IPCC Expert Meeting

Carbon Dioxide Removal Technologies and Carbon Capture, Utilization and Storage

Report of the IPCC Expert Meeting

1-3 July 2024, Vienna, Austria

Task Force on National Greenhouse Gas Inventories

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The IPCC Expert Meeting on Carbon Dioxide Removal Technologies and Carbon Capture, Utilization and Storage was organized by the IPCC Task Force on National Greenhouse Gas Inventories (TFI) with support from the Government of Austria. It was held on 1-3 July 2024 in Vienna, Austria.

This meeting report was prepared by the Co-Chairs of the IPCC TFI (Takeshi Enoki and Mazhar Hayat) and the TFI Technical Support Unit (TSU) and subjected to review by the meeting participants.

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Preface

The IPCC Working Group III (WGIII) contribution to the Sixth Assessment Report (AR6) states that "The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved" and provides a summary of the role for CDR technologies in future mitigation pathways (IPCC 2022 Table TS.7).

The IPCC Guidelines already provide for inventory compilers to estimate and report on anthropogenic sinks from **any** process, activity or mechanism which removes a greenhouse gas from the atmosphere, in their national GHG inventories (NGHGI). This includes direct air capture technologies, for example, which currently do not have explicit methodologies specified.

Still, with the emergence of new carbon dioxide removal technologies and the generation of new empirical data on relevant sources and sinks, it may be valuable to consider new methods in the IPCC Guidelines. If adopted, these new methods will broaden the base of sinks and sources that inventory compilers should routinely monitor and facilitate their estimation and reporting in future national inventories.

With this context in mind, the IPCC tasked the Task Force on National Greenhouse Gas Inventories (TFI), in January 2024, to develop a Methodology Report on *Carbon Dioxide Removal Technologies, Carbon Capture Utilisation and Storage* activities (Decision IPCC-LX- 9).

An Expert Meeting on this topic was also mandated by the IPCC and held in Vienna on 1-3 July 2024. This was the first step along the journey to prepare the Methodology Report and this document is a Report of that Meeting.

Later in the year, a formal IPCC Scoping Meeting will be held to make recommendations on the Scope of the Methodology Report for consideration by the IPCC in early 2025. Following the decision of governments, a Methodology Report will be prepared through four Lead Author Meetings with the final report to be considered for acceptance by the IPCC Panel by the end of 2027.

This preparation process will be steered by the IPCC TFI Bureau.

This Expert Meeting was aimed at collecting evidence and information about gaps in the existing IPCC guidance (or where existing guidance might be updated and elaborated) and the capacity of the process to be able to rigorously specify IPCC methodologies for CDR technologies or where

there was a need to update CCUS guidance. The meeting also aimed to identify knowledge gaps and any specific areas or issues to be prioritized in the development of methodologies.

This Report of the outcomes of the Expert Meeting is based on contributions by participants and includes materials prepared during Break Out Group discussions and considered by the Expert Meeting plenary. The Background document prepared by the TFI TSU and presentations made by invited experts have been published alongside this report.

We would like to thank the experts who gave their time to contribute to this Meeting and, in particular, we would like to express our sincere gratitude to the Government of Austria for its generous support as hosts.

The meeting was opened by the Federal Government of Austria Minister for Finance, Magnus Brunner, together with the IPCC Chair, Jim Skea, and closed by the Federal Government of Austria Minister for Climate Action, Environment, Energy, Mobility, Innovation and Technology, Leonore Gewessler.

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1. Introduction

The IPCC, at its 60th Session on 16-19 January 2024 in Istanbul, Türkiye, decided that the Task Force on National Greenhouse Gas Inventories (TFI) should hold an Expert Meeting and produce a Methodology Report on *Carbon Dioxide Removal Technologies and Carbon Capture, Utilization and* Storage (Decision IPCC-LX-9).

This IPCC TFI Expert Meeting was held on 1-3 July 2024 in Vienna, Austria.

The Meeting was supported with a Background Paper prepared by the IPCC TFI TSU.

The Meeting process comprised presentations by invited experts and discussions held in 3 Break Out Groups (see Appendix 1 for the Agenda). The invited presentations are listed in Table 1. See Appendix 2 for the list of participants.

Table 1: List of Speakers and Presentations

	Presenter/Title
1	Simon Pang (Lawrence Livermore National Laboratory), *Engineered Solutions to Carbon Dioxide Removal*
2	Mai Bui, (Imperial College London), *Assessing the deployment potential of direct air capture and BECCS technologies*
3	Mark De Figueiredo (US DoE) *Monitoring, Reporting and Verification of CDR and CCUS: US Experiences and Lessons Learned for National GHG Inventories*
4	Paul Zakkour (Carbon counts) *Experiences with the 2006 IPCC Guidelines for CO_2 transport and storage: a rapid review of national reporting practices*
5	Dario Gomez (Atomic Energy Commission of Argentina) [On-line] *Existing guidance and need for updating on carbon dioxide capture in Volume 2 of the IPCC Guidelines*
6	Karen Scrivener (Ecole Polytechnique Federale de Lausanne), *CO_2 Uptake by Cement Based Materials: Principles, estimation, unknowns and future trends*
7	Anu Khan (carbon180) *Jurisdiction-Level Monitoring for Enhanced Weathering: Infrastructure, Data, and Maintenance Needs*
8	Andrew Lenton (CSIRO) *CDR in territorial waters: the challenges and opportunities*
9	Claudia Kammann, (Hochschule Geisenheim University), *State of Biochar-CDR: Growth of industries, C persistence, CDR co-benefits and current C-sink certification and trading schemes.*
10	Mihri Ozkan (University of California), [On-line] *Advancing Direct Air Capture: Empirical Foundations and Methodological Innovations for Emission Reduction*
11	Omkar Patange (IIASA) and Amit Garg (Indian Institute of Management) *The feasibility of developing new or updated IPCC default methods (and default emission factors) for various emerging technologies*

12	Steve Smith (University of Oxford) *Current CDR activity and gaps in existing IPCC Guidelines*
13	Freya Chay (Carbon Plan) *Open scientific questions across carbon removal approaches*
14	Dr. Katherine Romanak (Bureau of Economic Geology, The University of Texas at Austin) and Tim Dixon, (IEAGHG), *Improving the Protocols for CO2 Leakage Monitoring with Attribution*
15	Miguel Ángel Sanjuán, (Spanish Institute of Cement and its Applications), *State of the art on the quantification of natural carbonation of cement-based materials as a CO_2 capture mechanism*

Days 2 and 3 of the Meeting were devoted to discussions among experts in Break Out Groups (BOGs):

1. BOG1 – Engineered capture, utilisation & geological storage;
2. BOG2 – Inorganic processes and storage; and
3. BOG3 – Biogenic processes and storage.

The Break Out Groups considered the following guiding questions for each of the identified CDR technologies:

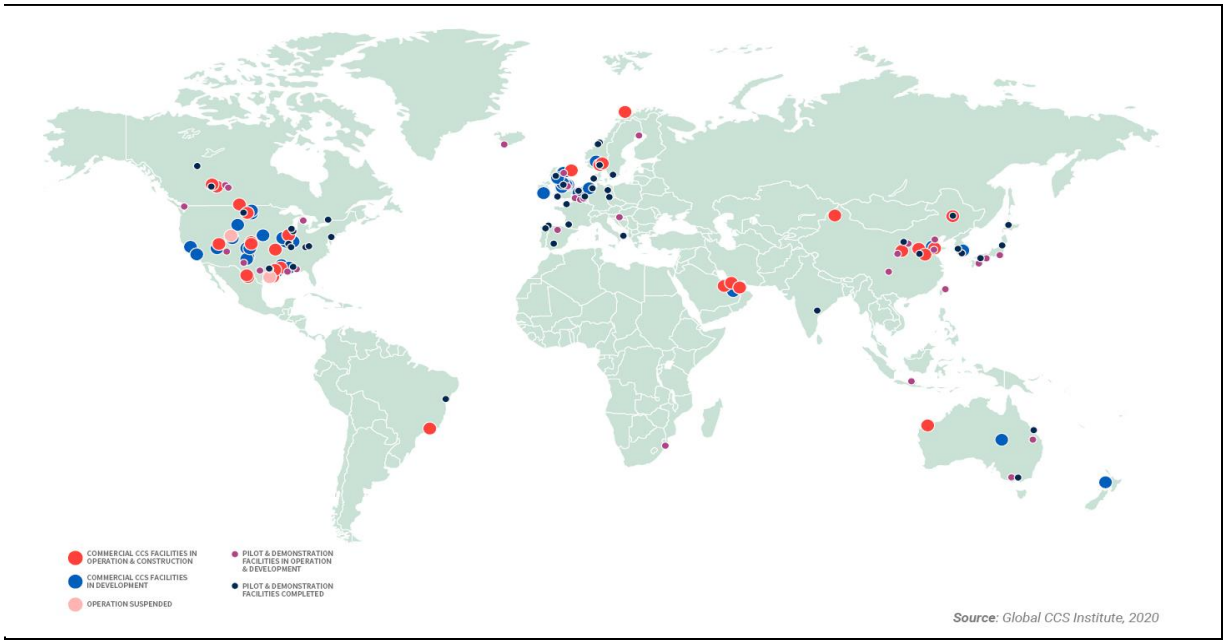
- Question 1 – Assessment Criteria
- Question 2 – Completeness
- Question 3 – Taxonomy of sources and sinks
- Question 4 – Preliminary assessment of existing IPCC Guidelines estimation methodologies
- Question 5 – Feasibility of Tier 1 methods
- Question 6 – Higher tier methods
- Question 7 – Verification Activities

The BOGs also considered additional questions which are reported in the next sections.

The Scoping Meeting presentations (invited presenters, BOGs and TSU) are available together with this report at the IPCC-TFI website: https://www.ipcc-nggip.iges.or.jp/ .

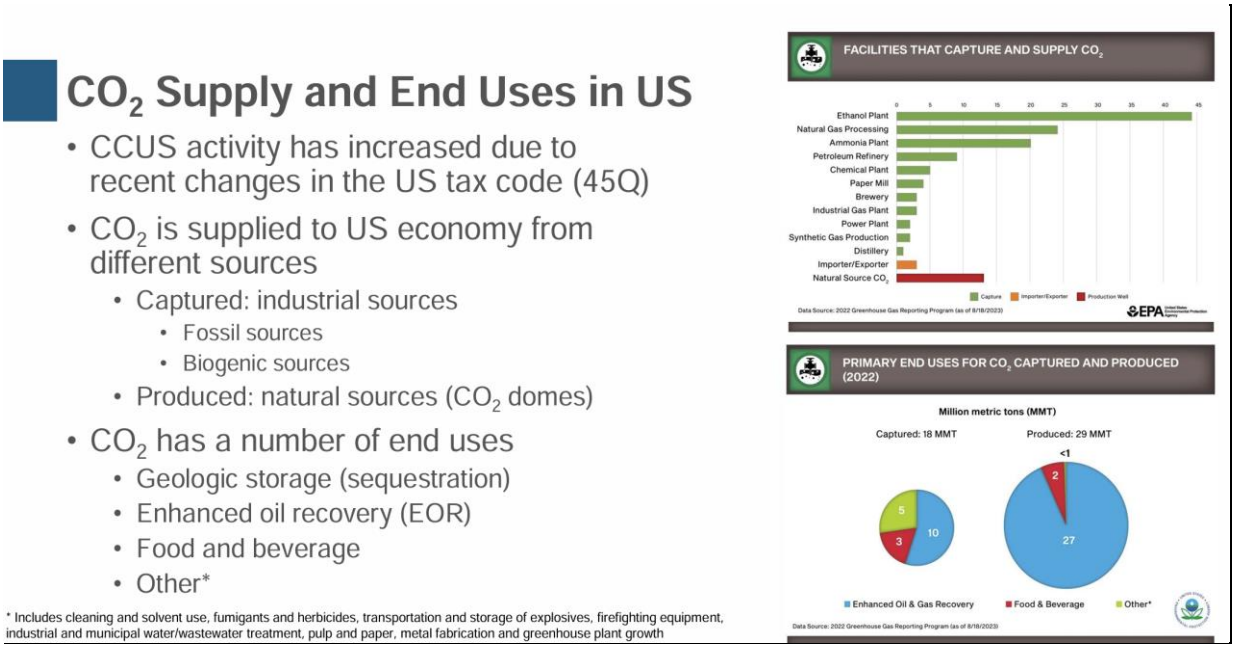
The presentations brought forward evidence and supporting material as to the prevalence of emerging CDR technologies and CCUS activities, some of which is captured in the following figures.

Figure 1: Carbon capture and storage sites



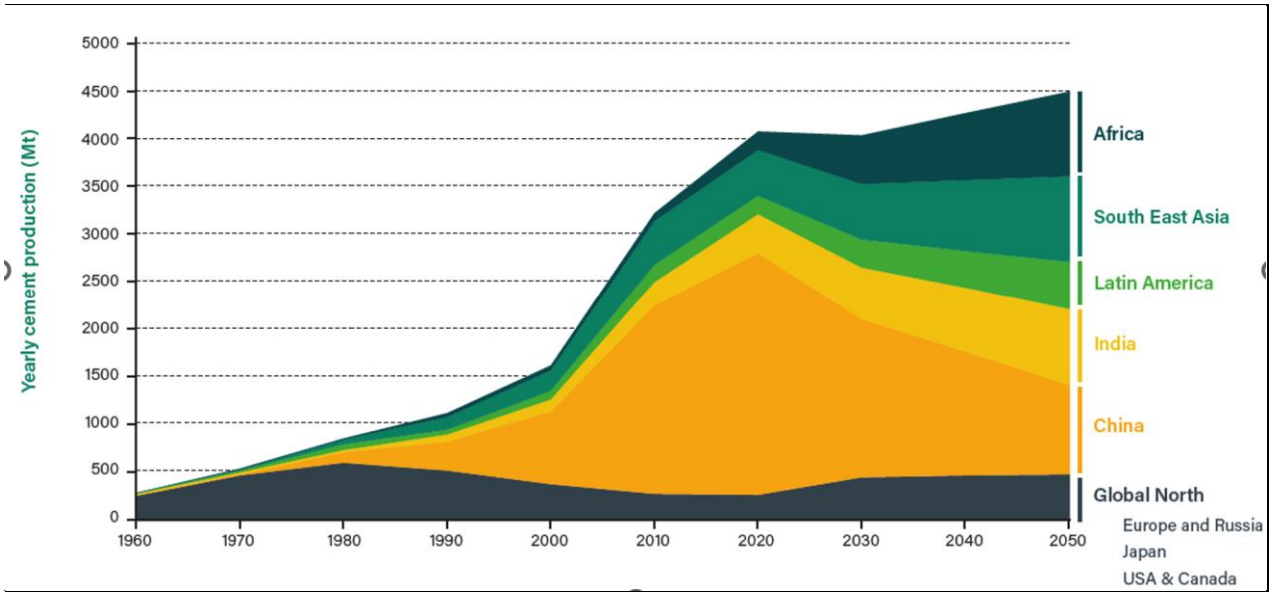
Presented by Paul Zakkour

Figure 2: Example of carbon dioxide supply and utilisation: United States



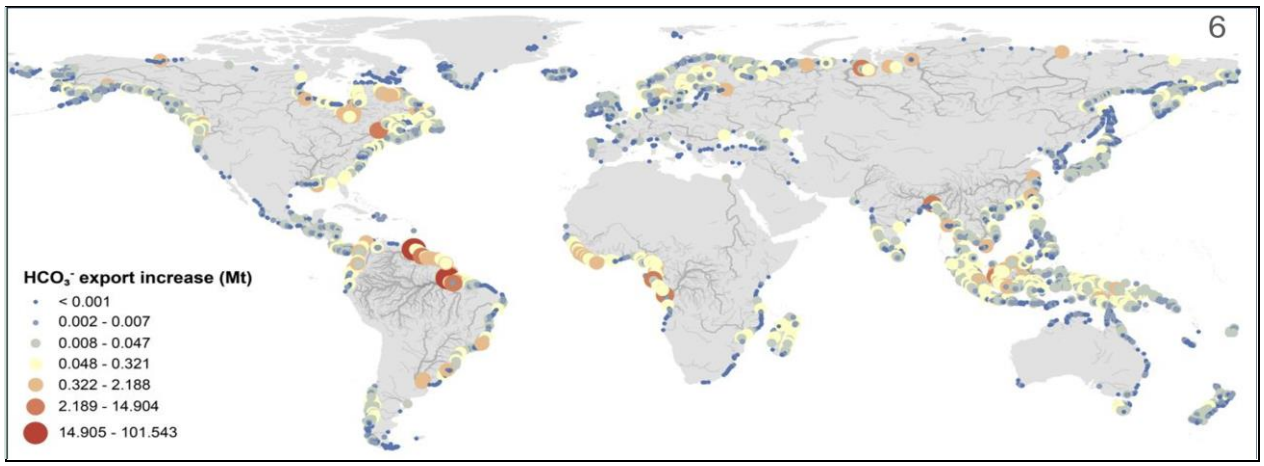
Presented by Mark de Figueiredo

Figure 3: Projections for future cement supply



Presented by Karen Scrivener

Figure 4: Expected significance of river weathering



Presented by Anu Khan

Figure 5: Map of field trials for ocean activities

Presented by Andrew Lenton

These descriptions of the extent of activities vary in significance from technology to technology. In Figure 1 the sites for existing carbon capture and storage activities are provided whereas in Figure 5 the map represents locations of the more limited concept of field trials for different types of ocean activities.

For more information, please refer to the published presentations on the IPCC TFI website.

2. Meeting Discussions

The reports prepared by each BOG are reported in full in the following sections. In this section, the results of discussions across the BOGs for certain elements are aggregated together for ease of reference.

2.1 Criteria for assessing scope of the future Methodology Report

This Meeting recommended criteria to assess sinks and sources for inclusion in the draft scope of the future Methodology Report to be used by participants to the Scoping Meeting. These criteria were supported by all BOGs and include:

1. the **identification of gaps** in the existing IPCC Guidelines for specific anthropogenic sinks or sources; or the identification of relevant existing sources and sinks where an elaboration of the Guidelines is considered desirable;

2. the **delineation** of the anthropogenic sink or source to be estimated;

3. the current and **expected significance** of the anthropogenic activity;

4. the knowledge available to generalize an IPCC Tier 1 methodology applicable under any national circumstances:

    a. availability of necessary **activity data** to implement the methods (readily available national or international statistics); and

    b. the ability to specify **tier 1 default values**:

    i. sufficient availability of data[1] to calculate a global (at least) value from a sample large enough to have it as a central value; and

    ii. which should be expected to produce unbiased estimates, so far as can be judged.

[1] Including expert judgments provided according to the IPCC elicitation protocol.

5. the feasibility of being able to specify higher tier methods for use by inventory compilers; and

6. guidance for inventory compilers as to how they may be able to devise appropriate verification activities.

One issue further discussed by participants related to the concept of significance: – this has not been defined and could mean a range of things to participants including, as noted by BOG1, the Long-term Low-Emission Development Strategies of countries.

2.2 Processes/technologies considered

The meeting initially considered the list of CDR technologies provided in the IPCC WGIII sixth assessment cycle report (Table TS.7). During the Meeting, the list of technologies considered was expanded beyond the list initially identified (Table 2).

The concept of 'technologies' received some discussion since it is not defined and does not fit within the IPCC classification system, which is based on delineating sources and sink processes with common estimation methods. Discussions among experts at this Meeting tended to adopt a broad understanding of the meaning of 'technology'.

Table 2 List of CDR technologies considered

Type of process	IPCC WGIII	Final list identified by BOGs
Engineered carbon capture with geological storage in the lithosphere	Direct air carbon capture and storage	Direct air carbon capture and storage
	Bioenergy with carbon capture and storage	Bioenergy with carbon capture and storage
Carbon capture in products		Concrete carbonation (incl. enhanced concrete carbonation)
		Carbonatable by-product materials (where not included elsewhere in national GHG inventory, e.g. slags, precipitated)

Type of process	IPCC WGIII	Final list identified by BOGs
Anthropogenic mineral processes with storage of inorganic carbon in minerals or as bicarbonate ions	Enhanced weathering	Enhanced weathering on managed land
		Enhanced weathering in rivers
		Ex-situ mineralization (open and closed systems) including enhanced weathering using biogenic CO_2 (wastewater alkalinity dosing)
		In-situ mineralization (sub-surface injection and rapid mineralization)
	Ocean alkalinity enhancement	Ocean alkalinity enhancement (mineral based and electrochemical)
		Direct ocean CO_2 removal (stripping CO_2 from seawater)
Anthropogenic biological processes (photosynthesis) – biomass	Afforestation/Reforestation	Afforestation/Reforestation
	Agroforestry	Agroforestry
	Improved Forest Management	Improved Forest Management
	Blue carbon management" in coastal wetlands (seagrass meadow, macro algae)	Blue carbon management" in coastal wetlands (seagrass meadow, macro algae)
Anthropogenic biological processes (photosynthesis) – soils and waterways	Soil carbon sequestration in croplands and grasslands	Soil carbon sequestration in croplands and grasslands
	Peatlands and coastal wetlands restoration	Peatlands and coastal wetlands restoration
	Biochar	Biochar
	Ocean fertilization	Ocean fertilization
		Biomass burial, Slurry and Oil

Source: Derived from BOG reports (see sections 3-5).

2.3 **Processes/technologies preliminary assessments**

Each of the 3 BOGs considered the CDR technologies and CCUS activities in detail. The comments and BOG assessments reported for each of the CDR technologies and CCUS activities is included in the following sections 3-5. An overview of key findings is included in Table 3.

Table 3 Preliminary assessment of CDR technologies Carbon Capture, Utilisation and Storage

	For further consideration?	What would be required?		
Activity		**Update to IPCC classification**	**New Guidance**	**Review of existing guidance**
Direct air carbon capture and storage	Yes	Yes	Yes	-
Carbon capture, utilisation and storage	Yes	Maybe	No	Yes
Bioenergy with carbon capture and storage	Yes	No	No	Yes
Concrete carbonation (incl. enhanced concrete carbonation)	Yes	Yes	Yes	-
Carbonatable by-product materials (where not included elsewhere in national GHG inventory, e.g. slags, precipitates	Yes	Yes	Yes	-
Enhanced weathering on managed land	Yes	Yes	Yes	-
Enhanced weathering in rivers	Yes	Yes	Yes	
Ex-situ mineralization (open and closed systems) including enhanced weathering using biogenic CO_2 (wastewater alkalinity dosing)	Yes	Yes	Yes	-
In-situ mineralization (sub-surface injection and rapid mineralization)	Yes	Yes	Yes	-
Ocean alkalinity enhancement (mineral based and electrochemical)	Yes	Yes	Yes	-
Direct ocean CO_2 removal (stripping CO_2 from seawater)	Yes	Yes	Yes	-
Afforestation/Reforestation	No	-	-	-
Agroforestry	Maybe	No	No	Yes
Improved Forest Management	No	-	-	-
Blue carbon management" in coastal wetlands (seagrass meadow, macro algae)	Yes	Yes	-	Yes
Soil carbon sequestration in croplands and grasslands	Maybe	No	-	Yes
Organic Soils and Peatland and coastal wetlands restoration	Maybe	No	-	Yes
Biochar	Yes	No	-	Yes
Ocean fertilization	No	-	-	-
Biomass burial, Slurry and Oil	No	-	-	-

Source: Derived from BOG reports (see sections 3-5).

3. BOG 1: Engineered capture, utilisation & geological storage

Co-facilitators: Bill Irving and Songli Zhu

Rapporteur: Jongikhaya Witi

3.1 Engineered capture, utilisation & geological storage technologies

Q1: Assessment Criteria:

- General acceptance of the assessment criteria as presented in the background paper
- New guidance should also include an equivalent of Volume 1 of the 2006 IPCC guidelines to deal with cross-cutting issues and general principles
- Clear guidance on the treatment of import and export of captured CO_2 (and derived products) as well as cross-boundary transport and storage
- Significance - The Party's Long-term Low-Emission Development Strategies (LT-LEDS) provide some insights into the future uptake of CDR technologies
- Important to pay attention to durability as we cannot assume permanent storage
- Criteria for significance should also be considered.

Q2: Completeness

- Production and use of synthetic fuels from captured CO_2 sources from the atmosphere and biosphere
- BECCS – current guidance in Chapters 2 and 5 of Volume 2 addresses BECCS. Further enhancement of the guidance would allow the chapter to also deal with DAC
- Storage of other forms of biogenic carbon in the lithosphere (e.g., bio-oil injection/biomass burial)
- Consider guidance on in-situ and ex-situ mineralisation. enhanced weathering (check with BOG 2)
- Guidance Structure: guidance to be developed could focus on CDR/CCUS/CCS process steps rather than focusing on the various CDR technologies
- Sea water capture and its interaction with the atmosphere and ocean requires modeling to isolate the atmospheric CO_2 signal.

- Consider different types of mineralisation, especially mineral products (e.g. biogenic CO_2 going to mineral products, and in the future, we might have DAC going to mineral products)
- Consideration of fugitive CO_2 emissions from Shipping in international waters.
- Burial of carbon in an underground chamber (not geological storage) [cross-BOG issue] might require its own category.-

Q3: Taxonomy of sources and sinks

- Categorisation of DAC
    - Option 1: Air capture is distinctively different from other IPCC categories and could be treated in a separate category (e.g. Volume 6) and clarify different end-use cases (within or beyond IPCC categories) for any captured CO_2.
    - Option 2: Also consider DAC as an industrial activity that processes CO_2 and therefore placed under the IPPU sector
- Need to track CO_2 imports and exports (evaluate the adequacy of existing guidance – e.g. for shipping)
- Can consider the following options
    - Geological storage can remain in Chapter 5 of Volume 2
    - In accordance with the current IPCC guidance, CO_2 captured should be reported where it occurred
- Clear guidance on the treatment of cases with multiple capture sources that lead to single or multiple storage sites (attribution problem).
- Important to trace the origin and fate of CO_2 to allow for differentiation

Q4: IPCC Guidelines methodologies

- Chapter 5, Volume 2 already addresses EOR (including a T3 method) but authors could consider reviewing existing guidance in accordance with new developments.
- If a country is conducting these activities, it should use the data that is available from CDR and CCS projects (it is a mitigation project Afterall)
- Should we consider T1 and T2 methods for small-scale projects as using T3 might not be economically feasible (e.g. biogas to biomethane upgrading)?

- Tracking the connection between CO_2 capture by specific industries and use/stored (fate problem)

Q5. Feasibility of Tier 1 methods

- Some parts of the CDR and CCS technology value chain are pliable to tier 1 methods (e.g., pipeline transport), and others are not (e.g., storage).
- Authors can consider the principles followed in the treatment of non-energy use of fuels to deal with captured carbon in cases of CO_2 capture for utilisation (in particular, the conversion to mineralised products) instead of storage – might consider an approach equivalent to how the IPCC guidelines deal with non-energy use of fuels under IPPU
- Consider fugitive CH_4 EFs for displacement by CO_2 at geological storage sites (EOR).
- 2006 IPCC do not deal with fugitive CO_2 EF for transportation by Ship (T3 method only), rail, road any other form of transport.

Q6. Higher tier methods

- The general view is that there is less of a challenge in developing a T3 methodological guideline. However, therefore could be a practical challenge to implement a tier 3 method (e.g. in cases of long CO_2 pipelines (> 1000 km of pipeline)
- Even for T3 methods, more guidance is needed (e.g. clarifying minimum requirements such as monitoring points)
- New guidance needs to address the issue of baselines with respect to storage (e.g. to isolate natural CO_2)
- Need to reexamine the relevance of guidance in Annexure 5.1 on the summary description of potential monitoring technologies for geo CO_2 storage sites.

Q7. Verification Activities

- Assessment of the role of remote sensing, i.e., whether top-down measurements could be used to verify CDR activities, should be investigated.
- Current research is underway to look at top-down verification methods for CO_2 capture from point sources.

- Verification should not be prescriptive. Every project is different; therefore, the monitoring regime differs from project to project.
- Reach out to the community conducting top-down emission quantification approaches to enhance guidance on top-down methods for verification of CDR and CCS activities (e.g. tracking CO2 release episodes)
- Explore the use of data and information from market-based instruments that are linked to CDR and CCS technologies (e.g. ETS trading scheme.)
- Authors to emphasise the role of stakeholders involvement in the QA/QC processes for CDR and CCS processes.
- Consider qualitative indicators for verification
- Conducting material balance as a form of verification for the whole CDR/CCS/CCUS value chain.

Raised Issues to be consider in later stages/ Relevant issues to consider

- For cross-boundary transfers of captured carbon, the cradle-to-grave principle should apply (i.e. no negative accounting from the source if there is no evidence of storage);
- Addressing durability and permanence is important;
- Consider guidance with respect to CCS onboard a ship;
- Consider the circularity of CO_2;
- Injection of carbon-containing materials (e.g. bio-liquids);
- Geological CO_2 storage: Observation is that there is more storage capacity in shallow waters than in deep sea waters. Therefore, storage is unlikely in deep water, and more potential in shallow waters.
- Several elements of the system are not being reported (e.g. activity data for utilisation in most cases is not readily available) – Authors can consider some of the issues related to CDR and propose guidance on how to navigate some of the issues (e.g. treatment of confidential data)
- Address potential double-counting from the use of synthetic fuels (e.g. efuels)
- Assess the glossary of terms for any changes that may be needed.
- Revaluation of the principles concerning CO_2 purity in the existing IPCC guidance.

4. BOG 2: Inorganic processes and storage: rock weathering, ocean alkalinisation, concrete carbonation

Co-facilitators: Eduardo Calva and Laura Dawidowski

Rapporteur: Lisa Hanle

Overview

Inorganic processes and storage: concrete carbonation, rock weathering, ocean alkalinization

In some cases capture and storage activity are the same (e.g. weathering on croplands) and in some cases capture occurs, then storage (e.g. CO_2 removal from oceans)

Level of maturity of processes varies widely:

Experience on carbonation > rock weathering and oceans

General Considerations: All

Recognized activities that collectively offer significant removals/reductions in mitigation scenarios

They would benefit from international guidelines for MRV

Methods for CDR should be comparable and as rigorous as methods for capture

Q1. Assessment Criteria: Suggested evaluation criteria are valid; also considered what is scope of report/technology, “anthropogenic” versus “natural”, and whether annual removals/reductions could be assessed

Q2. Completeness: We started with three primary activities for consideration:

Concrete carbonation

Enhanced weathering

Ocean alkalinity enhancement

→ Discussions resulted in 9 activities to be considered in a future methodological report (Table 1).

4.1 **CDR pathways inorganic processes and storage**

Table 4 Activities identified for inorganic processes

Group	Activities discussed
Carbon capture in products	• Concrete carbonation (incl. enhanced concrete carbonation) • Carbonatable by-product materials (where not included elsewhere in national GHG inventory, e.g. slags, precipitates
Anthropogenic mineral processes with storage of carbon in minerals or as bicarbonate ions	• Enhanced weathering on managed land • Enhanced weathering in rivers • Ex-situ mineralization (open and closed systems) including enhanced weathering using biogenic CO_2 (wastewater alkalinity dosing) • In-situ mineralization (sub-surface injection and rapid mineralization) • Ocean alkalinity enhancement (mineral based and electrochemical) • Direct ocean CO_2 removal (stripping CO_2 from seawater)

These were considered significantly different to warrant consideration

4.1.1 Concrete carbonation

Scope: Concrete carbonation could include enhanced carbonation

Table 5 BOG2 Assessment of concrete carbonation

Question	BOG assessment
Is the activity worth considering further?	Y
Are there gaps in existing methods?	Y
Can you delineate anthropogenic and natural?	Y (all anthropogenic)
Can you generate annual estimates?	Y
Can you estimate within national borders?	Y

Relevant history:

- Proposed for inclusion in 2019 Refinement, but too late in the process for full consideration.
- Papers submitted to EFDB, but further revision was required (e.g. reflect historical use of concrete and annual emissions).
- View of the group: Methodological issues could be addressed.

Question 3 on Taxonomy

- Elements of technology chain are known; consider if clinker production in one country (emissions), and cement production and use in another country (uptake).
- Ensure that any methods reflect annual uptake
- If reported, is it reported in 2.H (Other) (consistent with text in 2006 IPCC Guidelines) or in 2.A (consistent with footnote 5 on "other reductions" in IPCC reporting tables).
    - 2.A. Is called "Cement Production" – if carbon capture in products consided here, would name of category change?

Question 4 – Preliminary assessment of existing IPCC Guidelines estimation methodologies

- Method for uptake not in Guidelines
- Possible options:
    - Amendment to existing equation to add uptake (could have negative emissions if uptake in current year greater than emissions)
    - Add CO_2 uptake separately
    - Adjust CO_2 EF for clinker to reflect year 1 uptake (category name would have to change)

Question 5 – Feasibility of Tier 1 methods

- Literature robust and growing; sufficient available evidence.
- Documented methods have been suggested (Sweden, UK). Methods may assume stable cement use; need to look where growth is.

- Can estimate year-by-year absorption applying an average carbonation rate to a type of concrete (know fraction of structural versus non-structural).
    - National level activity data for cement exists in most countries.

Question 6 – Higher tier methods

-Available in literature; we know factors leading to uptake.

-Analogues: waste model, HWP, F-gases, abandoned coal mines

Question 7 – Verification Activities

- If there are multiple tiers, can use alternative tiers.
- As we know factors that influence emissions, verification is possible

4.1.2 Other Carbonatable Materials

- Carbonatable materials can be used as inputs to products, storage medium, or feedstock to processes discussed (e.g. Fly ash, slags, PCC)
- Overlap with storage of carbon in minerals, particularly ex situ mineralization
- Not further discussed

4.1.3 Enhanced Weathering

- Approaches to quantifying anthropogenic removals from enhanced weathering are relatively immature
- Efficiency of carbon removal dependent on process specific information (e.g. mineralogy)
- Terminology needs to be refined

Scope suggested for further consideration:

Anthropogenic mineral processes with storage of inorganic carbon in minerals or as bicarbonate ions.

- Enhanced weathering on managed land *(more advanced)*
- Ex-situ mineralization (open and closed systems) including enhanced weathering using biogenic CO_2 (wastewater alkalinity dosing) *(closed systems including wastewater more advanced)*
- Enhanced weathering in rivers
- In-situ mineralization (sub-surface injection and rapid mineralization) *(important, but is this the correct place)*

- Valid to consider all activities; focused mostly on EW on managed land

Table 6 BOG2 Assessment of enhanced weathering

Question	**BOG assessment**
Is the activity worth considering further?	Y
Are there gaps in existing methods?	Y
Can you delineate anthropogenic and natural?	Process: Y CO2 uptake: ? (questions of baseline)
Can you generate annual estimates?	Probably
Can you estimate within national borders?	Where does uptake and reversal occur? Land-based- Probably Other - Y

Question 3 on Taxonomy:

- Enhanced weathering on Managed Land:
  - Single category, if so where, OR updating EFs throughout GL to take account of EW practices (e.g. rice, croplands, wastewater treatment).
  - Boundary question: how do you separate EW and ocean alkalinity, as the ocean may ultimately be the fate.
  - Overlap with soil organic carbon ; emissions of other GHGs (CH_4 and N_2O)
- Other EW:
  - Single category, if so where, OR updating EFs throughout GL to take account of EW practices (e.g. energy (CCS), IPPU (chemical industry), wastewater)

Question 4 – Preliminary assessment of existing IPCC Guidelines estimation methodologies

- Method for EW not in Guidelines, but do have
    - CO_2 emissions from liming of soils;
    - Organic stocks from mineral soils
- Regarding dissolved inorganic carbon (DIC)- there are pools in soil, rivers and ocean. To understand the weathering you need to understand the impact on DIC. There is discussion on DIC in appendix to Wetlands Supplement.

Question 5 -7 – Feasibility of methods

- Limited data for all EW approaches, but growing rapidly.
- Tier 3 methods considered, insufficient information to develop Tier 1/ 2.

Table 7 Factors to consider for higher tier methods: enhanced weathering

Activity	**Factors that may need to be considered in a higher tier method (list not complete)**
Enhanced weathering on managed land	Rocks react at different rates, impact water chemistry, soil storage. Because it impacts soil storage and biomass, relationship with other AFOLU pools needs to be considered Monitoring: How do we consider here organic carbon. Interaction with SOC, carbonate precipitation, rate of mineral weathering, secondary mineral formation (carbonate, clay formation), non-carbonic acid neutralization, methane and N_2O emissions, mineral composition, mineral type, diameter and quantity. Soil type, soil moisture, crop type…
Enhanced weathering in rivers	Dissolution kinetics, secondary precipitation, interactions with ecosystems, interaction with DIC
Ex-situ mineralization (open versus closed systems) including enhanced weathering using biogenic CO_2 (wastewater alkalinity dosing)	Potential depends on the removal potential per ton of processed mineral and annual total production of mineral, CO_2 uptake rate

In-situ mineralization	Boundaries of in-situ and ex-situ mineralization

Verification: Limited field data available to assess removal efficiency. Signal-to-noise problem common across open system pathways. Review paper from Cascade climate about EW on managed lands

4.1.4 Ocean-based Activities

Scope

- Ocean alkalinity enhancement : Mineral-based and electrochemical acid removal
- Direct ocean CO_2 removal: Stripping CO_2 from seawater
- Would need to consider possible emissions/reversals related to the ocean-based activities
- How does IPCC definition of national boundary apply to Oceans? *National inventories include GHG emissions and removals taking place within national territory and* ***offshore areas over which the country has jurisdiction.***

Table 8 BOG2 Assessment of ocean-based activities

Question	**BOG assessment**
Is the activity worth considering further?	Y (listed ones)
Are there gaps in existing methods?	Y
Can you delineate anthropogenic and natural?	Process: Y CO_2 uptake: ?
Can you generate annual estimates?	Probably
Can you estimate within national borders?	Unknown

Question 3 on Taxonomy

- Single category, if so where, OR include throughout GL (e.g. "Other", separate CDR category, IPPU (chemical industry or other))
- Technology chain of removals and emissions; all steps required for a net removal :
    - Adding alkalinity / remove CO_2
    - Sequester CO_2 / neutralize or sequester acid
    - Enhanced ocean uptake
- But consider –
    - How to handle oceans in national GHG Inventory (beyond Wetlands Supplement?)
    - Relationship with London Protocol, CBD, IMO

Question 4 – Preliminary assessment of existing IPCC Guidelines estimation methodologies

- No existing methods
- Who is responsible for monitoring and verification of reversals. Consider international law

Question 5 – Feasibility of Tier 1 methods

Not applicable

Question 6 – Higher tier methods

- Tier 3 method may be possible

Question 7 – Verification Activities

- Requires secure storage of the CO_2 (direct ocean removal), acid (electrochemical OAE), to avoid reversal

- Not possible to do measurement based verification; challenging to monitoring uptake in temporally and spatially and delineation of anthropogenic/natural) ; difficult to assess signal to noise

- Ocean alkalinity and CO_2 removal: both have air sea exchange. Facility level data required. But for mineral based, there may be additional elements that come in. This latter will require more experiments.

Table 9 Factors to consider for higher tier methods: oceans

Activity	**Factors that may need to be considered in a higher tier method (list not complete)**
Ocean alkalinity enhancement : Mineral based and electrochemical	Measurement perturbation, how much CO_2 removed, how much alkalinity added (quantity, when and where), chemical distribution, biochemical behavior, mineralogy, biological impact, etc.
Direct ocean CO_2 removal: Stripping CO_2 from seawater	CO_2 removed (quantity, when and where), tracking CO_2 extraction, transport, storage.

5. BOG 3: Biogenic processes and storage

Co-facilitator: Stephen Ogle

Rapporteur: Martial Bernoux

Breakout Group main objectives

1. Discuss and refine the **evaluation criteria**.
2. Learn about new **CDR** based on biological processes and develop methods for estimating CO_2 capture and long-term storage.
3. Identify and highlight potential important **issues for future meetings and authors** of the methodological guide.

Guiding Questions:

- Question 1 – Assessment Criteria
- Question 2 – Completeness
- Question 3 – Taxonomy of sources and sinks
- Question 4 – Preliminary assessment of existing IPCC Guidelines estimation methodologies
- Question 5 – Feasibility of Tier 1 methods
- Question 6 – Higher tier methods
- Question 7 – Verification Activities

Appendix

- Possible Criteria for assessing new methods
- CDR pathways by type of technology

Framing issue

- “Technology” issue:

- In the absence of clear definition we assume all what was considered is “technology”;
- depending on the definition that will be adopted this can have impact/consequences on the “anthropogenic” approach for the AFOLU which is based on managed land proxy.
- We discuss both completely new methods as well as refining methods

- Geographical scope: our discussion went beyond land into territorial waters

5.1 CDR pathways for biogenic processes and storage

Table 10: Activities considered for biogenic processes

Group	The IPCC WGIII AR6 Report examples of CDR methods
Anthropogenic biological (photosynthesis) – biomass	• Afforestation/Reforestation • Agroforestry • Improved Forest Management • "Blue carbon management" in coastal wetlands
Anthropogenic biological (photosynthesis) – soils and waterways	• Soil carbon sequestration in croplands and grasslands • Peatland and coastal wetland restoration • Biochar

Source: Derived from IPCC 2022 – IPCC WGIII Mitigation of Climate Change, Technical Summary.

*Additional – not included in the source data

Table 11: BOG3 consideration of technologies

Group	The IPCC WGIII AR6 Report examples of CDR methods	Q3-Taxonomy	Q4—Methodology
Anthropogenic biological (photosynthesis) – **biomass**	Afforestation/Reforestation	No	No need for improvement at Tier 1; No need for improvement > Tiers.
	Agroforestry	No	May be (update EF1 – Cstock **or** EFDB update)
	Improved Forest Management	No	No need for improvement at Tier 1; No need for improvement > Tiers.

	Blue carbon management" in coastal wetlands (seagrass meadow, macro algae)	Yes	Develop Tier 1 EF (not covered in Wetlands Supplement - Chapter Coastal Wetlands) for seagrass, tidal marshes; develop Tier 1 EF for macro algae#. Develop Tier 2 (but see "Guidance for authors on taxonomy"); Lateral transfer of biomass
	Ocean fertilization	No*	No
Anthropogenic biological (photosynthesis) – **soils and waterways**	Soil carbon sequestration in croplands and grasslands	No	Tier 1 - May be: SOCref possible to develop for deeper depths; inputs/LU factors might be updated and extended to a deeper depth); Could consider develop an alternative Tier 1 approach taking into account changes before and after 20 years for LUC, or at least elaboration on the impact (box) > Tiers: additional guidance to consider DEM at Tier 3 level)
	Organic Soils and Peatland and coastal wetlands restoration	Yes**	Tier 1: Not sure (no expert in the BOG). Default EF1 factors in the 2013 Wetland Supplement - Chapter 3: Rewetted Organic Soil, might be updated; Update the DOC EF; Develop lateral transfer (DIC, POC); Revisit EF Tier 1 for CH4 and N2O. Consider stratify EF based on water table depth > Tiers: Lateral transfer (DIC, POC); Probably enough new science to consider the impact of the water table level at higher Tiers.
	Blue carbon management" in coastal wetlands (mud flats,seagrass bed, subtidal sediments)	No	Tier1: might expand (sea grass) or develop (mud flats and subtidals), considering DIC, DOC, POC; > Tiers: Need to considered lateral transfer of sediment;
	Biochar	Yes	No Tier 1 for soil, (Basis for future methodological development of a

			Tier1 method in Appendix, but only for cropland/grassland); Need to consider the effect on the direct N_2O emissions. Developing/updated information on derivation of FC_p and $Fperm_p$ values need to be considered (including evaluation of the feasibility of develop alternative methods based on pyrolysis temperature or ratios, e.g. H/OC). Consider expands at Tier1 to other land use (settlement, wetlands, forest) and other sectors (e.g. construction material) Develop production level (sub)category for Biochar and **consider the trade issue in the methodology** to avoid double counting, based on where the biochar is applied. Production of syngas and oil in the Energy Sector and potential for storage in geological reservoir. > Tiers: Some guidance already available. Impacts of different soil types / Impact of climate zones on EFs (for biochar with H/OC between 0.4 and 0.7) where it is applied; Considered eventual priming effect for verification.
Anthropogenic biological (photosynthesis) – **Soils? <u>Oceans? Or geological reservoirs</u>**	Biomass burial, Slurry and Oil***	May be (new category [on top of] HWP or waste)	May be not enough information for EF Tiers; Need a taxonomy (type of burial, type of material: raw, dried, processed, etc); need to consider all GHGs (likely not enough science/information); > Tiers: no further consideration

*In view of international agreements allowing or prohibiting certain activities, e.g. according to the **London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter**); no clear evidence of C sequestration from experiments (satellite monitoring); issue of national boundaries (less nutrient limitation in territorial waters: probably more affected in open ocean – international waters - that in territorial waters)

Most probably not enough information to develop Tier 1 EF

*** Risk of leakage on mid to long-term to be evaluated (risk of pollution from the "products" and/or "additives" and/or "packaging"); Loss of carbon and/or nutrients for the terrestrial or ocean agro-ecosystems; Changing oxygen levels in oceans; Impact on the waste sectors; National regulations/laws on waste/biomass deposition; Ensure the loss of biomass and the GHG associated with the production, is counted in the productive system(s); international trade and potential issues with double counting (similar to HWP); Verification: not feasible if ocean, should be possible in terrestrial.

VERIFICATION: Blue Carbon: might be challenging due to lateral transfer (floating biomass) in the tidal zone

VERIFICATION: Soil C (Possible and guidance available as needed); Blue Carbon: might be challenging for the sediments, due to lateral transfer in the tidal zone

VERIFICATION: Biochar consider using available registry on biochar/CDR at country level; Verification at production phase seems not an issue, might be more complex at application side

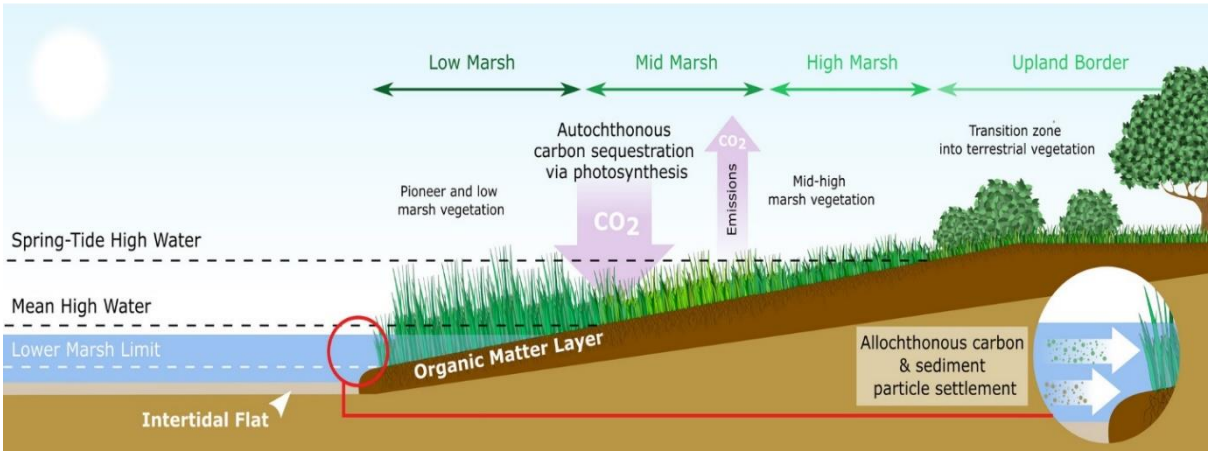
<u>Further guidance for authors for "blue carbon"</u>

- Consider developing a clear taxonomy for "Blue carbon management" in coastal wetlands
- Consider different species for each 'subcategory'
- Potential lateral transfer (potential double counting in sediments)

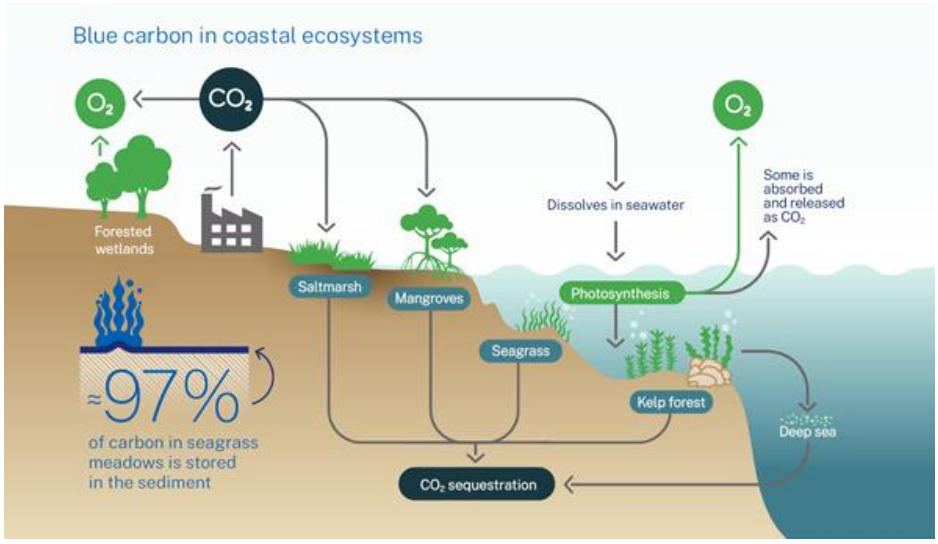
Figure 6: Further guidance for authors of 'blue carbon'

Source: https://cdn.naturalresources.wales/media/692035/nrw-evidence-report-428_blue-carbon_v11-002.pdf

https://cdn.naturalresources.wales/media/692035/nrw-evidence-report-428_blue-carbon_v11-002.pdf



Source: https://onlinelibrary.wiley.com/doi/10.1111/gcb.16943



https://www.environment.nsw.gov.au/topics/water/coasts/blue-carbon-strategy

Appendix 1. Agenda of the Expert Meeting

IPCC Task Force on Inventories

Expert Meeting on Carbon Dioxide Removal Technologies and Carbon Dioxide Capture, Use and Storage

online and in Vienna, Austria
5 Johannesgasse Vienna
1-3 July 2024

Agenda

Day 1	8:30 - 9:15	Registration
	9:30 - 10:00	**Welcome addresses** Magnus Brunner, Federal Minister of Finance of the Republic of Austria Jim Skea, IPCC Chair Leonore Gewessler, Austrian Minister of Climate Action, Environment, Energy, Mobility, Innovation and Technology **[video]**
	10:00 – 10:40	**Plenary session 1 (Presentations and discussion)** Takeshi Enoki and Mazhar Hayat, Co-Chairs of IPCC TFI Rob Sturgiss, Background and objectives of the meeting (IPCC TFI TSU) Q&A
	10:40 -11:00	*Morning tea*
	11:00 – 13:00	**DACS/BECSS/CCUS - Presentations (15 minutes each)** Simon Pang (Lawrence Livermore National Laboratory), *Engineered Solutions to Carbon Dioxide Removal*

		Mai Bui, (Imperial College London), *Assessing the deployment potential of direct air capture and BECCS technologies* Mark De Figueiredo (US DoE) *Monitoring, Reporting and Verification of CDR and CCUS: US Experiences and Lessons Learned for National GHG Inventories* Paul Zakkour (Carbon counts) *Experiences with the 2006 IPCC Guidelines for CO_2 transport and storage: a rapid review of national reporting practices* Dario Gomez (Atomic Energy Commission of Argentina) **[On-line]** *Existing guidance and need for updating on carbon dioxide capture in Volume 2 of the IPCC Guidelines* Speakers Panel Discussion, Q&A, [30-45 minutes]
	13:00-14:15	*Lunch break*
Day 1	14:15 – 15:40	**Inorganic carbon - Presentations (15 minutes each)** Karen Scrivener (Ecole Polytechnique Federale de Lausanne), *CO_2 Uptake by Cement Based Materials: Principles, estimation, unknowns and future trends* Jens Hartman (Universität Hamburg), **[On-line]** *Enhanced weathering and ocean alkalinity enhancement – TBC* Anu Khan (carbon180) *Jurisdiction-Level Monitoring for Enhanced Weathering: Infrastructure, Data, and Maintenance Needs* Andrew Lenton (CSIRO) *CDR in territorial waters: the challenges and opportunities* Speakers' Panel Discussion: Q&A
	15:40-16:00	*Afternoon tea*
	16:00-16:30	**Biogenic – Presentations (15 minutes each)** Claudia Kammann, (Hochschule Geisenheim University), *State of Biochar-CDR: Growth of industries, C persistence, CDR co-benefits and current C-sink certification and trading schemes.*

		Speakers' Panel Discussion: Q&A
	16:30-18:00	**General (15 minutes each)** Mihri Ozkan (University of California), **[On-line]** *Advancing Direct Air Capture: Empirical Foundations and Methodological Innovations* *for Emission Reduction* Omkar Patange (IIASA) and Amit Garg (Indian Institute of Management) *The feasibility of developing new or updated IPCC default methods (and default emission factors) for various emerging technologies* Steve Smith (University of Oxford) *Current CDR activity and gaps in existing IPCC Guidelines* Freya Chay – (Carbon Plan) *Open scientific questions across carbon removal approaches* Speakers' Panel Discussion: Q&A

Day 2	09:00 - 13:00	**BOG sessions** BOG 1 - engineered capture, utilisation & geological storage BOG 2 - inorganic processes and storage: rock weathering, ocean alkanisation, concrete, BOG 3 - Biogenic processes and storage: soils, ocean fertilisation and blue carbon
	13:00 - 14:30	*Lunch break*
	14:30 - 17:00	**BOG sessions** BOG 1: Engineered capture, utilisation & geological storage BOG 2: Inorganic processes and storage BOG 3: Biogenic processes and storage
	17:00 - 18:00	**Plenary session**

		Day 2 catch-up, discussion and Q&A Information on reception logistics
	19:00 -	**Reception hosted by the Austrian Government** 10er Marie (https://10ermarie.at/) - a bus will be provided by the Austrian Government.

Day 3	09:00 - 13:00	**BOG sessions continued** BOG 1: Engineered capture, utilisation & geological storage BOG 2: Inorganic processes and storage BOG 3: Biogenic processes and storage
	13:00 - 14:30	*Lunch break*
	14:30 – 18:00	**Plenary session (Discussion based on reports from BOGs & wrap-up)** Closing remarks

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Appendix 3: List of Acronyms and Abbreviations

AD	Activity Data
AFOLU	Agriculture, Forestry and Other Land Use
AR	IPCC Assessment Cycle
BECCS	Bioenergy Carbon Capture and Storage
BOG	Break-out Group
CCUS	Carbon Capture, Utilisation and Storage
CDR	Carbon Dioxide Removal
DAC	Direct Air Capture
EF	Emission Factor
EFDB	Emission Factor Database
GHG	Greenhouse Gas
HWP	Harvested Wood Product
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
KCA	Key Categories Analysis
TFB	IPCC Task Force Bureau
TFI	Task Force on National Greenhouse Gas Inventories
TSU	Technical Support Unit
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
WG	IPCC Working Group

BECCS, CCUS, CDR, DAC