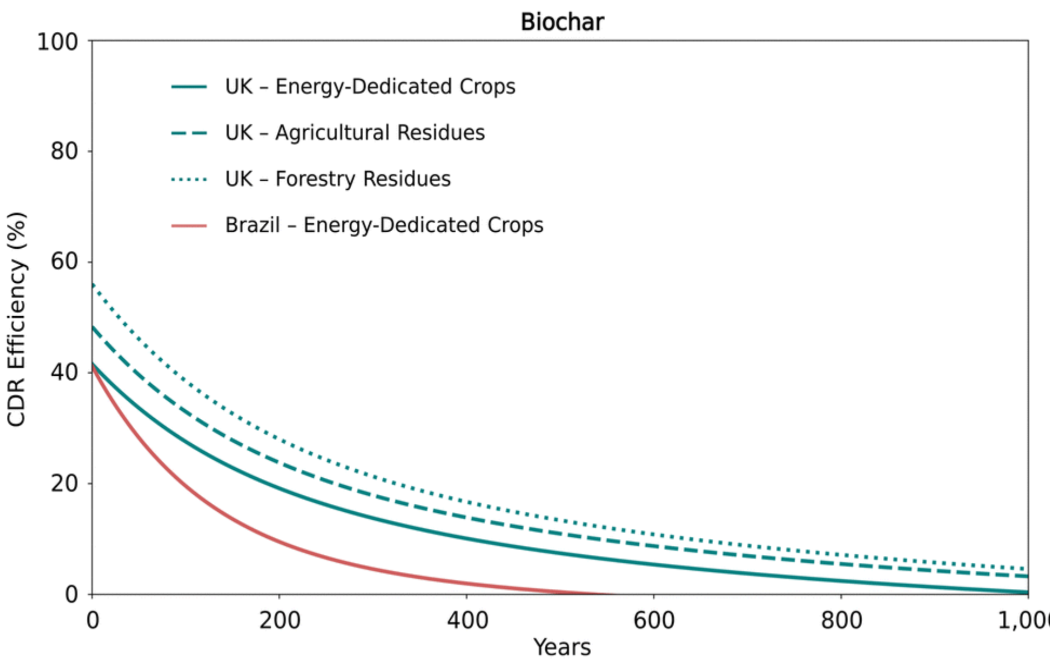

Figure 14. Stylised example of greenhouse gas flows in an afforestation system.

Furthermore, even when the supply chains are wholly domestic, global harmonization of accounting for emissions and extractions for standing biomass stocks is lacking. While the IPCC territorial accounting framework makes necessary concessions to practicality and resources different countries have for accounting, CDR accounting requires a more standardized and robust framework to reduce uncertainty and bias. This is particularly important if CDR via biomass stocks is used when reporting a nation's total net emissions or otherwise used to, essentially, compensate for residual fossil emissions[55].

The impermanent nature of standing biomass requires constant maintenance and monitoring to minimise the risk of biomass carbon being re-released into the atmosphere due to forest fires, disease, drought, pests, or mismanagement, particularly as a warming climate increases these risks. It is this risk of reversal that leads to the low CDR efficiency seen in Figure 15, and creates the same accounting challenges as noted with biochar, above.

Furthermore, reversals of biomass stocks are also not always accounted for, such as if afforestation that occurred initially on managed land later becomes "unmanaged land", any reversal that then happens would no longer be consider anthropogenic, and thus not accounted for in national inventories. In the EU framework, this is addressed in the LULUCF accounting rules where under some specific circumstances, member states do not need to report emissions from natural disturbances (e.g., wildfires, insect and disease infestations, extreme weather events and geological disturbances)[56].

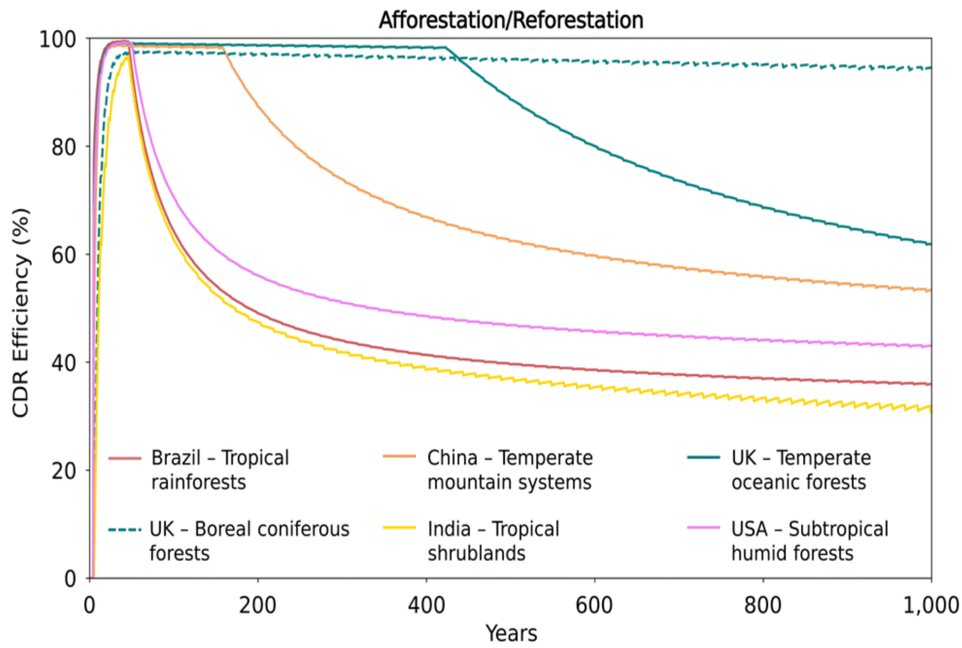

Figure 15. Figure 11 from Chiquier et al (2022), "Evolution of the CO_2 removal efficiency of AR over 1000 years for different climates and regions."[57]

RECOMMENDATIONS

A robust accounting system for CDR needs to answer two questions: "when is a removal a removal?" and "whose removal is it?" The question of "when" requires defining CDR; developing comprehensive accounting and monitoring methodologies for diverse NETP systems; and addressing temporal issues such as impermanence and delays between extraction, storage, and/or associated emission. The question of "who" requires agreeing on jurisdictions for accounting for all emissions in a CDR system and ensuring that liability is assigned for all of those emissions regardless of when or where they occur. These are all matters that become more complicated for NETP systems that cross boundaries, particularly as there is an inherent dichotomy between the life cycle accounting framework needed to answer the "when is a removal a removal?" and the territorial accounting framework used for assessing jurisdiction and liability for (inter)national emissions. Alone, neither is sufficient to ensure that CDR is effectively accounted for.

Improving greenhouse gas accounting for NETP systems has three distinct tasks: addressing existing gaps in LCA accounting for CDR; addressing existing gaps in territorial accounting; and creating a hybrid accounting framework for CDR that keeps the system perspective for CDR yet assigns jurisdiction and liability for the emissions and removals.

7.1 Adressing Gaps in CDR life cycle accounting

The most important piece in any potential CDR framework is a clear and robust definition of what is carbon dioxide removal. Since the goal of CDR is to reduce atmospheric concentrations of greenhouse gases, such a definition must involve the physical extraction of CO_2 from the atmosphere, the permanent storage of that CO_2, and the accounting for all associated emissions in the extraction and storage processes and associated supply chains so that only *net* removal is considered CDR. For successful development of efficient transboundary CDR system, definition must be agreed on an international level.

Secondly, development is still ongoing for accurate and usable methodologies to measure and monitor greenhouse gas flows in heterogenous NETP systems. This includes the development of tools to physically measure and increase understanding flows of stored carbon and indirect impacts, particularly for disperse carbon storage, such as biochar, enhanced weathering, and ocean CDR. For an efficient CDR system to be truly transboundary, these tools must be agreed on an international level as well.

Methodologies for life cycle assessment also need to be specifically tailored to the complexities of CDR, including a mandate that only "cradle-to-grave" system boundaries are acceptable for LCA of NETP systems. Other elements not in standard LCA practices but needed for rigorous CDR accounting include:

- ensuring all carbon that enters the system is accounted for from source to sink—carbon balances should always close,
- separate accounting of emissions, extractions, and avoided emissions
- separate accounting of CO_2 stored

- in biological sinks and CO_2 stored in geological sinks
- standardised internalisation of indirect impacts, such as induced changes in land use or energy systems, and albedo impacts,
- explicit accounting of temporal issues and their uncertainties, such as delays between emissions and storage, carbon payback period, (the risk of) impermanence
- separate treatment and uncertainty analyses for more predictable (e.g., biochar decay rate) and less predictable (e.g., forest fires) forms of impermanence.

7.2 Addressing Gaps in territorial accounting

Unlike life cycle accounting, territorial accounting does not seek to estimate the GHG balance of any specific system, but rather the total emissions of a region for a given timeframe. The IPCC accounting framework used for the UNFCCC national greenhouse gas inventories accounts for domestic emissions of nations, broken down by sector. Before CDR could potentially be incorporated into territorial accounting, pertinent gaps in the existing framework need to be addressed, including:

- accounting for non-biological extraction of CO_2 from the atmosphere
- accounting for non-geological storage of CO_2
- assigning liability for emissions from international transport
- assigning liability for CO_2 leakage in international waters
- assigning liability for all re-releases of stored carbon, including ensuring that any carbon sink used for CDR can never be considered "unmanaged" or that forfeiture of management is assumed to be a reversal
- separation of reporting of emissions, extractions, and storage of CO_2, instead of reporting net changes in flows or stock

7.3 Merging CDR life cycle accounting with territorial accounting

Good governance of CDR requires both accurate measurement of greenhouse gas flows throughout a CDR system and assigning appropriate liability for those emissions, removals, and risks. Furthermore, the CDR accounting framework needs to avoid diluting the purpose of the existing territorial framework, which is to provide annual accounting of regional GHG flows. Therefore, a transboundary CDR accounting framework may need to sit on top of, or next to the existing territorial framework—supplementing, not supplanting or superseding, the territorial framework. This is particularly needed as transboundary CDR accounting requires two features that territorial accounting does not supply: aggregating flows of greenhouse gases that occur in disparate locations and aggregating flows of greenhouse gases that occur across time.

A framework for transboundary CDR must take into account:

- all associated emissions of the extraction and storage processes, including intermediate transport and conversion and upstream supply chains
- uniformly high quality of methodologies used for accounting extraction, storage, and associated emissions
- the timing of extractions, storage, and emissions, so that CDR is only accounted for after net removal is achieved, including accounting for the "carbon payback period" of indirect impacts and land use change
- liability for reversals and leakage, regardless of when or where they occur

To determine when net CDR occurs and manage liability of reversals, some aspect of cumulative emission accounting may be needed, adding together the emissions and extractions of a CDR system as they occur over time. Separation of biological and geological emissions and storage can also help clarify the reversal risks and ensure that biologically stored CDR with a high reversal risk is not being used to compensate for emissions of greenhouse gases from geological stores.

A robust accounting framework is not the only need for successful transboundary governance of CDR. CDR is resource intensive, and guardrail regulations are necessary to ensure that CDR does not lead to overexploitation or inefficient use of resources such as land, water, and energy. Of particular primary concern is the need for explicit CDR targets that sit on top of emission reduction targets—CDR must never be allowed to cannibalize or slow down the direct reduction of greenhouse gas emissions. Other pertinent guardrail regulations include:

- minimum acceptable CDR efficiencies, to reduce the risk of uncertainties in the system leading to “false CDR”, where a CDR system—due to direct or indirect effects—leads to an increase in atmospheric greenhouse gas emissions
- maximum acceptable carbon payback period or an increasing penalty as the payback period increases, particularly given the urgency of near-term action to reduce and remove emissions.
- Strict sustainability criteria for biomass, energy, land, water, and other resources used in a CDR system.

In the near term, CDR accounting will be easier for NETP systems with short supply chains, that minimise the geographic and temporal distance between extractions, storage, and associated emissions, as well as for NETP systems with geological storage that has a low risk of reversal. Furthermore, in the absence of a harmonised international governance framework, multilateral contracts could be used to negotiate on liability and ownership between actors in a given NETP system. To build momentum for robust deployment of CDR, smaller, national scale projects could provide the stepping stones for large scale international projects.

CONCLUSION

NETP systems are resource-intensive and can have complex supply chains, involving the transport of biomass, CO_2, energy, and other materials across international boundaries. They also vary in the time between extraction and storage of CO_2, and emissions associated with the extraction and storage processes and their supply chains, as well as the risk of re-releasing stored carbon over time.

Existing accounting frameworks are not yet adequate for large-scale implementation of NETPs. There are several types of gaps remaining: no international agreement on a robust definition of negative emissions; high uncertainties of the behaviour of carbon flows over time for disperse storage for biochar and enhanced weathering; lack of clearly decomposed metrics that clearly account for emissions and extractions, including separation of biogenic and geologic carbon; lack of liability for emissions from international transport or unmanaged land; and a lack of treatment in territorial accounting of non-biologic extraction of atmospheric CO_2 and storage not in geologic reservoirs or biomass stocks.

Developing a robust accounting framework for NETPs is as fundamental as developing the NETPs themselves. While the NETPs aim to physically reduce atmospheric concentrations of greenhouse gases, accounting frameworks ensure that a NETP system leads to a real reduction in atmospheric GHG and measure what that reduction is. The most critical component is a reliance on tracking physical flows of carbon and ensuring that all greenhouse gases associated with an NETP system are both counted. A system to assign liability for these flows should not lead to direct alternation of territorial inventories, but rather stand beside those inventories, to avoid obscuring where extractions and emissions occur.

Transboundary greenhouse gas accounting for NETPs needs to keep all these goals in mind. It requires comprehensive and science-based measurement modelling of physical flows of greenhouse gases. It requires that liability for emissions and removals are fully and fairly assigned. It must not obscure or hinder the progress of rapid and massive reduction of emissions. And it must not discount indirect or future impacts that our children will then have to suffer the consequences of.

Endnotes

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