PERMANENT AND SECURE GEOLOGICAL STORAGE OF CO₂ BY IN-SITU CARBON MINERALIZATION

Processes and requirements for greenhouse gas emissions accounting for CO₂ capture, transport, and geological storage by rapid in-situ carbon mineralization.

Abstract

This methodology outlines processes, requirements, and emission quantification for permanent and secure CO₂ capture, transport, and geological storage by rapid in-situ carbon mineralization. In-situ carbon mineralization replicates and accelerates natural processes, in which carbon dioxide is dissolved in water and interacts with reactive rock formations to form stable minerals providing a permanent and safe carbon sink.

Methodology Information

Basic Information	
Methodology Name	Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization
Version	1.0
Date of Issue	15.06.2022
Sector	Processes and requirements, for greenhouse gas emissions accounting for CO_2 capture, transport, and geological storage by rapid in-situ carbon mineralization.
Prepared by	Thomas Ratouis
Contact	Thomas Ratouis, Measurement, Monitoring, and Verification. Thomas.ratouis@carbfix.com

1. Differentiation from existing methodologies

Methodology	Title	GHG Program	Comments
ACR CCS	Methodology for Greenhouse Gas Emission Reductions from Carbon capture and storage	American Carbon Registry	The ACR CCS methodology outlines requirements and process for CCS projects to CO_2 in oil and gas reservoirs. It sets out requirements for the capture, transport and storage. This methodology differs from ACR CCS methodology as it excludes sedimentary basins and oil and gas reservoirs and only applies to in situ carbon mineralization in ultramafic, mafic, intermediate, or silicic rock formation underground. CO_2 is permanently stored via solubility and mineral trapping with negligible risk of leakage as the CO_2 mineralizes in the storage reservoir. This methodology further allows for combination with different methods for CO_2 capture and CO_2 transport as it only sets out general requirements for capture and transport.

2. Sources

This methodology is based upon the following methodologies:

- Methodology for Greenhouse Gas Emission Reduction from Carbon capture and storage Projects" prepared by American Carbon Registry version 1.0

This methodology further refers to the following tools/modules/regulation/standards:

- CDM-EB67-A25-GUID "Guidelines for completing the proposed new carbon capture and storage baseline and monitoring methodology form" prepared by UNFCCC version 01.1
- TOOL02 "Methodological tool: Combined tool to identify the baseline scenario and demonstrate additionality" Prepared by UNFCCC version 7.0.
- TOOL01 "Tool for the demonstration and assessment of additionality" Prepared by UNFCCC version 7.0.
- Modalities and procedures for a clean development mechanism as defined in Article 12 of the Kyoto Protocol Decision 3/CMP.1
- Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC
- ISO 14064-2:2019; Greenhouse gases — Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements

3. Summary Description of the Methodology

This methodology is for the application of in-situ carbon mineralization in ultramafic, mafic, intermediate, or silicic rocks hereby referenced as "mineral storage". Mineral storage relies on two trapping mechanisms: (1) solubility trapping; achieved immediately prior to, or during injection, by CO_2 dissolution in water, and (2) mineral trapping, achieved once carbonate minerals are formed within the geological storage reservoir (Appendix 1 - In-situ mineralization primer). With precipitation of CO_2 as carbonate minerals, its permanent immobilization occurs, and the CO_2 is permanently and securely trapped within the geological reservoir (Appendix 2 - Permanence Risk Assessment).

The methodology establishes applicability conditions and procedures to quantify project emissions and greenhouse gas (GHG) emissions mitigations for projects using mineral storage. The basic principle of the methodology is that:

- CO_2 is measured at the injection wellhead of the storage site
- Project emissions are subtracted from the stored CO_2 quantities

It also defines the monitoring approach, including data and parameters to be monitored over the duration of the project injection period and sets out requirements for the post closure and liability transfer to the state or competent authorities. The methodology sets rigorous conditions for the selection of a storage site and for the monitoring of CO_2 injection, to ensure immediate solubility trapping within the injection system and the geological storage reservoir. Additional requirements for the field monitoring are defined to ensure mineral trapping is achieved.

This methodology includes all the components of a CO_2 capture-transport-storage project and describes the general requirements of CO_2 capture (Appendix 5 – General requirements for CO_2 Capture), CO_2 transport (Appendix 6 – General requirements for CO_2 Transport) and specific requirements for CO_2 mineral storage. Alternative approved methodologies can be used to describe the capture and transport components of the mineral storage project. At the project level application of the methodology, it must be complemented by a project-based assessment of CO_2 capture and the CO_2 transport using the requirement set out in Appendix 5 – General requirements for CO_2 Capture for the capture of CO_2 and Appendix 6 – General requirements for CO_2 Transport for transportation of CO_2 from the capture site to the storage site or with approved methodologies (Appendix 4 – Approved Methodologies).

The methodology is developed in accordance with requirements of ISO 14064-2:2019.

4. Definitions

CCS Directive means the Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006.

Carbon Dioxide Removal (CDR) means anthropogenic activities that seek to remove CO_2 from the atmosphere and durably store it in geological, terrestrial or ocean reservoirs, or in products. CO_2 is removed from the atmosphere by enhancing biological or geochemical carbon sinks or by direct capture of CO_2 from air and storage (DAC+S).

Carbon Capture and Storage (CCS) means carbon dioxide (CO_2) capture and storage (CCS) which is a process consisting of the separation of CO_2 from point-source emitters (industrial and energy-related), transport to a storage location and permanent isolation from the atmosphere.

Carbonate Minerals means minerals characterized by the presence of the carbonate ion (CO_3^{2-}) in their structure. Carbonate minerals include calcite ($CaCO_3$), aragonite ($CaCO_3$), magnesite ($MgCO_3$), siderite ($FeCO_3$), ankerite ($Ca(Fe,Mg,Mn)(CO_3)^2$), and dolomite ($CaMg(CO_3)^2$).

Closure means the period that follows the operational phase and begins when CO_2 injection permanently ceases. It includes withdrawal of the geological storage permit, if applicable.

(CO_2) Capture means the capture of CO_2 from a process stream or from the atmosphere to produce a stream of CO_2 amenable for conversion or storage.

CO_2 Injection means the injection of CO_2 into a geological CO_2 storage reservoir.

CO_2 Release means any release of CO_2 from the storage complex and/or the injection facility after the last monitoring point.

CO_2 Stream means a flow of concentrated CO_2 in gaseous or liquid (liquified or water-dissolved) form that results from a CO_2 capture process.

(CO_2) Transport means the process of moving captured CO_2 through a pipeline or by other means (e.g. ship) from the CO_2 capture site to a suitable geological CO_2 storage site.

Conformance means the degree of agreement between past reservoir model predictions and current measured data from the storage facility.

Containment means the restriction of the movement of a fluid to a designated volume, here the geological storage reservoir.

Continuous Measurement means a set of operations having the objective of determining the value of a quantity by means of periodic measurements, applying either measurements in the pipeline or other process equipment with a measuring instrument located close to the equipment, whilst excluding measurement methodologies based on the collection of individual samples (*modified from Regulation (EU) 2018/2066*).

Direct Air Capture (DAC) means atmospheric carbon.

Existing Infrastructure means equipment such as piping, heat-exchangers, wells, casings, and well-heads that are already on-site and re-used for the purpose of capture, transport, injection or monitoring in the project. This should be excluded from project emissions, apart from any repurposing and/or retrofitting of this equipment for the specific use of the project.

Fracture means a break in rock formations. Fractures can occur at many scales (<mm to >km), and a network of interconnected fractures can create permeability in a rock unit.

Geological Formation means a formally named rock stratum or geological unit. It is a rock unit that is distinctive enough in appearance that a geologist can tell it apart from the surrounding rock layers and is a fundamental unit of lithostratigraphy (the scientific study and categorization of rock strata based on lithology; color, texture, and composition).

(Geological) CO$_2$ Storage means the permanent storage of the CO$_2$ in a geological storage reservoir. In this document CO$_2$ storage refers to geological CO$_2$ storage and is used interchangeably.

(Geological) Injection Facility means the surface infrastructures, sub-surface infrastructures used in the injection of CO$_2$ into a geological formation. Includes the storage surface conditioning facility and injection systems.

(Geological) Storage reservoir means a subsurface geological formation, group of formations, or part of a formation, suitable for permanent CO$_2$ storage. The geological storage reservoir shall have sufficient porosity and permeability to receive and transmit fluids and appropriate trapping mechanisms to ensure containment within the storage reservoir. For the application of this methodology this means that divalent cations are available for in-situ carbon mineralization.

(Geological) Storage Complex means a subsurface geological system extending vertically to comprise geological storage reservoirs and overlying geological formations and extending laterally and vertically to the defined limits of the CO$_2$ storage project.

(Geological) Storage Site means the surface facilities, sub-surface facilities, and geological storage complex.

(Geological) Surface Conditioning Facility means surface facilities used upstream of the injection of CO$_2$. This excludes the injection system(s).

(Geological) Injection System means the injection facilities that penetrate the geological storage reservoir. This includes injection well and associated installations.

(Geological) Injection Well means a well utilized for injecting fluids into the subsurface.

(Geological) Storage Permit means a written and reasoned decision(s) authorizing the geological storage of CO$_2$ in a storage site by the storage operator in the projects. This shall specify the conditions under which storage may take place and is issued by local authorities.

GHG means greenhouse gases such as CO$_2$, CH$_4$, and N$_2$O that cause the greenhouse effect.

In-situ Carbon Mineralization means the reaction of dissolved CO$_2$ with divalent cations (such as Ca^{2+}, Mg^{2+}, and Fe^{2+}) leached from reactive rocks (such as ultramafic, mafic, intermediate, or silicic geological formations) to form geologically stable, environmentally benign carbonate minerals in a geological formation. This process results in the mineral trapping of CO$_2$.

The Intergovernmental Panel on Climate Change (IPCC) means the United Nations body for assessing the science related to climate change.

Last Monitoring Point means the last mass flow measurements in the injection system of the CO$_2$ stream before it enters the injection well. This measurement point shall be as close as possible to the injection well (at the wellhead or within the injection system).

Migration means the movement of fluids within storage complex.

Mixing Point means the physical point in the CCS/CDR chain where two or more CO$_2$ streams are mixed. The CO$_2$ streams become indistinguishable after mixing. A mixing point occurs between process steps.

Monitoring means the quantification of GHGs entering or leaving the project boundary (CO$_2$ Capture, CO$_2$ Transport, and CO$_2$ Storage), and the evaluation and demonstration of the performance of the storage site in terms of permanent storage. It provides data and parameters to be monitored over the duration of the project injection period and sets out requirements for the post closure and liability transfer to the state or competent authorities. It includes:

- Collecting data for emission accounting (emission reductions or carbon removals, project emissions, and CO$_2$ release from the storage site),
- Collecting data to ensure optimal injection and full dissolution of the CO$_2$ prior to entering in the storage reservoir,
- Detecting CO$_2$ release from the storage reservoir to trigger timely corrective measures, and

- Mineral storage monitoring including chemical monitoring and verification of in-situ carbon mineralization. The data collected as part on the monitoring plan is used to build and maintain a numerical model of the CO_2 injection that is used for conformance monitoring and compared with the forecast and to demonstrate the validity of long-term forecasts. Besides monitoring for conformance and containment the monitoring plan provides data to support transfer of long-term liabilities after closure of the storage site.

Mineral Storage Monitoring System means the facilities and methods that are used to monitor the geological storage reservoir.

Monitoring Well means a well installed to allow the observation of subsurface conditions. Also called an observation well. An injection well can also serve the purpose of a monitoring well.

Permeability means the ability of a porous and fractured material to allow fluids to flow through it. For geological CO_2 storage it refers to the ability of a porous or fractured rock to allow injected CO_2 fluid to flow through it.

Pilot injection means a field experiment where CO_2 (>100 tonnes) is injected into an injection well and the reservoir response is monitored (e.g. using non-reactive tracers) for the rock dissolution in the storage reservoir (release of cations) and/or mineralization of the injected CO_2.

Pore Space means the microscopic space between the individual grains of a rock.

Porosity means the percentage of pore space over the total volume of a rock.

Post Closure Period means the period after site closure, including post-closure monitoring and liability transfer to the state.

Bubble Point Pressure means the pressure where the first bubble of gas (including CO_2) is formed when depressurizing a liquid.

Process Step means the successive steps in the full CCS/CDR chain, usually represented by the CO_2 capture, CO_2 transport, and CO_2 storage steps. CO_2 capture and CO_2 transport can be composed of multiple successive steps. For a multi-source project, CO_2 storage can be further divided into three steps representing the surface conditioning system, injection system, and geological storage reservoir.

Project Emissions means any carbon emissions (or carbon equivalent) accounted for using electricity, material, combustion, thermal energy, or any other process input in the production activity within the project boundary.

Project means an activity or activities that alter the conditions of a GHG baseline and which cause GHG emission reductions or GHG removal.

Single Source Project means a capture-transport-storage project that encompasses CO_2 capture from a single proponent and CO_2 transport to a single storage site.

Multi-Source Project means a project where CO_2 streams originating from two or more capture sources are stored at the same storage site. For a multi-source project to be eligible all projects must adhere to the requirements of the methodology. Projects can become multi-source projects at any point during the lifetime of the project but project descriptions for all CO_2 streams within the multi-source project must be updated to include the additional stream of CO_2.

Project Proponent(s) means an individual(s) or organization(s) that has overall control and responsibility for the project, or an individual or organization that together with others, each of which is also a project proponent, has overall control or responsibility for the project. The entity(s) that can demonstrate project ownership in respect of the project.

Capture Operator: means a registered individual(s) or organisation(s) for capturing CO_2, as documented by a certified trade registry extract or a similar official document.

Transport Operator means registered individual(s) or organisation(s) for transporting CO_2, as documented by a certified trade registry extract or a similar official document.

Storage Operator: a registered individual(s) or organisation(s) for storing CO_2 under national laws as documented by a certified trade registry extract or a similar official document stating that the Storage Operator holds a permit under the laws of the project's host country to store CO_2 in the targeted Geological Storage Site.

Project Operator(s): means one of the above (Capture Operator, Transport Operator, Storage Operator) or a combination of multiple operators.

Renewable Energy means energy which is produced from renewable, non-fossil fuel sources such as wind, solar (solar thermal and solar photovoltaic), geothermal, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas as defined by the Directive (EU) 2018/2001[1]. It is demonstrated with a certificate of origin, renewable energy certificate which has been cancelled/retired or a local statement coupled with unique right to the renewable component of the origin of energy production.

Site Characterization means the assessment of storage complex(es) for the purposes of geological CO_2 storage.

Solvent means a liquid that can dissolve carbon dioxide. In the present methodology solvent refers to water with varying levels of salinity but without artificially added chemicals and is referred to as "water".

Mineral Trapping means the incorporation of CO_2 in a stable mineral phase via in-situ carbon mineralization. CO_2 is immobilized in carbonate minerals (e.g. calcite) and is regarded to be stored permanently over geological timescales. As a result, mineral trapping is considered as the safest mechanism of geological CO_2 storage. It requires prior solubility trapping. The resulting fluid reacts with the bedrock to form solid carbonate minerals, permanently trapping the injected CO_2.

Solubility Trapping means the dissolution of CO_2 in water prior to or during injection, or in formation fluids. Solubility trapping is based on the density difference between the CO_2-charged water and other formation fluids. The CO_2-charged water is denser than the formation fluid and flows downward due to gravity, thus ensuring dissolved CO_2 is trapped and securely stored in the reservoir. Solubility trapping is a reversible state as exsolution can occur under depressurization or heating when the bubble point pressure is not exceeded within the reservoir.

Trapping (other) (see Appendix 1)

Ultramafic, Mafic, Intermediate, or Silicic Rock means a type of igneous basic rock of volcanic origin that are rich in iron and magnesium and relatively poor in silica. Examples include volcanic basalts, young oceanic ridges, large igneous provinces, and ophiolites. These rocks may have porosity and permeability in the fractures or cavities between blocks of solid rock; it is a candidate rock for mineralization of CO_2 through reaction with calcium and magnesium.

Uncertainty means a parameter, associated with the result of the determination of a quantity, that characterizes the dispersion of the values that could reasonably be attributed to the particular quantity, including the effects of systematic as well as of random factors, expressed in per cent, and describes a confidence interval around the mean value comprising 95 % of inferred values taking into account any asymmetry of the distribution of values (adapted from Regulation (EU) 2018/2066).

Water Supply System means the water supply facilities that provides the water required for the dissolution for the injection System.

Water Well means a well utilized for the supply of water.

---

[1] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

5. Applicability Conditions

This methodology applies to:

- Project and operation activities where CO_2 from a capture facility is transported to a geological storage facility for mineral storage.
- CO_2 streams that have no more than 5 volume percent of CH_4.
- CO_2 capture at point sources emitting fossil-based CO_2 as well as point sources of biogenic CO_2 or Direct Air Capture of CO_2. Hence, the methodology provides the opportunity to generate CO_2 emission reductions as well as carbon dioxide removal.

The methodology is focused on the storage of CO_2 by in-situ mineralization and does not set specific requirements towards the CO_2 capture or the CO_2 transport to the geological CO_2 storage site (Figure 1). The project shall thus be complemented by a project-based assessment of CO_2 capture and the CO_2 transport. The project-based assessment may be according to general requirements towards the CO_2 capture (Appendix 5Appendix 5 – General requirements for CO_2 Capture) and the CO_2 transport Appendix 4 – Approved Methodologies(Appendix 6) or according to approved methodologies (Appendix 4Appendix 4 – Approved Methodologies).
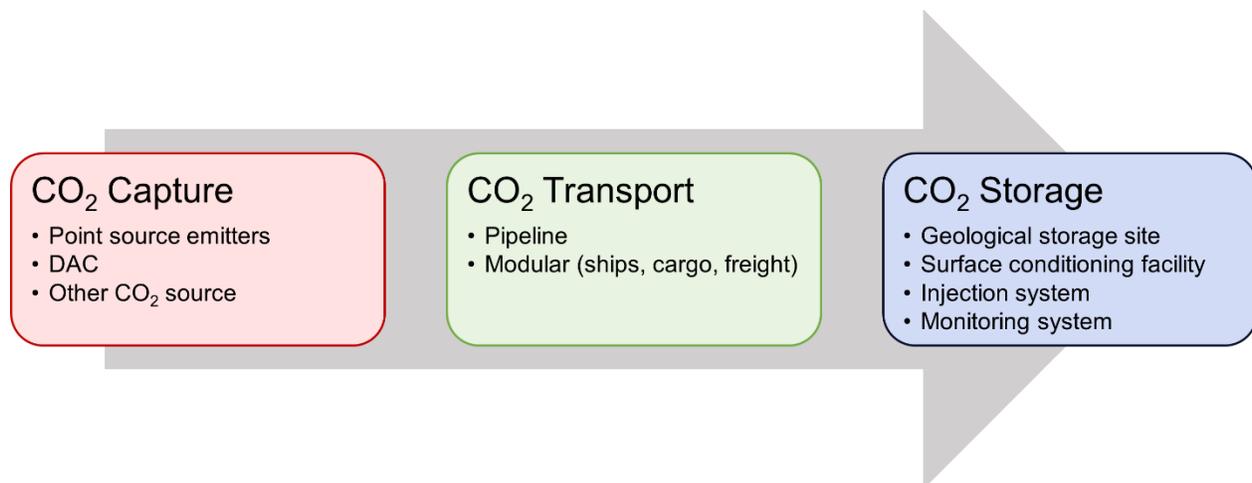

Figure 1: Process steps of application of the methodology.

The methodology allows for multiple CO_2 capture processes to connect with one or different modes of CO_2 transport to one CO_2 storage site (multi-source project) as well as splitting of CO_2 streams (Appendix 7Appendix 7 – Multi-CO_2 Stream projects: Emission Mitigation and Carbon Dioxide Removal).

5.1. Applicability Conditions for CO_2 Capture

According to approved methodologies (Appendix 4 – Approved Methodologies) or fulfilling requirements described in Appendix 5 – General requirements for CO_2 Capture.

5.2. Applicability Conditions for CO_2 Transport

According to approved methodologies (Appendix 4 – Approved Methodologies) or fulfilling requirements described in Appendix 6 – General requirements for CO_2 Transport.

6. Additionality

The application of the methodology shall undergo additionality testing and additionality shall be demonstrated for the full process chain, i.e. from the perspective of CO_2 capture, CO_2 transport or geological CO_2 storage. For demonstration of additionality, the stages of the project shall be assessed with the following requirements:

1. A statutory requirement test, and
2. An additionality test using the UNFCCC CDM TOOL01 for the demonstration and assessment of additionality.

If this methodology is used in conjunction with approved methodologies in Appendix 4, additionality testing shall follow the requirement listed above. If the requirements listed above are not satisfied, the project is not additional.

If the project implementation and operation is due to statutory requirements the project is not additional. If no statutory requirements are in place for the implementation and operation or it exceeds the statutory requirements, additionality testing is needed.

When/if statutory requirements change during the crediting period of a project resulting the project no longer being additional, this does not affect the current crediting period but results in that the crediting period cannot be renewed.

If this methodology is applied for installations for the purpose of deducting GHG emission from their GHG emission inventory according to article 49 of the EU Regulation on the monitoring and reporting of greenhouse gas emissions pursuant to the amended Directive 2003/87/EC of the European Parliament and of the Council, the application is not additional. This also applies to similar compliance operations outside Europe.

7. Baseline Scenario definition

The methodology relates to the permanent storage of CO_2 that would otherwise be emitted (CCS) or has been captured independent of a clearly identifiable emission source (CDR). Without the implementation of the project there would not be any CO_2 transport or geological CO_2 storage, therefore the baseline scenario shall be assessed and described at the CO_2 capture project level according to approved methodologies (Appendix 4 – Approved Methodologies), or Appendix 5 – General requirements for CO_2 Capture.

7.1. Applicability Conditions for CO_2 Storage

This methodology applies to CO_2 Storage project and operation activities that meet all the following conditions:

- Do no net environmental or social harm.
- The project activities shall comply with applicable local environmental, ecological, and social statutory requirements.
- Installations shall be installed according to national best practices and national statutory requirements.
- All geological storage sites shall be approved by local authorities and hold relevant geological storage permit for CO_2 injection.
- All measurement devices shall be calibrated according to manufacturer recommendations or industry best practices and allow measurements with uncertainty of 5% or better.
- Access to water shall be according to local permits.
- All wells shall be drilled according to national or international best practices and national statutory requirements.
- Well closure shall follow local statutory requirements. Well cementing is not required as part of this methodology as when solubility trapping has been confirmed the risk of release from the geological storage reservoir is negligible.

In addition, this methodology is applicable for CO_2 storage under the following geological conditions specific to in-situ mineralization:

- The geological storage reservoir shall be igneous (ultramafic, mafic, intermediate, or silicic) to allow in-situ mineralization of CO_2.
- The geological storage reservoir shall be characterized and deemed suitable as defined in section 10.1
- The geological storage reservoir shall demonstrate a sufficient storage capacity to store the total anticipated amount of the injected CO_2 over the lifetime of the project operations.
- Full dissolution of the CO_2 must be ensured upon entry into the geological storage reservoir regardless of where the mixing takes place - at the surface or within the injection well (Figure 2).
- The pressure at the point where the injected CO_2 enters the storage formation shall be greater than the bubble point pressure of the mixture of all streams entering the injection well with a reservoir pressure of at least 5 bara higher than the bubble point pressure in the injected CO_2 to enable immediate solubility trapping.

The methodology explicitly excludes:

- Forms of geological CO_2 storage other than solubility trapping and in-situ carbon mineralization and excludes pure-phase injections, such as Enhanced Oil Recovery (EOR) and applications in sedimentary basins.
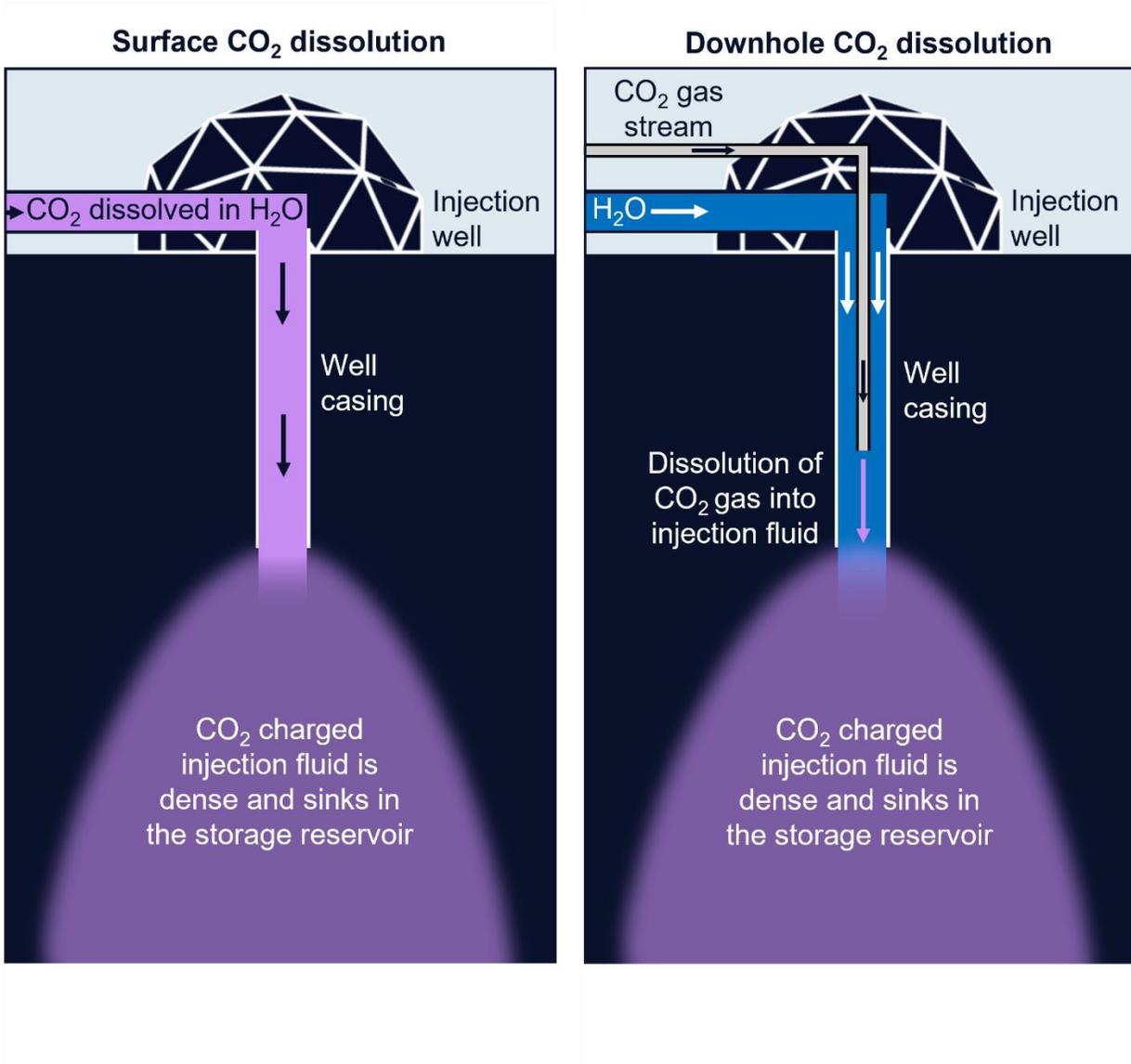

Figure 2: The dissolution in water can occur anywhere in between capture and injection into the geological storage reservoir, e.g. at the CO_2 capture site prior to CO_2 transport or within the CO_2 injection well at the geological CO_2 storage site.

8. Project Boundary

8.1. Activity Boundary

The full process of the application of the methodology is divided into three process steps which consist of:

1) CO_2 capture,
2) CO_2 transport from the CO_2 capture site to the geological CO_2 storage site, and
3) CO_2 storage by CO_2 injection into the geological storage reservoir, where the CO_2 is stored permanently through solubility and mineral trapping.

Therefore, the extent of the project boundary shall encompass CO_2 capture, CO_2 transport, and geological CO_2 storage. All emission sources, CO_2 from the CO_2 site, and CO_2 streams out of each step shall be included (Figure 3). The project proponent(s) shall ensure that the operator(s) comply with all the requirements stipulated in this methodology.
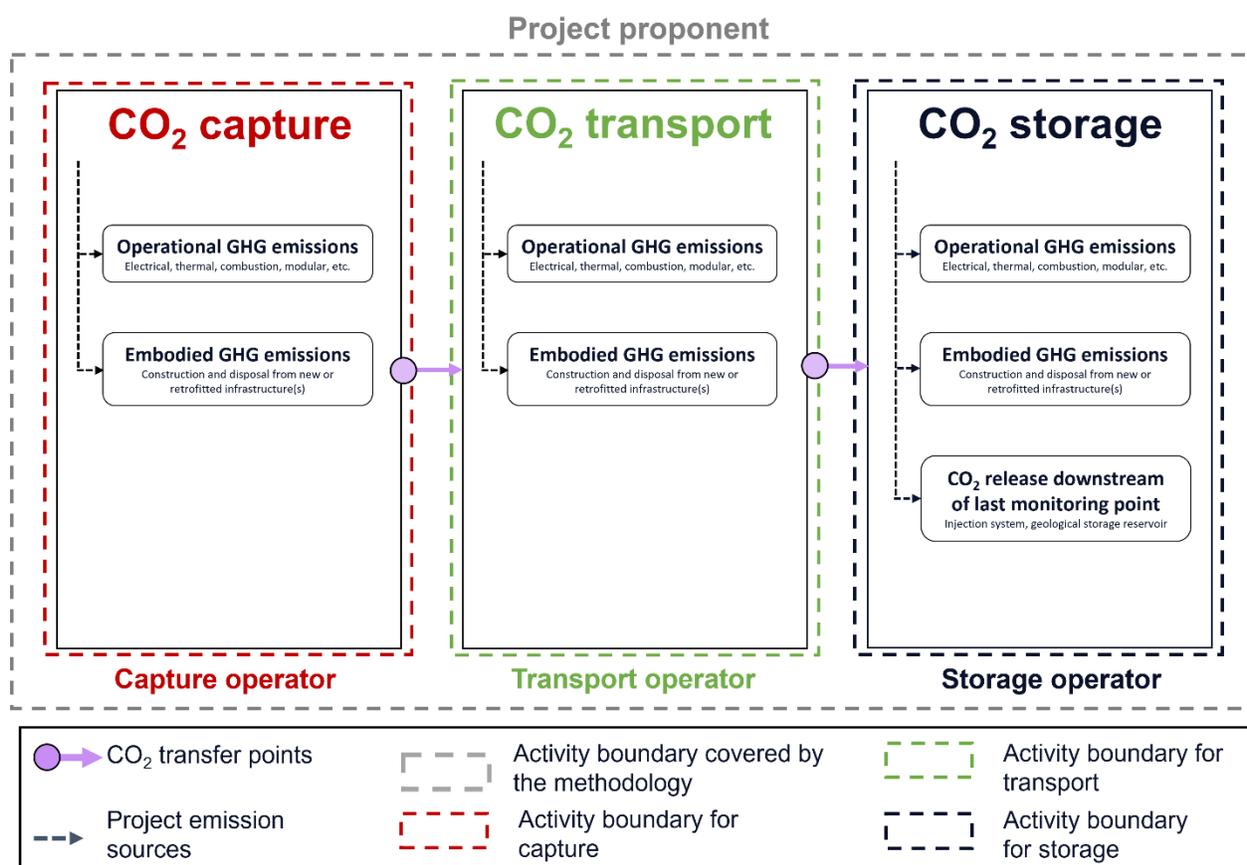
Figure 3: Project activity boundary and full chain processes.

The methodology does not set a limit to the number of consecutive capture and transport step in the capture-transport-storage project and the GHG emissions from each individual step must be calculated from Appendix 5 or Appending 6 or according to approved methodologies in Appendix 4.

The project proponent shall establish and maintain a monitoring plan that includes procedures for measuring or otherwise obtaining, recording, compiling, and analyzing data and information important for

quantifying and reporting GHG emissions and/or removals relevant for the project and baseline scenario for each monitoring period. The objective of the monitoring plan is to quantify GHGs entering or leaving the project boundary (CO_2 capture, CO_2 transport, and CO_2 storage). This is completed through appropriate and effective collection of data to support continued and evolving assessment and management of mitigation measures.

8.2. Baseline Scenario

The baseline scenario shall be determined according to applied methodology in Appendix 4 or according to Appendix 5.

8.3. Project Scenario

8.3.1. CO_2 Capture

The project scenario for the CO_2 capture shall be determined according to applied methodology in Appendix 4 or according to Appendix 5.

8.3.2. CO_2 Transport

The project scenario for the CO_2 transport shall be determined according to applied methodology in Appendix 4 or according to Appendix 6.

8.3.3. CO_2 Storage

Physical Boundary

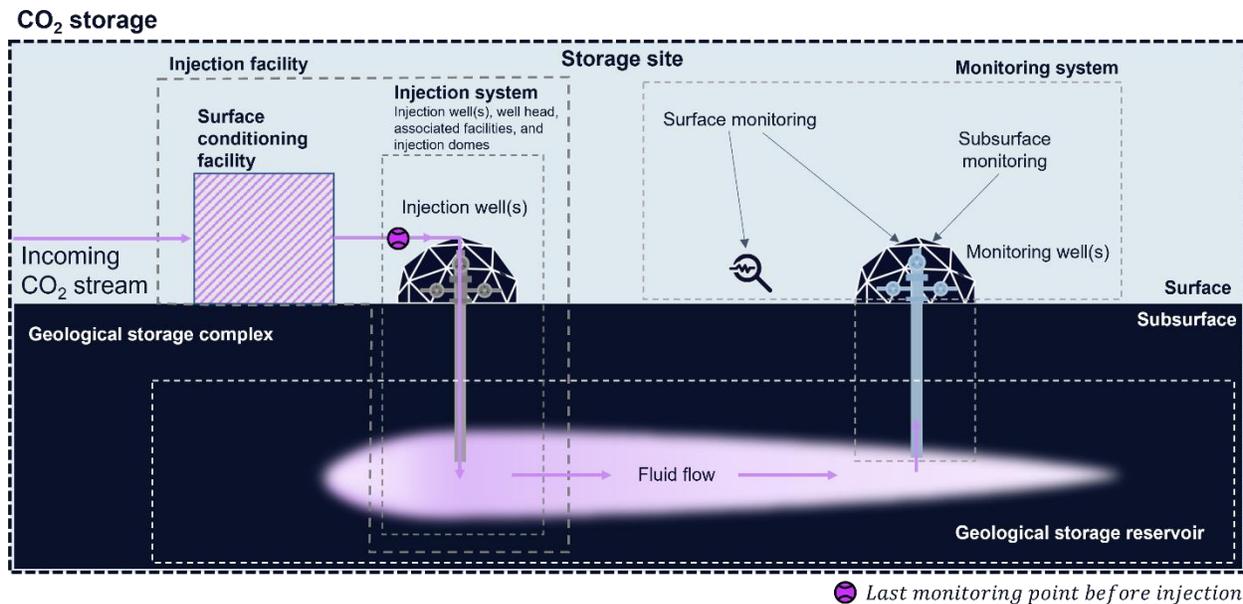The physical boundary Geological CO_2 storage is illustrated in Figure 4.

Figure 4: Physical boundaries of the storage site.

It includes the following within its boundaries:

- Interface with CO_2 transport (incoming CO_2 stream) in which the CO_2 is offloaded to the CO_2 geological storage facility
- Geological injection facility (surface conditioning facility and injection system)
- Injection well(s)
- Monitoring well(s) and above ground monitoring device(s)
- Vertical and lateral limits of the geological storage reservoir

Project emissions

CO_2 storage emissions includes the emissions from construction and disposal of the geological storage facility as well as the emissions associated with the operation of the geological storage facility. The project emissions exclude the CO_2 release downstream of the last monitoring point (from the injection system and geological storage reservoir) at the storage site which is addressed in section 9.4.

The emissions from construction and disposal of the geological storage facility may include, but are not limited to:

- site preparation
- mobilization of drill rigs and drilling
- manufacturing of drill heads and casing
- infrastructure construction
- embodied emissions from materials used, e.g. from steel and cement in the installations
- embodied emissions from heavy machinery and groundworks.

The operational emissions of the geological storage facility include, but are not limited to:

- electricity consumed for CO_2 compression
- electricity for supply of water
- electricity to operation the sensors, control valves, etc.
- embodied emissions linked to monitoring activities.

Overall, project emissions related to the geological CO_2 storage site depend on the source of the low carbon energy, i.e., electricity grid, on-site electricity, and heat generation (low carbon), waste heat recovery, etc. and must be calculated accordingly. All emissions shall account for usage intensity ($I_{type\ of\ emission}$) and associated emission factors ($ef_{type\ of\ emission}$).

CO_2 release from the storage site

All CO_2 release from the geological CO_2 storage site, defined as any release downstream of the last monitoring point on the injection system, shall be assessed by the project proponent.

CO_2 Storage project scenario

The project scenario and GHGs entering or leaving the project boundary that shall be included is summarized in Figure 5.
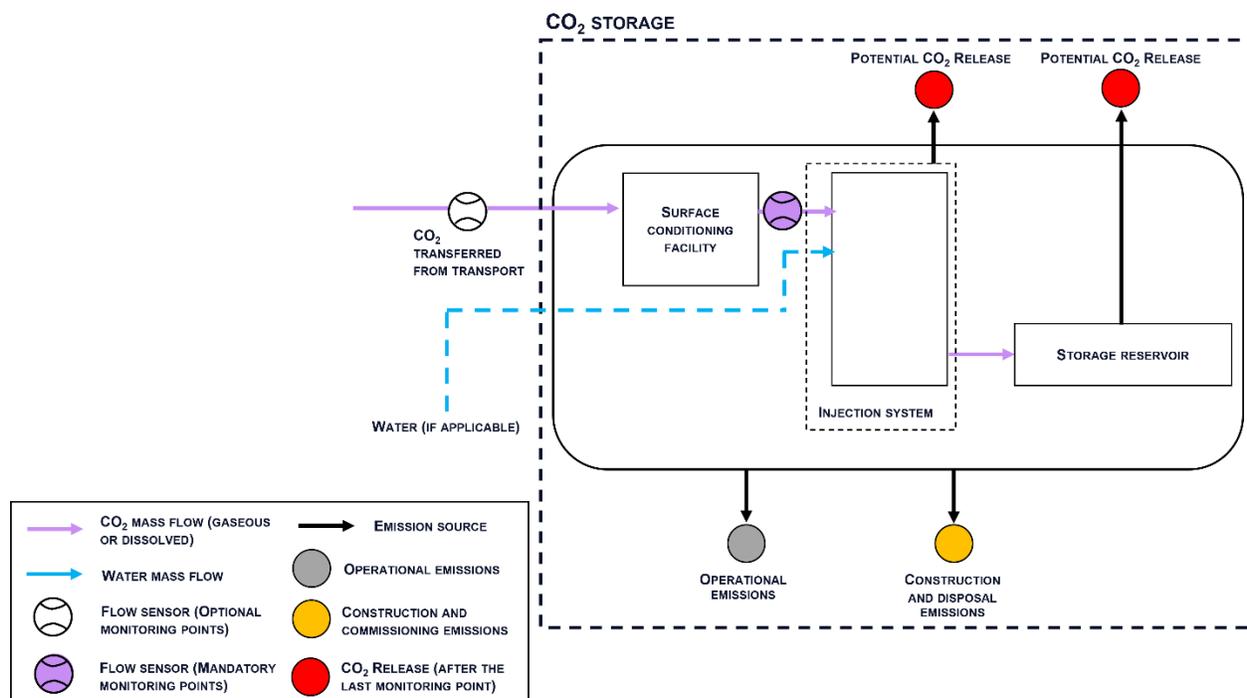
Figure 5: CO$_2$ storage project boundary.

Project Scenario			
Source	**GHGs**	**Incl.**	**Justification/Explanation**
mCO$_{2,released}$	CO$_2$	Yes	May be an emission source. If contributing as a source CO$_2$ is always included. Other GHG may be included if demonstrated they are not negligible. Following proper site selection and characterization, release from the storage complex is improbable when solubility and/or mineral trapping is confirmed. However, to remain conservative, preemptive measures for detection shall be implemented (see section 9.4).
	CH$_4$	No	
	N$_2$O	No	
mCO$_{2,storage,operation}$	CO$_2$	Yes	May be an emission source. If contributing as a source CO$_2$ is always included. Other GHG may be excluded if demonstrated they are negligible. Direct or indirect emissions from energy usage to operate the CO$_2$ capture, transport, and storage facilities. Must be calculated for each individual process step.
	CH$_4$	Yes	
	N$_2$O	Yes	
mCO$_{2,storage,embodied}$	CO$_2$	Yes	May be an emission source. If contributing as a source CO$_2$ is always included. Other GHG may be excluded if demonstrated they are negligible. Emissions due to construction and disposal of the capture-transport-storage installations. Must be calculated for each individual process step and distributed over the crediting period.
	CH$_4$	Yes	
	N$_2$O	Yes	

9. Emission Accounting

9.1. Baseline Emission

Baseline emissions shall be calculated according to the baseline scenario determined in Appendix 4 or Appendix 5.

9.2. Emission Mitigation and Carbon Dioxide Removal

Overall, net removals achieved through the considered activities shall be quantified as the difference between the amount of CO_2 removed and the emissions generated by the project activities, i.e. emissions related to the characterization and access of the geological storage reservoir, and emissions associated with the operation of the CO_2 capture, CO_2 transport, and geological CO_2 storage.

For installations other than DAC facilities for the CO_2 capture, the carbon credited during reporting $mCO_{2,credited,y}$ should always be less or equal to the baseline emissions according to Appendix 5 – General requirements for CO2 Capture or approved methodologies in Appendix 4 – Approved Methodologies.

The operational and embodied emissions CO_2 capture and CO_2 transport shall be calculated according to Appendix 5 – General requirements for CO2 Capture or Appendix 6 – General requirements for CO2 Transport or to approved methodologies (Appendix 4 – Approved Methodologies).

9.2.1. From a single source

$mCO_{2,credited,y} = mCO_{2,\text{injected},y} - mCO_{2,\text{released},y} - mCO_{2eq,\text{project,operation},y} - mCO_{2eq,\text{project,embodied},y}$			Equation 1
Where			
$mCO_{2,credited,y}$	=	total amount of CO_2 credited in own accounting or sold/transacted to third parties in period *y*.	tonne (tCO₂)
$mCO_{2,\text{injected},y}$	=	Total amount of CO_2 injected at the storage site in period y, determined at the last monitoring point on the injection system.	tonne (tCO₂)
$mCO_{2,\text{released},y}$	=	Total amount of CO_2 released at the storage site downstream of the last monitoring point on the injection system in period y.	tonne (tCO₂)
$mCO_{2eq,\text{project,operation},y}$	=	Total GHG emissions due to project operations of the CCS/CDR value chain (CO_2 Capture, Transport, and Storage) in period y.	tonne (tCO₂)
$mCO_{2eq,\text{project,embodied},y}$	=	Total GHG emissions due to construction and disposal of the CCS/CDR value chain (CO_2 Capture, Transport, and Storage) scheduled for monitoring period y.	tonne (tCO₂)
y	=	Monitoring period during which credits are produced.	days

The amount of CO_2 injected into the geological storage reservoir must be measured or calculated at the geological injection site for each injection well.

$mCO_{2,\text{injected},y}$ shall be calculated as:

$$mCO_{2,injected,y} = \sum_i mCO_{2,i,y}$$			Equation 2
Where			
$mCO_{2,injected,y}$	=	Total amount of CO_2 injected at the storage site in period y, determined at the last monitoring point on the injection system.	tonne (tCO_2)
$mCO_{2,i,y}$	=	Mass of CO_2 injected at each injection well i in period y, determined at the last monitoring point on the injection system.	tonne (tCO_2)
i	=	Injection well(s).	unitless
y	=	Monitoring period during which credits are produced.	days

$mCO_{2,i,y}$ shall be calculated as:

$$mCO_{2,i,y} = \int_0^y \dot{m}_{CO2,i} \cdot x_{CO2,i}\, dt$$			Equation 3
Where			
$mCO_{2,i,y}$	=	Mass of CO_2 injected at each injection well i in period y, determined at the last monitoring point on the injection system.	tonne (tCO_2)
$\dot{m}_{CO2,i}$	=	Mass flow rate of the CO_2 stream entering the injection well.	tonne/sec (t/s)
$x_{CO2,i}$	=	The CO_2 weight fraction of the CO_2 stream entering the injection well.	$WCO_2/$ W_{stream} (unitless)
i	=	Injection well.	unitless
dt	-	Numerical integration over the period y.	seconds (s)
y	=	Monitoring period during which credits are produced.	days

9.2.2. From Multiple Source

For multi-source projects see Appendix 7 – Multi-CO2 Stream projects: Emission Mitigation and Carbon Dioxide Removal for examples. For the capture and transport steps, these shall be determined according to Appendix 5 or approved methodologies (Appendix 4 – Approved Methodologies).

9.3. Project Emissions

9.3.1. Emission from Project operation — $mCO_{2eq,project,operation}$

For application of the methodology all GHG emissions which are under the control of the project proponent which are significant shall be included. If sources are excluded from the baseline or the project activities, it must be justified. Emission from the project operation shall be calculated as follows:

$$mCO_{2eq,project,operation,y} = \sum_p mCO_{2eq,p,operation,y} = \sum_p \sum_z (I_{z,p,y} \cdot ef_{z,p,y})$$		Equation 4
Where		

$mCO_{2eq,\text{project,operation},y}$	=	Total GHG emissions due to project operations of the CCS/CDR value chain (CO_2 capture, transport, and storage) in period y.	tonne (tCO_2)
$mCO_{2eq,\text{p,operation},y}$	=	GHG emissions due to project operations of the CO_2 capture, transport, and storage in period y.	tonne (tCO_2)
$I_{z,p,y}$	=	Intensity of consumption of a process input.	quantity (qty)
$ef_{z,p,y}$	=	Emission factor or emission rate of a given pollutant relative to the intensity of a specific process input.	tonne/quantity (tCO_2 / qty)
p	=	Process Steps, these include the capture, transport, and storage steps in the CCS/CDR chain.	unitless
z	=	Process input	unitless
y	=	Monitoring period during which credits are produced.	days

Significant emissions are defined as those that amount to more than 0.5% of $mCO_{2eq,\text{project,operation},y}$. All emission sources that are less than 0.5% of $mCO_{2eq,\text{project,operation},y}$ individually can be assumed negligible and therefore not significant if the sum of all negligible emissions sources is less than 5% of $mCO_{2eq,\text{project,operation},y}$.

9.3.1.1. CO₂ Capture
According to an approved methodology (Appendix 4) or as defined in Appendix 5.

9.3.1.2. CO₂ Transport
According to an approved methodology (Appendix 4) or as defined in Appendix 6.

9.3.1.3. CO₂ Storage
A project-based assessment of all emission source shall be conducted according to the project scenario (8.3.3). All significant emission source shall be included in the calculation of the Project operational emissions. Significant emissions shall account for usage intensity ($I_{type\ of\ emission}$) and associated emission factors associated ($ef_{type\ of\ emission}$). Where available, emission factors shall be derived from the latest values published by the IPCC, except for electricity/thermal usage which shall be derived from nationally determined emission factors and/or information provided by the energy supplier.

9.3.2. Embodied Emission from Construction and Disposal — $mCO_{2eq,\text{project,embodied}}$

$$mCO_{2eq,\text{project,embodied}} = \sum_p mCO_{2eq,\text{p,embodied}}$$			Equation 5
Where			
$mCO_{2eq,\text{project,embodied},y}$	=	Total GHG emissions due to construction and disposal of the CCS/CDR value chain (CO_2 capture, transport, and storage) scheduled for monitoring period y.	tonne (tCO_2)
$mCO_{2eq,\text{p,embodied}}$	=	Emissions due to construction and disposal for each process step p attributed to the operational phase in period y.	tonne (tCO_2)
p	=	Process Steps, these include the capture, transport, and storage steps in the CCS/CDR chain.	unitless

9.3.2.1. CO$_2$ Capture

According to an approved methodology (Appendix 4) or as defined in Appendix 5.

9.3.2.2. CO$_2$ Transport

According to an approved methodology (Appendix 4) or as defined in Appendix 6.

9.3.2.3. CO$_2$ Storage

GHG emissions associated with the construction and disposal of facilities are to be quantified based on case specific assessments of the facilities constructed. In all cases, the minimal scope of the assessment of construction emissions shall be the cradle to grave GHG emissions from materials used, including embodied emissions. Construction emissions can be calculated according to an assessment before the start of operations and should be for a specific plant. Construction emissions only need to be accounted for once. If a plant gets reused or if its operational lifetime is expanded beyond what was assumed in the ex-ante estimate, the yearly accounting for construction emissions shall cease to zero once the entire amount has cumulatively been accounted for (i.e. similar to full depreciation of the value of a good at the end of its planned lifetime in financial accounting). Embodied emission from existing infrastructures, embodied emission can be excluded from the embodied emission sources estimation.

9.4. CO$_2$ Release from the Storage Site — $mCO_{2,\text{released},y}$

For the application of the methodology intentional or unintentional release of CO$_2$ from the injection system and the geological storage reservoir shall be monitored. In case of detection, corrective measures must be applied, and the amount of CO$_2$ released must be quantified. CO$_2$ release from the injection system and from the geological storage reservoir are assessed separately as they rely on distinct monitoring procedures and timescales.

$$\begin{aligned} mCO_{2,released,y} &= mCO_{2,released,injection\ system,y} + mCO_{2,released,geological\ storage,y} \\ &= \sum_j mCO_{2,\ release\ event,injection\ system,j} \\ &+ \sum_k mCO_{2,\ release\ event,geological\ storagem,k} \end{aligned}$$	Equation 6

Where			
$mCO_{2,\text{released},y}$	=	Total amount of CO$_2$ released at the storage site downstream of the last monitoring point on the injection system in period y.	tonne (tCO$_2$)
$mCO_{2,released,injection\ system,y}$	=	Amount of CO$_2$ released at the storage site from the injection system downstream of the last monitoring point on the injection system in period y.	tonne (tCO$_2$)
$mCO_{2,released,geological\ storage,y}$	=	Amount of CO$_2$ released at the storage site from the geological storage downstream of the last monitoring point on the injection system in period y.	tonne (tCO$_2$)
$mCO_{2,\ release\ event,injection\ system,j}$	=	Mass of CO$_2$ released intentionally or unintentionally from the injection system	tonne (tCO$_2$)

		downstream of the last monitoring point on the injection system during event j.	
$mCO_{2,\ release\ event,geological\ storage,k}$	=	Mass of CO_2 released intentionally or unintentionally from the geological storage reservoir during event k.	tonne (tCO_2)
j	=	CO_2 release event from the injection system.	unitless
k		CO_2 release event from the geological storage reservoir.	unitless
y	=	Monitoring period during which credits are produced.	days

9.4.1. CO_2 release from the injection system - $mCO_{2,released,injection\ system,y}$

As demonstrated in Appendix 2, $mCO_{2,released,y}$ is negligible unless injection does not ensure full CO_2 dissolution. Therefore, the injection system is the most likely pathway for potential CO_2 release from a geological storage site. The appropriate operation of the injection to ensure full dissolution shall be monitored as follows:

1. Full dissolution of the CO_2 upon entry into the geological reservoir can be confirmed by
   – Wellhead measurements that can detect unexpected changes of the water mass flow with sufficient accuracy and frequency to allow for the detection of gas bubble ascent in the well.
   – Downhole logging tools that can detect CO_2 gas bubbles within the injection well.
2. Sufficient reservoir pressure shall be ensured to keep the CO_2 in solution at the bottom of each injection well casing according to Equation 7.

$P_{reservoir,i} > P_{BubblePoint,i} + P_{margin}$			*Equation* 7
Where			
$P_{reservoir,i}$	=	Pressure at the bottom of the casing of injection well i.	bar-a
$P_{BubblePoint,i}$	=	Pressure where the first bubble of gas (including CO_2) is formed when depressurizing the liquid injected at injection well i.	bar-a
P_{margin}	=	Pressure safety margin	bar-a

The bubble point pressure ($P_{BubblePoint}$) of the injected stream, considering the injected mass flow of water, CO_2, and other fluids. $P_{BubblePoint}$ shall be calculated using appropriate equation of states, thermodynamic databases, and geochemical tools.

Calculation of $P_{BubblePoint}$ is performed as follows:

$P_{BubblePoint,i} = f(\dot{m}_{CO2,i},\ \dot{m}_{water,i},\quad T_{water,i},\quad T_{CO2,i},\quad Elem_{CO2,i},$ $Elem_{water,i})$			*Equation* 8
Where			
$P_{BubblePoint,i}$	=	Pressure where the first bubble of gas (including CO_2) is formed when depressurizing the liquid injected at injection well i.	bar-a
f	=	Appropriate equation of state and thermodynamic functions	unitless

$\dot{m}_{CO2,i}$	=	Mass flow rate of the CO_2 stream entering the injection well.	tonne/sec (t/s)
$\dot{m}_{water,i}$	=	Mass flow rate of the water stream entering the injection well.	kg/s
$T_{water,i}$	=	Temperature of the water stream entering the injection well.	degree Celsius (°C)
$T_{CO2,i}$	=	Temperature of the CO_2 stream entering the injection well.	degree Celsius (°C)
$Elem_{CO2,i}$	=	Elemental composition of the CO_2 stream entering the injection well.	Vol% (for gas streams) mg/kg (for liquid streams)
$Elem_{water,i}$	=	Elemental composition of the water stream entering the injection well.	mg/kg

For the detection of CO_2 release from the injection system or injection site the following shall be in place:

a. CO_2 gas detectors placed around the injection well. As an example, for good practice, a building around the injection wellhead and other infrastructure after the last monitoring point and measurements of the CO_2 concentration inside this building can effectively detect release.
b. Monthly visual inspection of the injection facility and surroundings by an operator equipped with a personal CO_2 detector.

The project proponent shall record each event for which Equation 7 is not fulfilled. The amount of CO_2 that may have been released during each event shall be accounted for in Equation 6. A conservative approach shall be used to estimate this amount, such as:

– The total amount of CO_2 injected during event j
– A percentage of the total amount of CO_2 injected during event j. The project proponent shall be able to demonstrate that this approach is conservative.

If CO_2 release is detected from the injection system or the injection site while Equation 7 is fulfilled, the project proponent shall identify the cause of the CO_2 release and must apply a procedure to conservatively quantify the amount of CO_2 released during the event. It shall also be accounted for in Equation 6.

9.4.2. CO_2 release from the Storage reservoir $mCO_{2,released,geological\ storage,y}$

Similarly, as demonstrated in Appendix 2 permanence risk, $mCO_{2,released,y}$ from the geological storage is negligible if reservoir pressures are sufficient to maintain the CO_2.

The procedure to monitor $mCO_{2,released,y}$ is described in the subsurface monitoring chapter section 10.2.1 and/or 10.2.3 and the project proponent shall recorded any CO_2 release event from the storage reservoir. The project proponent shall estimate the amount of CO_2 that may have been released during each event and shall be accounted for in Equation 6.

10. Monitoring of Mineral Storage

Injection of water-dissolved CO_2 accelerates rock dissolution reactions in the storage formation, providing divalent cations to the CO_2-charged water. Once supersaturation of the water with respect to carbonate minerals is achieved, reactions between the dissolved CO_2 and cations in the water results in the mineralization of the dissolved CO_2 (conversion to solid carbonate minerals) and therefore its permanent storage (Appendix 1 - In-situ mineralization primer). The long-term performance of rock formations as storage systems to safely sequester large amounts of CO_2 in the geologic subsurface is mainly controlled by the availability of cations and pore space. The characterization and monitoring of the subsurface storage reservoir must therefore include a continuous hydrological and geochemical reservoir-based performance assessment.

The project proponent(s) shall establish and maintain a subsurface monitoring plan. This should include procedures for measuring or calculating and analyzing data and information that demonstrate (1) injected CO_2 remains contained in the geological storage reservoir via solubility and mineral trapping and (2) that the storage reservoir conforms to expected behaviors. This is accomplished through appropriate and transparent collection of data to support continued and evolving assessment and management of non-permanence risks.

The subsurface monitoring plan shall address the following:

1. <u>Storage site characterization prior to a project validation:</u> The project proponent shall demonstrate the suitability of the considered site for mineral storage in terms of hydrogeology and geochemistry.
2. <u>Effective solubility trapping and in-situ mineralization of the CO_2 during operation:</u> The project proponent shall follow established procedures to monitor the performance of the storage reservoir.
3. <u>Closure and post closure requirements</u>: The project proponent shall demonstrate that the CO_2 is securely contained within the geological storage reservoir and is trending towards long term stability.

10.1. Site Characterization

The suitability of the geological storage reservoir shall be established prior to the validation of the project. This includes confirming that:

- the permeability of the formation is high enough to provide fluid pathways to facilitate migration of the injected CO_2
- the formation contains divalent cations available for the CO_2 mineralization process
- the surface area for the reactions to take place is sufficient

The suitability can be demonstrated via:

- Laboratory-based approaches in which the cation availability of the storage reservoir is demonstrated and/or
- Field based approaches which include a pilot injection and subsequent demonstration of solubility trapping and mineral trapping

The project proponent shall create reservoir models with information obtained from the site characterization activities (field and/or laboratory approach) to demonstrate that the reservoir conditions are favorable and define project specific performance metrics:

- Solubility trapping is ensured, i.e. the CO_2 cannot degas within the geological storage reservoir
- Spatial distribution and migration of the dissolved CO_2 is contained within the geological storage reservoir
- Expected mineralized percentage of CO_2 as a function of time

Reservoir models must include:

- Geostatic model: a representation of the geological storage complex that allows evaluation of potential behaviors
- Flow model: a representation of CO_2 and other fluid flow through the geological storage complex
- Geochemical model: a representation of possible geochemical reactions resulting from CO_2 injection between CO_2, rocks, minerals, and fluids in the geological storage reservoir.

Full reactive transport schemes and/or a combination of a transport model and a reaction path model are acceptable.

10.2. During operation

The project proponent shall demonstrate that solubility trapping is achieved and that favorable conditions for in-situ carbon mineralization exist within the geological storage reservoir. This shall be demonstrated using geochemical methods and modelling tools. Field sampling and reservoir models shall provide estimates of the degree of mineralization in the storage reservoir. Deviation from expected values established during site characterization shall be identified and discussed as well as concerns and vulnerabilities. This shall be demonstrated as part of a subsurface monitoring plan descried below.

The subsurface monitoring plan shall have the following components as a minimum:

10.2.1. Project specific monitoring objectives and performance metrics derived from the site characterization. This includes:
- a systematic risk analysis and identification of potential leakage pathways from CO_2 degassing
- percentage of the injected CO_2 contained by solubility trapping as a function of time
- percentage of the injected CO_2 contained by mineral trapping as a function of time

10.2.2. Description of monitoring locations, parameters, tools, detection limits, detection frequencies, spatial resolutions, and a description of how these are sufficient to accomplish the items in 10.2.1. This includes:

10.2.2.1.   Tracer test within the first two years of injection or once the project has reached stable operation, whichever occurs earlier. A tracer test includes:
- The injection of a non-reactive tracer in the injection well(s)
- Sampling of selected monitoring well(s).

Results from tracer test shall be reported within five years after start of injection activities or before the end of injection activities, whichever occurs earlier. Tracer

tests shall be conducted at an interval no longer than the project renewal period. Tracer tests shall be performed according to the industry best practices[2].

10.2.2.2.   Annual sampling of selected monitoring wells for temperature, pH, dissolved inorganic carbon (DIC) concentration and major elements shall begin from the start of the project operation. Major elements shall include Si, Ca, Mg, Fe, Al, Na, K, S, Cl and F. Fluid saturation states calculated using thermodynamic principles shall be used to determine if collected fluids from monitoring wells indicate conditions feasible for carbon mineralization. This can be further monitored as a function of time to monitor changes in the reservoir.

10.2.2.3.   Monitoring techniques for the atmosphere, near surface and sub-surface

1. CO_2 gas detectors placed around the injection well. As an example, for good practice, a building around the injection wellhead and measurements of the CO_2 concentration inside this building would effectively detect leakage.

2. Monthly visual inspection of the injection facility and surroundings by an operator equipped with a personal CO_2 detector.

3. Annual sampling of monitoring wells, water supply wells and/or wells in the vicinity of the injection for pH, conductivity and DIC concentrations. Furthermore, the water table and potential impact on competing water usage shall be monitored in relation to water wells.

4. Surface flux measurements every two years.

5. Identification of natural springs at the storage site and annual sampling of the water chemistry.

10.2.2.4.   The project proponent may use the following methods to further inform the behavior of the injected CO_2:

– Mass balance calculations: The fate of the injected CO_2 can be quantified using non-reactive tracers and mass balance calculations.

– The expected concentrations of DIC in the theoretical scenario that DIC is non-reactive shall be compared with those measured in collected samples in monitoring well(s). Loss of DIC compared to expected non-reactive behavior along the subsurface flow path to the monitoring well confirms carbonate mineral precipitation. The proportion of DIC lost shall then be compared to the quantity of CO_2 injected to quantify the percentage of CO_2 mineralized in the storage reservoir. This shall be further monitored through time to monitor changes in the reservoir.

– Reactive tracers: A reactive tracer such as ^{14}C (radiocarbon) may be used along with a non-reactive tracer to quantify the amount of carbonate precipitation. This method can lower uncertainties of mass balance calculations, especially if project specific or natural conditions at the geological storage reservoir site do not allow determination of natural baseline DIC concentrations in monitored waters.

---

[2] Shook, G. M., Ansley, S. L., & Wylie, A. (2004). Tracers and tracer testing: design, implementation, and interpretation methods. Bechtel BWXT Idaho, LLC: Idaho National Engineering and Environmental Laboratory.

– Natural stable isotope tracers: CO_2 mineralization reactions alter isotope ratios of the chemical elements involved (e.g. Ca and C). The magnitude and direction of these shifts are dependent on the isotope (e.g.[44]Ca), reaction temperature and proportion of CO_2 mineralized. By comparing pre- and post-CO_2 injection fluids, isotope measurements can be used to quantify the amount of carbonate precipitated, and hence CO_2 stored. For example, Ca-isotope ratios rapidly increase with pH and calcite saturation state, indicating calcite precipitation[3].

– Physical evidence: Drill cores may be retrieved from the geological storage complex and analyzed for signatures of in-situ carbon mineralization. This is challenging however, because the mineralization takes place at a certain distance from the injection well and there will be relatively small amount of carbon precipitated compared to the millions of cubic meters of mafic rock. Physical evidence of carbon mineralization can also be found on subsurface equipment such as pumps and injection pipes.

10.2.3. Reservoir model used to assess the movement of the CO_2, the conformance of CO_2 behavior to expectations (i.e. section 10.1), and confirmation of containment via solubility and mineral trapping.

The project proponent shall create/update reservoir model(s) in a sufficiently detailed way to evaluate conformance, predict future performance of the geological storage reservoir and shall at minimum include appropriate tools to inform:

– Percentage of the injected CO_2 contained by solubility trapping (as defined in Equation 7)

– Percentage of the injected CO_2 contained by mineral trapping as a function of time

Comparison between observed data collected from the geological storage reservoir (as described in 10.2.1) and the results of predictive numerical modelling of the injected CO_2 behavior shall be used to calibrate and update numerical models and modelling results.

If major deviations are reported between the expected and observed performance of the geological storage reservoir, the project proponent shall address them as follows:

1. if data collected as part of the subsurface monitoring plan and modelled storage reservoir show that solubility trapping is not ensured, the project proponent shall modify injection operations so that solubility trapping is ensured or otherwise stop injection activities and quantify amount released.

2. if data collected as part of the subsurface monitoring plan and modelled storage reservoir show that solubility trapping is ensured but mineral trapping is not observed and/or modelled, the project proponent shall modify injection operations so that solubility trapping is ensured or otherwise stop injection activities and monitor solubility trapping.

3. if data collected as part of the subsurface monitoring plan and modelled storage reservoir show that solubility trapping is ensured but show slower or lower mineral

---

[3] Pogge von Strandmann *et al.* (2019) Rapid CO_2 mineralisation into calcite at the CarbFix storage site quantified using calcium isotopes, *Nature Communications,* **10**:1983

trapping than expected, the project proponent may continue injection operation and update the subsurface monitoring plan and address the deviations accordingly.

4. if data collected as part of the subsurface monitoring plan and modelled storage reservoir show that solubility trapping is ensured and expected mineralization trapping occurs then the project proponent may continue injection operation.

10.2.4. A discussion of concerns and vulnerabilities (based on previous monitoring program results or the reservoir model),

10.2.5. Any evidence or reasoning to justify modifications to the monitoring program going forward, including a description of the modifications,

The project proponent shall execute activities in the subsurface monitoring program for the duration of the project injection period and post-injection period until closure. The project proponent shall execute post closure monitoring as defined in the Monitoring Program.

10.3.   Closure and Post Closure Requirements

The project proponent(s) shall create and maintain a closure plan that describe the closure activities, the monitoring requirements for the post closure period, and performance indicators and conditions to be met before liability transfer to the relevant authorities can be achieved.

The closure plan shall be updated periodically according to the following criteria:

- at an interval no longer than the project renewal period,
- upon identification of a non-negligible CO_2 release from the geological storage reservoir.

Given the long life of CO_2 storage projects, the evolving nature of the risk, and changes to technology, proponents may update the closure plan as appropriate. Storage site closure, post closure monitoring, and transfer of liability to the relevant authorities must follow requirement defined by local legislation, if available. Otherwise, the project proponent(s) must follow the provision described below.

Proponents shall apply the reservoir model to predict at the time of closure and post closure:

1. The dissolved CO_2 spatial extent and associated pressure front.
2. Reservoir pressures in compliance with Equation 8.
3. The amount of CO_2 mineralized at the time of closure.

For Closure:

Closure activities include the cessation of the injection of CO_2 and decommissioning of the installation. The project proponent must retain access to the storage site and to (all or selected) monitoring wells throughout the post closure period.

For Post Closure Period and transfer of liability:

The post closure period monitoring can be done with reduced frequencies as compared to before closure but must meet the following requirements:

1. Sampling of the selected monitoring wells every other year,

2. Update of model predictions every other year and,
3. Above-surface measurements every other year.

The post closure period monitoring shall be no less than 10 years and can be terminated when the project proponent(s) demonstrate that all existing data indicate that the CO_2 is or will be permanently stored or mineralized by solubility trapping and in-situ carbon mineralization. To establish permanency of the CO_2 containment within the geological storage reservoir, the project proponent(s) must have achieved and documented the following requirements:

1. no evidence for CO_2 released from the geological storage complex,
2. the behavior of the CO_2 has trended towards increased conformance with modelled predictions and,
3. the CO_2 has trended towards a situation of increased long-term stability.

However, if the project proponent(s) demonstrate at least 95% mineralization of the injected CO_2 during the post closure period, then the post closure period monitoring can be terminated before the 10 years period and transfer of liability process launched.

11.   Equations and parameters

11.1.   Equation 1: CO_2 credited during monitoring period

$$mCO_{2,credited,y} = mCO_{2,\text{injected},y} - mCO_{2,\text{released},y} - mCO_{2eq,\text{project,operation},y} - mCO_{2eq,\text{project,embodied},y}$$

Parameter	$mCO_{2,credited,y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total amount of CO$_2$ credited in own accounting or sold/transacted to third parties in period *y*.
Equations	Equation 1
Source of data	NA
Calculation method/equations	Equation 1
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited
Comments	-

Parameter	$mCO_{2,\text{injected},y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total amount of CO$_2$ injected at the storage site in period *y*, determined at the last monitoring point on the injection system.
Equations	Equation 1 and 2
Source of data	NA
Calculation method/equations	Equation 2
Description of measurement methods and procedures to be applied	NA

Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited
Comments	-

Parameter	$mCO_{2,\text{released},y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total amount of CO$_2$ released at the storage site downstream of the last monitoring point on the injection system in period *y*.
Equations	Equation 1 and 6
Source of data	NA
Calculation method/equations	Equation 3
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited
Comments	-

Parameter	$mCO_{2eq,\text{project},\text{operation},y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total GHG emissions due to project operations of the CCS/CDR value chain (CO$_2$ Capture, Transport, and Storage) in period *y*.
Equations	Equation 1 and 4
Source of data	NA

Calculation method/equations	Equation 4
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited
Comments	-

Parameter	$mCO_{2eq,project,embodied,y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total GHG emissions due to construction and disposal of the CCS/CDR value chain (CO$_2$ Capture, Transport, and Storage) scheduled for monitoring period *y*.
Equations	Equation 1 and 5
Source of data	NA
Calculation method/equations	Equation 5
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited
Comments	Embodied emissions from capture total 841 tCO$_2$ over the project life. LCA for transport and storage is pending and will be added to this amount.

Parameter	
Parameter type	NA
Data unit	days
Description	Monitoring period during which credits are produced.
Equations	Equation 1, 2, 3, 4 and 6
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

11.2. Equation 2: CO_2 injected during the monitoring period

$$mCO_{2,injected,y} = \sum_i mCO_{2,i,y}$$

Parameter	$mCO_{2,i,y}$
Parameter type	Calculated
Data unit	tonne (tCO_2)
Description	Mass of CO_2 injected at each injection well i in period y, determined at the last monitoring point on the injection system.
Equations	Equation 2 and 3
Source of data	NA
Calculation method/equations	Equation 3
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly

QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	CO$_2$ injection
Comments	-

Parameter	i
Parameter type	NA
Data unit	unitless
Description	Injection well(s)
Equations	Equation 2 and 3
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

11.3. Equation 3: CO$_2$ entering the injection well

$$mCO_{2,i,y} = \int_0^y \dot{m}_{CO2,i} \cdot x_{CO2,i} \, dt$$

Parameter	$\dot{m}_{CO2,i}$
Parameter type	Measured
Data unit	Tonne/second (t/s)
Description	Mass flow rate of the CO$_2$ stream entering the injection well.
Equations	Equation 3 and 8
Source of data	On-site measurement

Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Continuous measurement in the injection system by a mass flow meter with an uncertainty of 5% or less. The measurement point shall be as close as possible to the injection well (at the wellhead or within the injection system) and correspond to the last monitoring point.
Frequency of monitoring	At least monthly
QA/QC procedures to be applied	Recalibration according to manufacturer's specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	-

Parameter	$x_{CO2,i}$
Parameter type	Measured or fixed
Data unit	W_{CO2}/W_{stream} (unitless)
Description	The CO_2 weight fraction of the CO_2 stream entering the injection well.
Equations	Equation 3
Source of data	One of the following options shall be chosen: a) On-site measurement b) Periodic sampling and on-or-off-site laboratory analysis if a) is technically not feasible or incurs unreasonable cost c) Manufacturer specification of the process equipment generating this CO_2 stream if it has a constant CO_2 weight fraction. In case contamination of the stream from the capture to the injection facility can be rules out (e.g., due to transfer inside a pressurized pipeline without intermediate steps), the weight fraction at the exit of the capture step can be used.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Depending on choice of source of data: a) Continuous measurement in the injection system b) Sampling in the injection system and laboratory analysis twice a year c) Fixed at the time of validation.
Frequency of monitoring	Depending on choice of source of data: a) At least monthly b) At least twice a year

	c) Fixed value, confirmed at least twice a year (see QA/QC)
QA/QC procedures to be applied	Depending on choice of source of data: a) Recalibration according to manufacturer's specifications. If not available, according to industry best practice. b) Laboratory analysis of samples twice a year using a method resulting in the highest feasible accuracy without incurring unreasonable cost. c) Analysis of samples in accredited laboratory twice a year.
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	-

Parameter	dt
Parameter type	NA
Data unit	seconds (s)
Description	Numerical integration over the period y.
Equations	Equation 3
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

11.4. Equation 4: CO_2 emissions from project operations

$$mCO_{2eq,\text{project,operation},y} = \sum_p \sum_z \left(I_{z,p,y} \cdot ef_{z,p,y} \right)$$

Parameter	p
Parameter type	NA
Data unit	unitless

Description	Process steps. These include the capture, transport, and storage steps in the CCS/CDR chain.
Equations	Equation 4 and 5
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

Parameter	z
Parameter type	NA
Data unit	unitless
Description	Process input
Equations	Equation 4
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

Parameter	$I_{z,p,y}$
Parameter type	Measured
Data unit	quantity (qty)
Description	Intensity of consumption of a process input
Equations	Equation 4
Source of data	Provider of process input (e.g., electricity supplier, sorbent manufacturer, etc.)
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Dependent on process input and therefore assessed at project level.
Frequency of monitoring	At least annually
QA/QC procedures to be applied	Measuring apparatus (e.g., meter) shall be maintained according to manufacturer and/or national standard and/or industry best practice.
Justification of choice of data source	NA
Purpose of data	Operational emissions
Comments	-

Parameter	$ef_{z,p,y}$
Parameter type	Fixed
Data unit	tonne/quantity (tCO$_2$/qty)
Description	Emission factor or emission rate of a given pollutant relative to the intensity of a specific process input.
Equations	Equation 4
Source of data	Provider of process input (e.g., electricity supplier, sorbent manufacturer, etc.)
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA

Justification of choice of data source	Values are to be taken from national or international standards, supported by literature, or supported by extensive data.
Purpose of data	Operational emissions
Comments	-

11.5. Equation 5: CO_2 emissions from construction and disposal

$$mCO_{2eq,\text{project,embodied},y} = \sum_p mCO_{2eq,p,embodied,y}$$

Parameter	$mCO_{2eq,\text{project,embodied},y}$
Parameter type	Fixed
Data unit	tonne (tCO_2)
Description	Emissions due to construction and disposal for each process step p attributed to the operational phase in period *y*.
Equations	Equation 5
Source of data	Cradle to grave based life cycle assessment.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	On a cradle to grave basis for all emission sources. International standards for conducting an LCA shall be respected. Only valid if the academic assessment is done for a corresponding facility of similar size, capacity, and estimated plant lifetime or can be scaled to the project specific installations in line with international standards of conducting an LCA.
Purpose of data	Embodied emissions
Comments	

Parameter	$mCO_{2eq,p,embodied,y}$
Parameter type	Fixed
Data unit	tonne (tCO_2)
Description	Emissions due to construction and disposal for each process step p attributed to the operational phase in period *y*.
Equations	Equation 5
Source of data	Cradle to grave based life cycle assessment.

Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	On a cradle to grave basis for all emission sources. International standards for conducting an LCA shall be respected. Only valid if the academic assessment is done for a corresponding facility of similar size, capacity, and estimated plant lifetime or can be scaled to the project specific installations in line with international standards of conducting an LCA.
Purpose of data	Embodied emissions
Comments	

11.6. Equation 6: CO$_2$ released at the storage site

$$mCO_{2,released,y} = \sum_{j} mCO_{2,\,release\;event,injection\;system,j} + \sum_{k} mCO_{2,\,release\;event,geological\;storage,k}$$

Parameter	$mCO_{2,\,release\;event,injection\;system,j}$
Parameter type	Measured
Data unit	tonne (tCO$_2$)
Description	Mass of CO$_2$ released intentionally or unintentionally from the injection system downstream of the last monitoring point on the injection system during event j.
Equations	Equation 6
Source of data	Quantification based on type of event.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	The project proponent must show the amount released is negligible or quantify this amount based on type of event. Any active injection well shall be fitted with a CO$_2$ sensor at its wellhead. For any occasion of P$_{BubblePoint}$ exceeding its limits, the injected mass of CO$_2$ leading to P$_{BubblePoint}$ exceeding its limits shall be attributed to this parameter.
Frequency of monitoring	At least monthly
QA/QC procedures to be applied	Recalibration of any measurement equipment used for detection or quantification according to manufacturer specifications. If not available, according to industry best practice.

Justification of choice of data source	NA
Purpose of data	CO_2 release
Comments	-

Parameter	$mCO_{2,\ release\ event, geological\ storage, k}$
Parameter type	Measured
Data unit	tonne (tCO_2)
Description	Mass of CO_2 released intentionally or unintentionally from the geological storage reservoir during event k.
Equations	Equation 6
Source of data	Quantification based on type of event.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	The project proponent must show the amount released is negligible or quantify this amount based on type of event. Atmospheric or CO_2 surface flux measurements shall be carried out around the injection site. Any monitoring well producing significant volumes of water will be fitted with a CO_2 sensor. Any monitoring well producing significant volumes of water shall be fitted with a CO_2 sensor at its wellhead.
Frequency of monitoring	At least annually
QA/QC procedures to be applied	Recalibration of any measurement equipment used for detection or quantification according to manufacturer specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 release
Comments	-

Parameter	j
Parameter type	NA
Data unit	unitless
Description	CO_2 release event from the injection system.
Equations	Equation 6
Source of data	NA
Calculation method/equations	NA
Description of measurement	NA

methods and procedures to be applied	
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

Parameter	k
Parameter type	NA
Data unit	unitless
Description	CO_2 release event from the geological storage reservoir.
Equations	Equation 6
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

11.7.   Equation 7: Ensuring solubility trapping of CO_2 in water

$$P_{reservoir} > P_{\text{BubblePoint},i} + P_{margin}$$

Parameter	$P_{reservoir}$
Parameter type	Fixed
Data unit	bar-a

Description	Pressure at the bottom of the casing of injection well *i*.
Equations	Equation 7
Source of data	Can be measured using water table measurements (acquired using a logger or camera) or down-well pressure gage in injection well.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	On-site measurements of pressure itself or the water table depth provide the most accurate estimate for this parameter.
Purpose of data	CO_2 release
Comments	-

Parameter	$P_{\text{BubblePoint},i}$
Parameter type	Calculated
Data unit	bar-a
Description	Pressure where the first bubble of gas (including CO_2) is formed when depressurizing the liquid injected at injection well *i*.
Equations	Equation 7 and 8
Source of data	NA
Calculation method/equations	$P_{\text{BubblePoint}}$ shall be calculated using appropriate equation of states, thermodynamic databases, and geochemical tools. As an example, $P_{\text{BubblePoint}}$ can be calculated using the Peng-Robinson equation of state for the solubility of gases. Specifically, the bubble point can be calculated using the PHREEQC software version 3 as the pressure of the system when an infinitesimally small volume of gas is formed from the mixture of the injected water and gas as measured by their mass flow rates, compositions, and temperatures. $P_{\text{BubblePoint}}$ shall be calculated using the following parameters: $m_{\text{water},i}$, $T_{\text{water},i}$, $T_{\text{CO2},I}$, $\text{Elem}_{\text{CO2},I}$, $\text{Elem}_{\text{water},i}$.
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	At least monthly

QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	CO_2 release
Comments	-

Parameter	P_{margin}
Parameter type	Fixed
Data unit	bar-a
Description	Pressure safety margin
Equations	Equation 7
Source of data	Operational experience
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	At least monthly
QA/QC procedures to be applied	NA
Justification of choice of data source	Determined through operational experience.
Purpose of data	CO_2 release
Comments	-

11.8. Equation 8: Bubble point

$$P_{\text{BubblePoint},i} = f(\dot{m}_{CO2,i}, \quad \dot{m}_{water,i}, \quad T_{water,i}, \quad T_{CO2,i}, \quad Elem_{CO2,i}, \quad Elem_{water,i})$$

Parameter	f
Parameter type	NA
Data unit	NA
Description	Appropriate equation of state and thermodynamic functions.
Equations	Equation 8
Source of data	NA
Calculation method/equations	NA

Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	NA

Parameter	$\dot{m}_{water,i}$
Parameter type	Measured
Data unit	kg/s
Description	Mass flow rate of the water stream entering the injection well.
Equations	Equation 8
Source of data	On-site measurement
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Continuous measurement in the injection system.
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	Recalibration according to manufacturer's specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	This water stream shall include any water entering the injection well other than the CO_2 stream. In cases where such water streams do not exist, this parameter is not applicable.

Parameter	$T_{water,i}$
Parameter type	Measured

Data unit	°C
Description	Temperature of the water stream entering the injection well.
Equations	Equation 8
Source of data	On-site measurement
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Continuous measurement in the injection system.
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	Recalibration according to manufacturer's specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	This water stream shall include any water entering the injection well other than the CO_2 stream. In cases where such water streams do not exist, this parameter is not applicable.

Parameter	$T_{CO2,i}$
Parameter type	Measured or fixed
Data unit	°C
Description	Temperature of the CO_2 stream entering the injection well.
Equations	Equation 8
Source of data	One of the following options shall be chosen: a) On-site measurement b) Fixed value based on operational experience if fixing this value has negligible impact on calculation of $P_{BubblePoint}$.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Depending on choice of source of data: a) Continuous measurement in the injection system b) NA
Frequency of monitoring	Depending on choice of source of data: a) At least annually b) NA

QA/QC procedures to be applied	Depending on choice of source of data: a) Recalibration according to manufacturer's specifications. If not available, according to industry best practice. B) NA
Justification of choice of data source	Continuous measurements and/or operational experience show variation is negligible and fixing this value has negligible impact on calculation of $P_{BubblePoint}$.
Purpose of data	CO_2 injection
Comments	-

Parameter	$Elem_{CO2,i}$
Parameter type	Measured
Data unit	Volume % (for gas streams) or mg/kg (for liquid streams)
Description	Elemental composition of the CO_2 stream entering the injection well.
Equations	Equation 8
Source of data	On-site sampling in the injection system and on-or-off-site analysis.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Sampling and subsequent analysis twice a year.
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	Analytical equipment shall be calibrated according to manufacturer's specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	-

Parameter	$Elem_{water,i}$
Parameter type	Measured
Data unit	mg/kg
Description	Elemental composition of the water stream entering the injection well.
Equations	Equation 8
Source of data	On-site sampling in the injection system and on-or-off-site analysis.
Calculation method/equations	NA
Description of measurement	Annual sampling and analysis.

methods and procedures to be applied	
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	Analytical equipment shall be calibrated according to manufacturer's specification. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	This water stream shall include any water entering the injection well other than the CO_2 stream. In cases where such water streams do not exist, this parameter is not applicable.

Appendix 1 - In-situ mineralization primer

A.1.1 Global context

The anthropogenic emissions of carbon dioxide and other greenhouse gases have been identified as the main contributor to global warming and climate change. The atmospheric concentration of CO_2 has increased from 280 ppm, in the mid-1800s, to about 420 ppm in May 2022[4] and caused an increase in mean earth temperature from pre-industrial levels. It has been widely recognized by scientists, policy makers, and politicians that the mean earth temperature rise from pre-industrial levels should be kept well below 2 °C by 2100 in order to mitigate severe events of climate change[5]. In this context at COP 21 in Paris, on 12 December 2015, Parties to the UNFCCC reached a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future. Carbon capture and storage (CCS) plays a fundamental role in achieving the goals of the Paris agreement to limit global warming to within 1.5 to 2°C, with an estimated 115 Gt CO_2 needed to be captured and safely stored by 2060. CCS is a combination of technologies that capture CO_2 from point source emitters or directly from the atmosphere (CDR) for permanent underground storage preventing its release back into the atmosphere. CCS is considered as one of the most promising options and today the only technology available to mitigate atmospheric emissions of CO_2 from large-scale fossil fuel usage, industrial sources,[6] [7] and to deliver negative emissions by removing and sequestering CO_2 directly from air. There are three steps to the CCS process:

1. Capture: Include a range of technologies in which:
   a. The CO_2 is separated from flue gases produced in industrial processes, such as those at power generation plants or steel or cement factories; these can be referred to as avoided emissions or emission reductions.
   b. The CO_2 is captured directly from the atmosphere: these can be referred to as carbon removals.
2. Transport: The CO_2 is then transported via pipelines, road transport, or ships to a site for storage.
3. Storage: The CO_2 is injected into rock formations deep underground for permanent storage.

Geological CO_2 storage is the last step in the CCS chain and permanent containment underground can be ensured by physical and chemical trapping mechanisms.

A.1.2 CCS projects

CCS started as early as 1970 when a gas processing facility in Texas (USA), captured CO_2 and piped to a nearby oil field and injected to boost oil recovery. Enhanced Oil Recovery (EOR) has since been used to capture and store millions of tons of CO_2 – both from natural accumulations of CO_2 in underground rocks and captured from industrial facilities. In 1996 the oil company Statoil, started separating the CO_2 from produced natural gas from the Sleipner oil and gas field and injecting into the Utsira formation at approximately 800 m depth under the North Sea at a rate of approximately 1Mt/year. Other injection operations of note include the In Salah injection in Algeria, which was operational from 2004 to 2011 and

---

[4] Ed Dlugokencky and Pieter Tans, NOAA/GML (gml.noaa.gov/ccgg/trends/)
[5] https://unfccc.int/sites/default/files/resource/cma2021_08_adv_1.pdf
[6] CO_2 capture and storage: a key carbon abatement option. IEA/OECD: Paris; 2008.
[7] IPCC special report on carbon dioxide capture and storage. In: Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA, editors. Prepared by Working Group III of the Intergovernmental Panel on Climate Change; Cambridge, UK/New York, USA: Cambridge University Press; 2005

injected approximately 0.5 Mt CO_2/yr. Upcoming project include Northern Lights in which CO_2 captured onshore will be injected and permanently stored 2,600 meters below the seabed of the North Sea. Phase one of the project will be completed mid-2024 with a capacity of storing up to 1.5 Mt CO_2/yr. CCS projects have been mostly confined to supercritical injection of CO_2 in deep saline formations, depleted oil or gas fields that are no longer economic for oil or gas production, and as part of EOR operations as described above.

In 2007, Carbfix developed a new approach in which CO_2 is dissolved in water and injected into subsurface basaltic reservoirs for rapid mineralization, providing a permanent and safe carbon sink. Basalt offers numerous advantages for the mineralization of CO_2 and other acid gases, as it is relatively reactive compared to most rocks, and reaction with the dissolved gas liberates divalent metal cations such as Ca, Mg, and Fe, and helps neutralize acidic waters and lead to the formation of carbonate minerals. The Carbfix storage process includes the conditioning of the CO_2 and the injection of the dissolved gas in a mafic rock formation for permanently removing CO_2. The technology can provide a complete carbon capture and injection solution using a water scrubbing method or can be used in conjunction to other capturing methods. Carbfix has since demonstrated the technology with industrial scale injection of CO_2 at the Hellisheiði geothermal power plant with over 75,000 tons of CO_2 injected since 2014. Current projects include the first commercial project combining Climeworks Direct Air capture technology and Carbfix mineral storage technology with a capacity of 4,000 t CO_2/yr commissioned in September 2021. Future projects include the development of cross-border carbon transport and storage hub in Iceland, Coda terminal. Phase one of the project will be completed 2025 with an expected storage capacity of 300 kt CO_2/yr which will be gradually scaled up to 3 Mt CO_2/yr by 2030. in-situ carbon mineralization provides an attractive alternative or addition to the more common sedimentary injection CCS techniques: It offers an expanded geographic range of onshore (volcanic areas, large flood basalt provinces) and offshore (oceanic ridges) storage reservoirs and offers a global storage potential that exceeds anthropogenic emissions[8]. This increases the opportunities for pairing of sinks and sources, potentially reducing transport costs, and adds to the potential CO_2 storage worldwide.

A.1.3 CO_2 containment mechanisms

To ensure permanent CO_2 sequestration, CO_2 geological storage must meet the following requirements:

- available space (pore space) within the reservoir to store the CO_2;
- interconnected porosity providing permeability allowing the CO_2 to move and spread out within the formation;
- and a (physical or chemical) trapping mechanism to contain the CO_2 preventing migration to the surface. geological formations suitable for sequestration include saline aquifers, depleted oil and gas reservoirs, coal seams, ultramafic, mafic, intermediate, or silicic rock formations.

Research has increasingly focused on the sequestration processes and short- and long-term effects of CO_2 injection into reservoirs to assess the feasibility of CO_2 storage on a commercial scale. Sequestration processes involve different trapping mechanisms according to the hydrodynamic, physical, and chemical conditions in the formation. These mechanisms are commonly divided into four different categories:

---

[8] Snæbjörnsdóttir, S.Ó., Sigfússon, B., Marieni, C. *et al.* (2020) Carbon dioxide storage through mineral carbonation. Nat Rev Earth Environ **1**, 90–102.

1. Structural and stratigraphic trapping,
2. Residual trapping,
3. Solubility trapping, and
4. Mineral trapping.

Geological storage relies on one or a combination of these trapping mechanisms that contribute to CO_2 storage capacity. These trapping mechanisms show an increasing ability to immobilize CO_2 molecules thus increasing storage security and decreasing leakage risk (Figure 6).
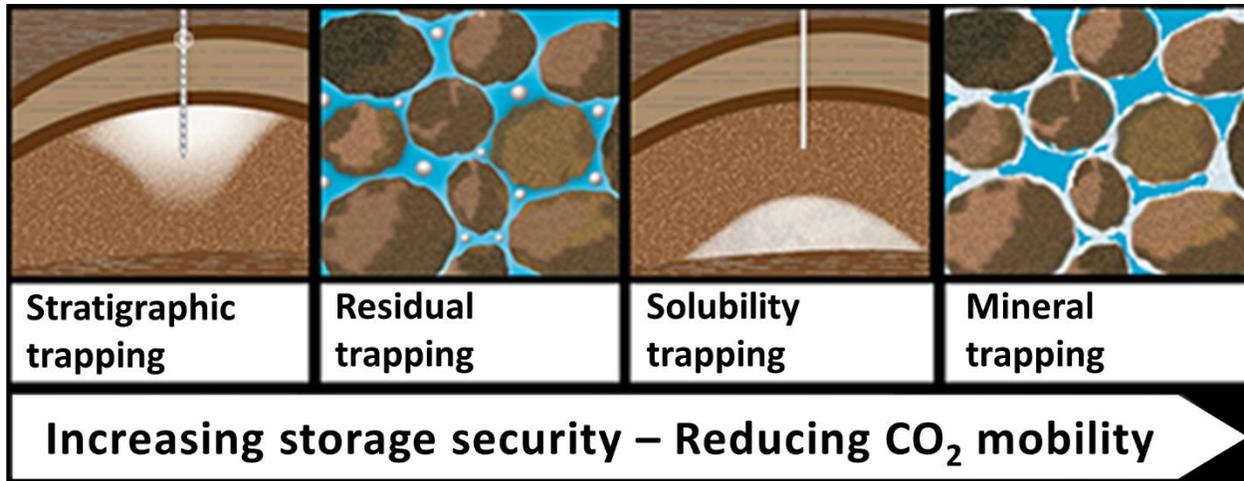

Figure 6: Trapping mechanisms for Geological Storage of CO2 (adapted from https://www.pecc.org/resources/minerals-a-energy/2508-research-challenges-and-opportunities-to-reduce-carbon-emissions-in-fossil-fuels/file).

Structural/stratigraphic trapping

Structural or stratigraphic trapping refers to the physical trapping of CO_2 in the rock by an overlying low Permeability caprock. The rock layers and faults within and above the storage formation where the CO_2 is injected act as seals, preventing CO_2 from moving out of the storage formation. Structural trapping is required when the injected CO_2 is more buoyant than other liquids present in the surrounding pore space, such as the brine in saline aquifers. If the CO_2 is less dense than the formation fluid, it will rise until it encounters a caprock that has a capillary entry pressure greater than the buoyancy or hydrodynamic force. Such impermeable seals can be of stratigraphic (impermeable formation) or structural nature (faults). The efficiency of structural or stratigraphic traps has been highlighted in reservoirs that have held oil and gas for millions of years. Stratigraphic trapping has been also recognized in saline aquifers of sedimentary basins that have extremely slow flow rates[9]. However, CO_2 sequestration by this physical trapping mechanism depends greatly on the sealing capacity of the caprock, making proper reservoir characterization an essential pre-requisite for site selection and injection[10].

---

[9] Gunter WD, Bachu S, Benson S. (2004) The role of hydrogeological ad geochemical trapping in sedimentary basins for secure geological storage of carbon dioxide. *Geological Society, London, Special Publications,* **233**: 129-145.
[10] Song J, and Zhang D. (2013) Comprehensive review of caprock-sealing mechanisms for geologic carbon sequestration. *Environmental Science and Technology*, **47**: 9-22

Residual trapping

Residual trapping or capillary trapping refers to the CO_2 that remains trapped in the Pore Space between the rock grains as the CO_2 Plume migrates through the rock. The existing porous rock acts like a rigid sponge. When CO_2 is injected into the formation, it displaces the existing fluid as it moves through the porous rock. As the CO_2 continues to move, small portions of the CO_2 can be left behind as disconnected, or residual, droplets in the Pore Spaces which are essentially immobile.

Solubility trapping

Solubility trapping refers to dissolution of CO_2 prior to or during injection or into the formation fluids. The solubility of CO_2 in water is dependent on the salinity, pressure, and temperature of the formation water.

If prior to injection CO_2 is fully dissolved in a water solvent, solubility trapping is immediate, provided reservoir conditions are suitable (reservoir pressures higher than the partial pressure of CO_2). In the case of supercritical CO_2, gaseous, or incomplete dissolution injection at the interface of free gas phase and formation water, CO_2 dissolves into water by molecular diffusion. The water in contact with CO_2 will be saturated with CO_2 and a concentration gradient of CO_2 would establish spatially. This process is usually slow because the molecular diffusion coefficient is small and may take thousands of years for CO_2 to be completely dissolved in brine. solubility trapping is based on the density difference between dissolved CO_2 and formation fluid. The dissolved gas fluid mixture is denser than the formation fluid and flows downward due to gravity. The complete CO_2 dissolution prevents upward mitigation and results in increased storage capacity and security.

Mineral trapping

Mineral trapping refers to the incorporation of CO_2 in a stable mineral phase via geochemical reactions in the geological formation. It requires prior solubility trapping and the formation of weak carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-). The resulting fluid reacts with the rock formation to form solid carbonate minerals, permanently trapping the injected CO_2. This process takes place at different rates from days to years to thousands of years depending on the rock formation and injection strategy. This trapping mechanism is usually referred as the final phase of trapping and is considered permanent over geological timescales.

A.1.4 CO_2 Injection strategies

A.1.4.1 Supercritical or gaseous injection

Despite the importance of CCS technologies in mitigating climate change, the few CCS methodologies that have emerged are limited to pure-phase CO_2 storage, which relies heavily on short term structural and stratigraphic trapping and long term (>100 years) residual, solubility, and mineral trapping. These projects deploy one of the most common approaches of carbon storage, that is, injection of gaseous or supercritical CO_2 into subsurface reservoirs, such as sedimentary basins. In such systems, CO_2 is physically trapped in porous rocks below an impermeable cap rock (structural trapping), some of which becomes trapped in small pores (residual trapping) and, over time, dissolves in the formation fluid (solubility trapping) and reacts with the subsurface rocks to form a mineral phase (mineral trapping). As the storage progresses

from structural to mineral trapping, the CO_2 becomes more immobile, increasing the security of storage and decreasing the reliance on the efficacy of the cap rock.

Mineral trapping in sedimentary basins and depleted oil field may be limited by the absence of the silicate-bound divalent metals needed for carbonate formation and can take thousands of years, owing to low rock reactivity[11]. In addition, mineral storage is slowed by the need for the injected CO_2 to dissolve into the formation waters before it is mineralized. Therefore, the CO_2 must be adequately stored to avoid surface migration. Even though the likelihood of such leakage from a well-regulated site is predicted to be negligible[12], the lack of long- term storage feasibility has inhibited the broader application of sedimentary storage of CO_2. As such during the project life, most of the CO_2 is contained by the first trapping mechanism and specific tools (geophysical) have been developed to properly characterize and monitor the integrity of the caprocks. Seismic, gravity, or electromagnetic tools have been developed to monitor the CO_2 plume migration to confirm containment by the caprock. The presence of faults in the geological storage site must be determined to assess any potential pathways outside of the storage reservoir. The caprock ability to impede upward flow is essential and injection pressure may be limited to avoid compromising its integrity and fault reactivation. The later trapping mechanism(s) are usually only confirmed by numerical modelling.

Supercritical or gaseous CO_2 can also be injected into reactive rock formations under favorable geological conditions, including offshore locations, where the risks of potential leaks are mitigated by the overlying seawater and the presence of a low-permeability sediment layer near the seafloor–seawater interface[13,14]. In such cases, stratigraphic/structural trapping must still be demonstrated until all the CO_2 has been dissolved in the formation fluid (Figure 7a).

A.1.4.2 Dissolved CO_2 injection

Injection of dissolved CO_2 in a storage reservoir allows for immediate solubility trapping if reservoir pressures are sufficient to keep the CO_2 in solution. This negates the requirement for physical and residual trapping of CO_2. In addition the formation of weak carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-) promotes fluid-rock interaction. If the storage reservoir contain reactive rocks such as mafic or ultra-mafic lithologies, which contain high concentrations of divalent cations, such as Ca^{2+}, Mg^{2+} and Fe^{2+}, it may lead to the mineralization to calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), magnesite ($MgCO_3$), siderite ($FeCO_3$), or solid-solutions thereof. In which case the in-situ carbon mineralization results in a negligible risk of the CO_2 migrating back to the atmosphere both over the short term (due to the dissolution of CO_2 and the density-related inhibition of surface migration) and the long term (due to conversion into carbonate minerals) (Figure 7b). In-situ carbon mineralization is based on the latter to form geologically stable, environmentally benign carbonate minerals in a geological formation. In-situ carbon mineralization accelerates the natural carbonation process at a rate fast enough to contribute to climate change mitigation.

Physical trapping (including structural/stratigraphic) is not relevant and as such geochemical tools that monitor the mineral storage are preferred over geophysical tools to determine the fate of the CO_2 in the storage reservoir. Once mineralization is achieved, the need for long term monitoring is limited as the risk

---

[11] Benson, S. *et al.* (2005) in *IPCC Special Report on Carbon Dioxide Capture and Storage* (eds Metz, B. et al.) Ch. 5 (Cambridge Univ. Press).
[12] Alcalde, J. *et al.* Estimating geological CO_2 storage security to deliver on climate mitigation. *Nat. Commun.* **9**, 2201 (2018).
[13] Goldberg, D. S., Kent, D. V. & Olsen, P. E. (2010) Potential on- shore and off- shore reservoirs for CO_2 sequestration in Central Atlantic magmatic province basalts. *Proc. Natl Acad. Sci.USA* **107**, 1327–1332.
[14] Goldberg, D. S., Takahashi, T. & Slagle, A. L. (2008) Carbon dioxide sequestration in deep-sea basalt. *Proc. Natl Acad. Sci. USA* **105**, 9920–9925.

of leakage is eliminated (Appendix 2). As such in-situ carbon mineralization provides an attractive alternative: via immediate solubility trapping rapid mineralization of CO_2 through injection into reactive rock formations, the storage security is increased. In addition, once mineralization is achieved, the need for long term monitoring is limited as the risk of leakage is eliminated.
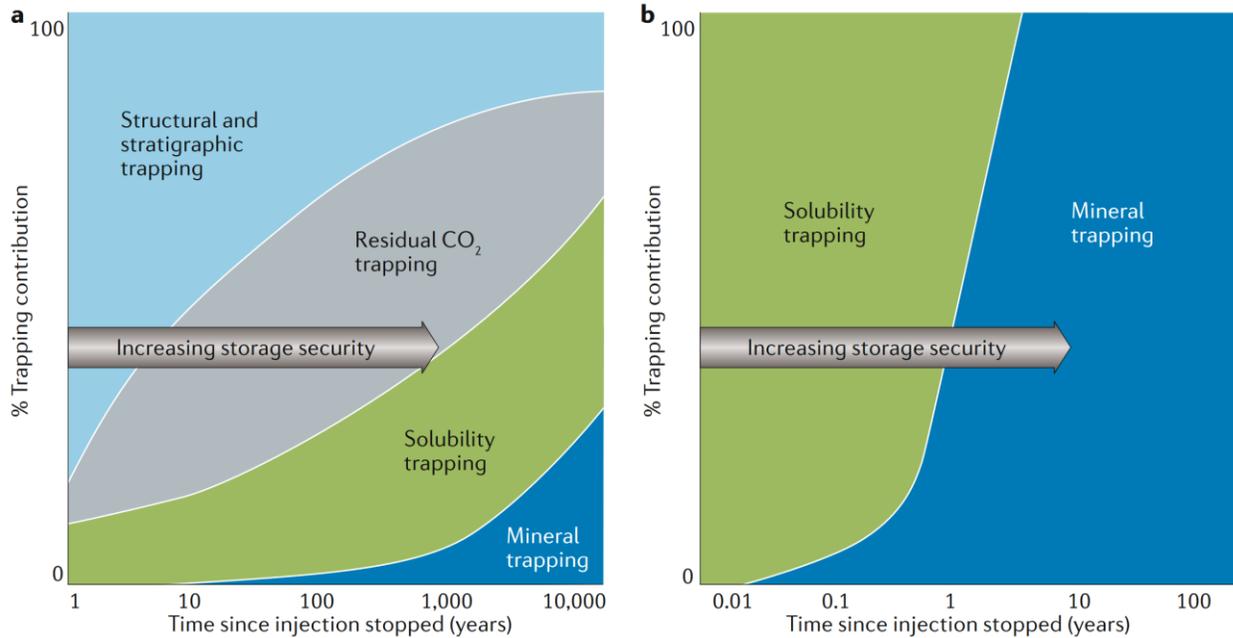

Figure 7: Comparison of CO_2-trapping mechanisms for supercritical and dissolved CO_2 injections. Change in the contribution of the carbon- trapping mechanism of CO_2 storage over time when injecting pure supercritical CO_2 into sedimentary basins (part a) and when injecting water- dissolved CO_2 for mineralization (part b) [8]

A.1.5. Mineral storage

In-situ carbon mineralization proceeds through the reaction of water containing dissolved CO_2 with rocks, notably ultramafic, mafic, intermediate, or silicic rocks. Water charged with CO_2 is acidic, with a typical pH of 3–5, depending on the partial pressure of CO_2, water composition and temperature of the system. This acidic solution promotes the dissolution of silicate minerals, such as pyroxene, a common mineral in basalt and peridotite:

$$2H^+ + H_2O + (Ca, Mg, Fe)SiO_3 = Ca^{2+}, Mg^{2+}, Fe^{2+} + H_4SiO_4$$
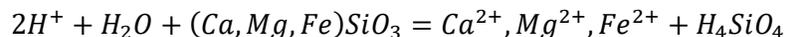
Such reactions promote CO_2 mineralization in two ways:

1) Protons are consumed, neutralizing the acidic gas- charged water and facilitating the precipitation of carbonate minerals as the pH of the water increases;
2) and they provide cations (Eq. 1) that can react with the dissolved CO_2 to form stable carbonate minerals.

The degree to which the released cations form minerals depend on the element, pH and temperature. Dissolved calcium readily reacts with CO_2 in aqueous solution at temperatures below ~300 °C, forming

calcite ($CaCO_3$) and/or aragonite once the solutions are supersaturated [15,16]. Dissolved magnesium precipitates as the carbonates magnesite ($MgCO_3$) and dolomite ($CaMg(CO_3)_2$) at temperatures above ~65 °C [17,18,19]; at lower temperatures, the precipitation of these minerals is kinetically inhibited. Under such conditions, less stable hydrous Mg- carbonate minerals, such as hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), dypingite ($Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$) and nesquehonite ($MgCO3 \cdot 3H_2O$), can form[20]. The degree to which dissolved iron (Fe^{2+}) combines with dissolved injected CO_2 to form carbonates in the subsurface remains unclear. Under oxic conditions, Fe^{2+} oxidizes before it can react to form a divalent metal carbonate, and, thus, the mineral siderite ($FeCO_3$) is only rarely observed in modern sedimentary and basaltic rocks[21]. The formation of the mineral ankerite ($CaFe(CO_3)_2$), however, may be favored under certain conditions at ambient to moderate temperatures when the pH of the solution is low enough to prevent Fe^{2+} from oxidizing to Fe^{3+} [22,23]. Other important factors for efficient subsurface carbon mineralization are the permeability and/or active porosity of the storage reservoir[24]. The pores and fractures provide pathways for migrating fluids, access to mineral surfaces that contribute cations to the mineralization and space for the carbonate precipitates. The overall mass of carbon-bearing precipitates is also affected by the formation of other secondary minerals, most importantly clay minerals, but also minerals such as zeolites[25] and anhydrites in seawater systems[26]. These minerals may compete with carbonates for the divalent cations liberated from dissolving primary minerals and for the available Pore Space. It should also be noted that, owing to the acidity of water–CO_2 solutions, they tend to dissolve minerals during injection, opening up Pore Space and flow paths near the injection well. The precipitation of pore- filling secondary minerals is expected to occur only at a distance from the injection well after sufficient rock dissolution in the storage reservoir has neutralized the acidic CO_2-rich injection fluids[27].

The Carbfix technology imitates and accelerates natural processes, in which CO_2 is dissolved in water and interacts with reactive rock formations to form stable minerals, providing a permanent and safe carbon sink with in-situ mineralization[8]. For the technology to work, three things are required: favorable rock formation, water, and a source of CO_2 (Figure 8).

[15] Ellis, A. J. (1959) The solubility of calcite in carbon dioxide solutions. *Am. J. Sci.* **257**, 354–365.

[16] Ellis, A. J. (1963) The solubility of calcite in sodium chloride solutions at high temperatures. *Am. J. Sci.* **261**, 259–267.

[17] Saldi, G. D., Jordan, G., Schott, J. & Oelkers, E. H. (2009) Magnesite growth rates as a function of temperature and saturation state. *Geochim. Cosmochim. Acta* **73**, 5646–5657.

[18] Johnson, N. C. *et al.* (2014) Olivine dissolution and carbonation under conditions relevant for in-situ carbon storage. *Chem. Geol.* **373**, 93–105.

[19] Gadikota, G., Matter, J., Kelemen, P. & Park, A. H. Chemical and morphological changes during olivine carbonation for CO_2 storage in the presence of NaCl and NaHCO3. *Phys. Chem. Chem. Phys.* **16**, 4679–4693 (2014).

[20] Turvey, C. C. *et al.* (2018) Hydrotalcites and hydrated Mg- carbonates as carbon sinks in serpentinite mineral wastes from the Woodsreef chrysotile mine, New South Wales, Australia: controls on carbonate mineralogy and efficiency of CO_2 air capture in mine tailings. *Int. J. Greenh. Gas Control* **79**, 38–60.

[21] Rogers, K. L., Neuhoff, P. S., Pedersen, A. K. & Bird, D. K. (2006) CO_2 metasomatism in a basalt- hosted petroleum reservoir, Nuussuaq, West Greenland. *Lithos* **92**, 55–82.

[22] Gysi, A. P. & Stefánsson, A. (2012) CO_2-water–basalt interaction. Low temperature experiments and implications for CO_2 sequestration into basalts. *Geochim. Cosmochim. Acta* **81**, 129–152.

[23] McGrail, B. P. *et al.* (2017) Field validation of supercritical CO_2 reactivity with basalts. *Environ. Sci. Technol. Lett.* **4**, 6–10.

[24] Snæbjörnsdóttir, S. Ó. *et al.* CO_2 storage potential of basaltic rocks in Iceland and the oceanic ridges. *Energy Procedia* **63**, 4585–4600 (2014).

[25] Gysi, A. P. & Stefánsson, A. (2011) CO_2–water–basalt interaction. Numerical simulation of low temperature CO_2 sequestration into basalts. *Geochim. Cosmochim. Acta* **75**, 4728–4751.

[26] Voigt, M., Pearce, C. R., Baldermann, A. & Oelkers, E. H. (2018) Stable and radiogenic strontium isotope fractionation during hydrothermal seawater-basalt interaction. *Geochim. Cosmochim. Acta* **240**, 131–151.

[27] Clark, D. E. *et al.* (2018) The chemistry and potential reactivity of the CO_2-H_2S charged injected waters at the basaltic CarbFix2 site, Iceland. *Energy Procedia* **146**, 121–128.

*Figure 8: Simplified diagram of in-situ carbon mineralization (Carbfix)*

Only rock formations that are applicable for the application of the methodology are ultramafic, mafic, intermediate, or silicic rock types–formations known to contain the major minerals that promote reactions with dissolved CO_2 and form solid carbonates. A mapping tool that shows the geological feasibility of applying the methodology has been developed (Figure 9 and https://www.carbfix.com/atlas).

Other necessary factors for the methodology are water availability and the Permeability of the bedrock which can vary greatly between regions. The mineralization process requires water to carry the dissolved CO_2 and to promote reactions underground. Based on the potential usage of seawater[28,29], coastal or dry regions that lack fresh may still be good candidates.

Natural mineral storage is most efficient in ultramafic, mafic, intermediate, or silicic rocks, owing to their high reactivity and the abundance of divalent metal cations contained in silicates. Of these, basaltic rocks are the most abundant: most of the ocean floor, ~70% of the Earth's surface and >5% of the continents is basaltic (Figure 9).

---

[28] Snæbjörnsdóttir, S. Ó. *et al.* (2014) CO_2 storage potential of basaltic rocks in Iceland and the oceanic ridges. *Energy Procedia* **63**, 4585–4600
[29] Voigt, M. *et al.* (2021) An experimental study of basalt–seawater–CO_2 interaction at 130°C. *Geochimica et Cosmochimica Acta* **308** 21–41
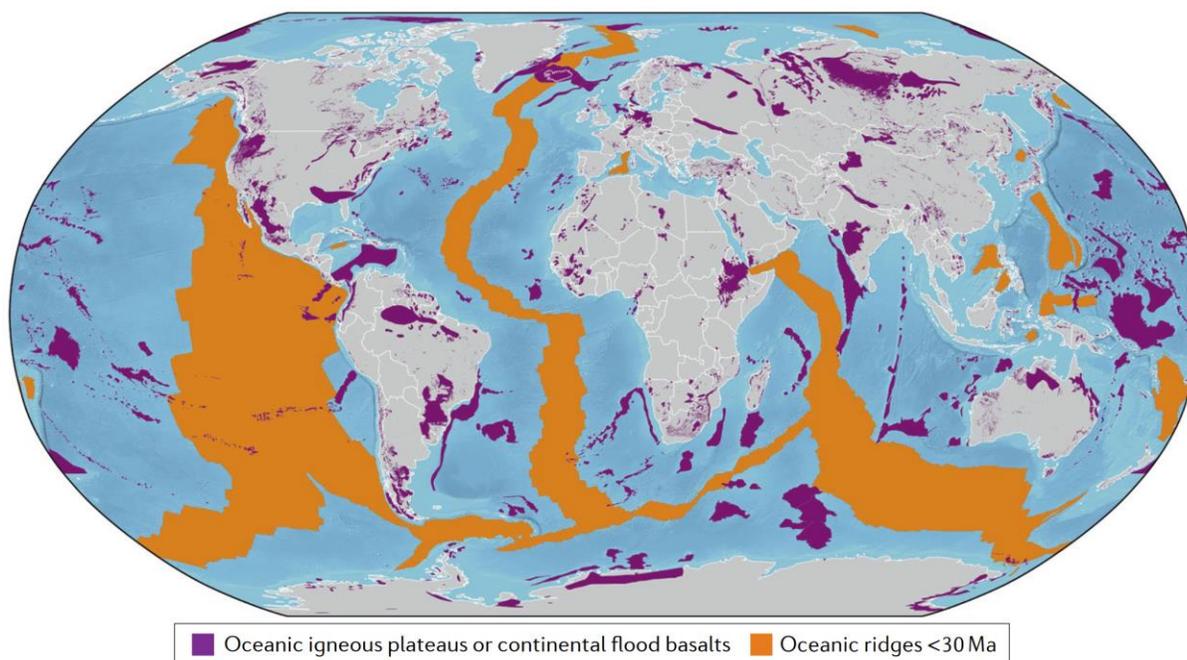
Figure 9: Locations of feasible geological formations for in-situ carbon mineralization. Map showing the potential onshore and offshore targets for in-situ mineral storage of CO_2. Oceanic ridges younger than 30 Ma are shown in orange, and oceanic igneous plateaus and continental flood basalts are shown in purple. [8]

Abundant flood basalt fields are found in central India, Siberia, the United States, Canada and Yemen. Although the occurrence of basalts onshore is limited (about 5%), the weathering of basaltic rocks on the continents and volcanic islands is responsible for ~30% of the natural drawdown of CO_2 from the atmosphere attributable to continental silicate weathering. This demonstrates the relative advantage of these rocks compared with other terrestrial rocks in-situ carbon mineralization. Natural analogues for large-scale CO_2 mineralization are found in various environments. In terms of scale, one of the most substantial natural analogues for CO_2 mineralization is the carbon uptake of the oceanic crust; basalts in volcanic submarine geothermal systems receive substantial amounts of CO_2 from the degassing of magma intrusions located in their roots. The oceanic crust is typically 6–7 km thick and has a remarkably consistent stratigraphy on a global scale. Hydrothermal circulation through ridge flanks is focused in the uppermost 1 km of the ocean crust, resulting in extensive CO_2–water–basalt interaction. This hydrothermally active crust mineralizes ~40 $MtCO_2$ annually.

The storage potential of hydrothermally active geothermal systems located onshore in Iceland, the largest land mass above sea level along the mid- oceanic ridges, has been estimated by direct measurements of CO_2 bound in carbonates in drill cuttings from three basalt-hosted geothermal fields. Although these carbonates are precipitated over long timescales (10,000–300,000 years), the results provide insight into the Permeability and active Porosity of natural systems and indicate that young and fresh basalts can naturally store >100 kg of CO_2 per m^3. On the basis of this estimate, the theoretical storage capacity of the ocean ridges is on the order of 100,000–250,000 $GtCO_2$ — orders of magnitude larger than the amount of CO_2 that would be derived from the burning of all fossil fuel. This value agrees with other estimates that verify the enormous storage capacity of both sub- ocean and onshore basalts.

Evidence for natural carbon mineralization is apparent at various other onshore locations. For example, in Oman, tectonically exposed mantle peridotites remove CO_2 directly from the atmosphere, with this CO_2 – water– rock interaction resulting in the formation of travertines. Owing to the reactivity of the Omani peridotites, they are estimated to consume in the range of 10–100 $ktCO_2$ per year through natural carbon mineralization. The complete natural carbonation of the peridotites leads to the formation of listwanites, with the ultra-mafic rocks transforming through a series of reactions: serpentine + olivine + brucite → serpentine + magnesite → magnesite + talc → magnesite + quartz. This mineralogical transformation serves as a geological analogue for the technically assisted in-situ CO_2 mineralization described in this methodology. Similarly, in West Greenland, extensive carbonate mineralization in basalts associated with petroleum Migration was documented, suggesting that CO_2-bearing fluids may be readily mineralized, even in extensively altered rocks.

title changes A.1.6 Monitoring techniques

Geologic CO_2 storage requires monitoring and accounting to ensure safety and permanence. Existing monitoring techniques such as seismic or electromagnetic imaging are insufficient to quantitatively characterize CO_2 stored in dissolved (solubility trapping) or mineral (mineral trapping) form. In contrast, geochemical monitoring techniques using non-reactive tracers are useful to directly monitor the reactivity of the injected CO_2-charged fluid. The varieties of tracers are transported differently, and measurement of their concentrations and changes in their ratios can be used to quantitatively characterize different processes at field scale. This led to the development of the geochemical monitoring techniques that have been applied during injections, that provide the means to accurately determine the fate of the injected CO_2.

The feasibility of geochemical monitoring has been tested and confirmed during pilot injections and scaled-up industrial activities[30]. Non-reactive tracers are co-injected to characterize the flow paths of the CO_2-charged fluid. The fate of the injected CO_2 is then quantified using mass balance calculations. Additionally, the injected CO_2 can be spiked with carbon-14 (^{14}C) to monitor its transport and reactivity. The resulting calculated dissolved CO_2 (dissolved inorganic carbon, DIC) is then compared to the measured concentrations, revealing that DIC measurements, and ^{14}C measurements if applicable, confirm significant reduction of CO_2 along the flow-path through mineralization reactions (Figure 10).

This is supported by:

(i)   Calculation of fluid saturation states showing that the collected monitoring fluids are at saturation or supersaturation with respect to calcite (the predominant CO_2 mineralization product) at all times, except during the initial first breakthrough of the injected fluids;

(ii)   Calcium (Ca) isotopes in both pre- and post-CO_2 injection waters which indicate rapid calcite precipitation in agreement with mass balance calculations;

(iii)   X-ray diffraction and scanning electron microscopy with energy-dispersive x-ray spectroscopy analysis of secondary mineral precipitates collected from the submersible pump in the first Monitoring Well showing these precipitates to be calcite with similar ^{14}C concentration of the injected CO_2 (Figure 11)

---

[30] Matter, J. M. *et al.* (2016) Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science* **352**, 1312–1314.

Extensive geochemical monitoring has been used together with the tracer data to analyze the geochemical response of the reservoir. This data can be used for modelling saturation states of carbonate minerals, and the reaction paths of the CO_2 charged fluid through the reservoir [e.g.30].
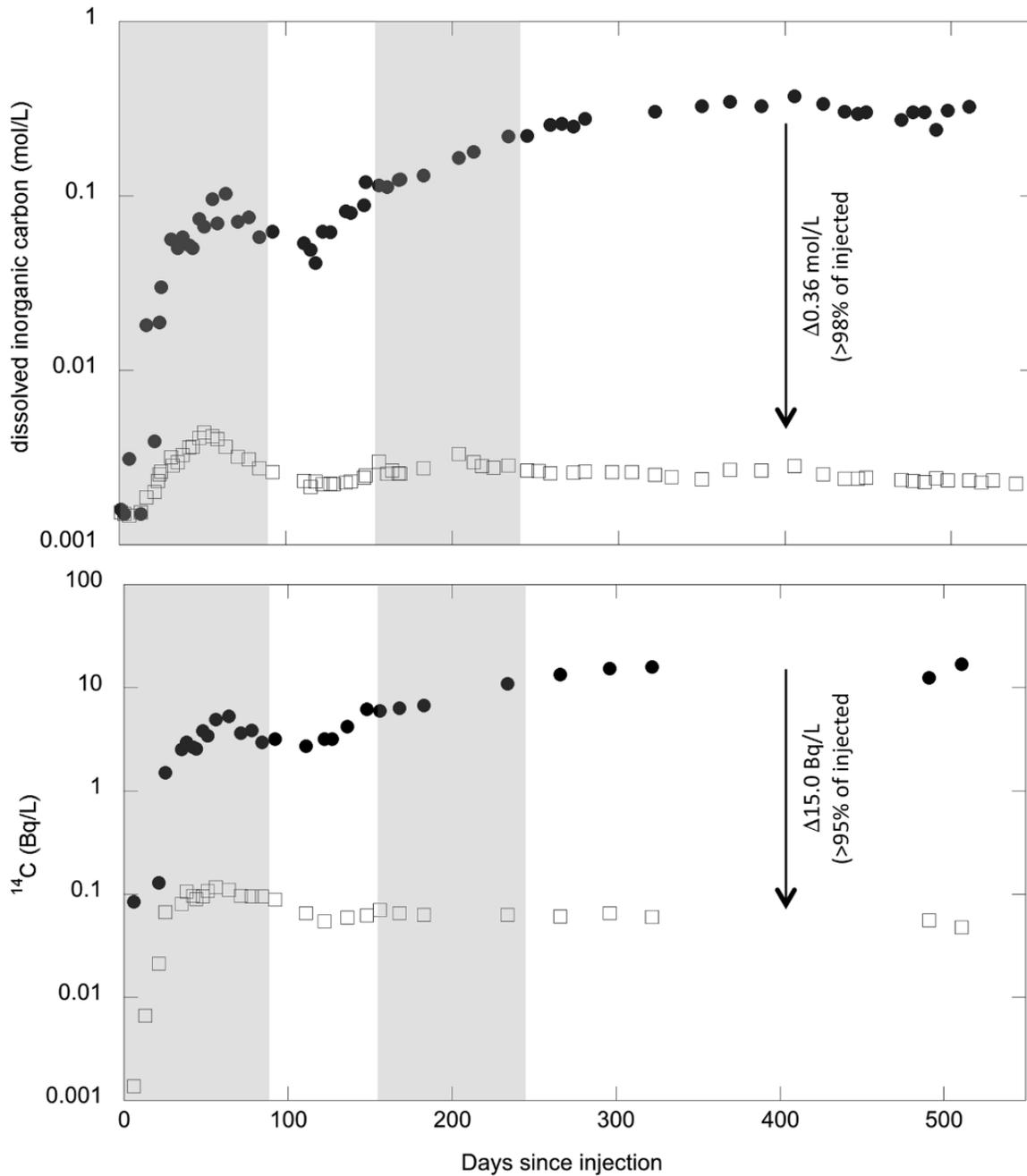

Figure 10: Comparison of calculated and measured DIC and ^{14}C concentrations in the target CO_2 storage formation fluid during Carbfix 1 injection. (Left graph) Time series of expected (solid circles) versus measured (open squares) DIC (mol/liter) in the first monitoring well indicating >98% conversion of injected CO_2 to carbonate minerals, and (Right graph) time series of expected (solid circles) versus measured (open squares) ^{14}C (Bq/liter) in the first Monitoring Well showing >95% of injected CO_2 to be converted to carbonate minerals. [30]

Figure 11: Precipitates collected from a submersible pump in a Monitoring Well during the original Carbfix pilot injection after it was hauled to the surface. X-ray diffraction and scanning electron microscopy confirmed these precipitates to be calcite with similar ^{14}C concentration of the injected CO_2 and the precipitated collected calcite.

Appendix 2 - Permanence Risk Assessment

CCS has recently gained more and more attention as a serious climate change mitigation option. However, the risk of CO_2 re-entering the atmosphere or the ocean after injection into geological reservoirs and net reversal of storage during and after the project life must be assessed. It has been suggested that any technology used to geologically store CO_2 underground should store it for a minimum of 1000 years with a leakage rate of less than 0.1% per year.

The permanence risk or leakage risk for CCS is directly linked to the mobility of CO_2. A higher mobility equates to a higher risk of leakage. The "traps" or trapping mechanisms provides the mean of the storage site to contain the CO_2 over long period of time. CO_2 can be physically trapped in porous rocks below an impermeable cap rock (structural trapping), some of which becomes trapped in small pores (residual trapping) and, over time, dissolves in groundwater (solubility trapping) and reacts with the subsurface rocks to form stable Carbonate minerals (mineral trapping). As the storage progresses from structural to mineral trapping, the CO_2 becomes more immobile, thus increasing the security of storage.

In traditional CCS projects, highly mobile, supercritical or gaseous CO_2 is injected at the storage site. The main trapping mechanism relies on structural or stratigraphic seals to impede the flow of the mobile, buoyancy-driven flow of CO_2 back to the surface. Deficient structural/stratigraphic can lead to large, short- or long-term net reversal of storage. Due to the high mobility of CO_2, the sealing capacity and long-term integrity of caprock used in structural trapping is critical has been therefore an important issue for site approval and public acceptance.

Mineral storage however relies on immediate solubility trapping (ensured by full CO_2 dissolution prior to entering the storage formation) and subsequent fast mineralization of the CO_2 (due to enhanced geochemical reaction within the storage reservoir). By dissolving CO_2 in water, the risk of CO_2 leaking back to the atmosphere is negligible due to the high

er density of the injected fluids, achieving solubility trapping immediately as discussed above. The carbonated water is acidic, with a typical pH of 3-5 (dependent on the applied partial pressure of CO_2 during injection). Water composition and temperature of the system promotes dissolution of the rocks releasing cations into the fluid. These cations react with the dissolved CO_2 to form stable carbonate minerals in pore space and fractures. The degree to which the released cations form minerals depends on the rock formation, pH and temperature, and has been proven to occur on the time scale of months to years[31,32]. Risk of leakage in suitable storage reservoir is negligible as the trapping of CO_2 achieves solubility trapping immediately, and mineral trapping within two years[30].

Therefore, the permanence risk is negligible where monitoring confirms that the CO_2 has entered solubility and eliminated where monitoring confirms that the CO_2 has entered mineral trapping. Mineral Trapping when properly implemented has no leakage risk and limits the need for long term monitoring once mineralization is achieved.

---

[31] Snæbjörnsdóttir, SO, Oelkers, EH, Mesfin, K. et. al. (2017) The chemistry and saturation states of subsurface fluids during the in-situ mineralisation of CO_2 and H_2S at the CarbFix site in SW-Iceland. *International Journal of Greenhouse Gas Control*, Volume 58, pp 87-102

[32] Snæbjörnsdóttir, S.Ó., Gislason, S.R., Galeczka, I.M., Oelkers, E.H. (2018) Reaction path modelling of in-situ mineralization of CO_2 at the CarbFix site at Hellisheidi, SW-Iceland. *Geochimica et Cosmochimica Acta*, Volume 220, pp. 348-366.

Appendix 3 – Ownership

Operation of projects applying the methodology involves three steps of implementation and operation, i.e. the CO_2 capture, the CO_2 transport and the geological CO_2 storage which may be conducted by different Project proponents. Where there are multiple Project proponents implementing and operating projects the ownership of climate benefits associated with the geological CO_2 storage shall be clearly defined on a contractual basis, in order to prevent double accounting. Further where there are more than one Project proponent operating the project one shall be assigned overall responsibility of implementation and operation of the project.

In order to prevent double counting, the owner of the CO_2 Source cannot claim emission mitigations for its own operations due to the operation to the project if climate benefits generated are transferred to a third-party organization.

Appendix 4 – Approved Methodologies

All methodologies applying for approval for CO_2 capture and CO_2 transport shall conform to requirements of current version of ISO 14064-2 and be consistent with the structure of this methodology and be submitted to Carbfix for approval.

Approved methodologies/modules that can be applied for CO_2 capture are:

-   Direct Air Capture Methodology – Developed by Climeworks

Approved methodologies that can be applied for CO_2 transport:

-

Appendix 5 – General requirements for CO$_2$ Capture

Here are outlined the general requirement for other methodologies or if no other methodology is available the minimum requirement in the project assessment of CO$_2$ capture.

A5.1. Applicability

This methodology applies to CO$_2$ Capture project and operation activities that meet all the following conditions:

- Eligible CO$_2$ capture which includes without limitation capture of CO$_2$ emitted through:
    - Combustion,
    - Industrial processes and,
    - DAC.
- The CO$_2$ capture installations and operations shall comply to applicable local environmental, ecological, and social statutory requirements.
- All capturing installations shall be installed according to national best practices and national statutory requirements.
- All installations shall be approved by local authorities and hold relevant permits for the capture.
- Transparent and rigorous accounting of the CO$_2$ reduction or removal avoiding any double counting.
- All measurement devices shall be calibrated according to the manufacturer's recommended procedures or best practice consensus standard to an accuracy of 5%. All calibration records shall be maintained and documented.

The methodology explicitly excludes CO$_2$ capture that:

- Are solely generated and captured for the purpose of application of the methodology without any other benefits e.g. industrial processes and electricity generation.

A5.2. Baseline Scenario definition

Baseline is the scenario that most reasonably represents the anthropogenic emissions by sources of greenhouse gases that would occur in the absence of the proposed project activity. The baseline is characterized by three approaches (paragraph 48, modalities and procedures for a clean development mechanism):

1. the existing actual or historical emissions, as applicable;
2. the emissions from a technology that represents an economically attractive course of action, taking into account barriers to investment;
3. the average emissions of similar project activities undertaken in the previous five years, in similar social, economic, environmental and technological circumstances, and whose performance is among the top 20 per cent of their category.

The baseline should be determined for the output generated by the facility or project activity implemented and for the entity that has or would have emitted a higher amount of greenhouse gases in the absence of the project activity, for the generation of the same output.

The methodology relates to the permanent storage of GHG (CO_2) that would otherwise be emitted (CCS) or has already been emitted (DAC+S). Therefore option (1) is the most appropriate approach for baseline determination.

The methodology applies to project activities that are connected to a capture technology of where CO_2 is transported to the CO_2 injection site before injection. Therefore, the project shall be complemented by a project-based assessment of the CO_2 capture or the CO_2 stream provided for the mineral storage and the baseline scenario analysis for the CO_2 capture. According to this approach, the Project proponent shall determine projection-based baseline emissions according to actual measured quantities of CO_2 captured and injected from the project, which would without the implementation of the project been emitted to the atmosphere.

A5.3. Boundary

A5.3.1. Baseline Scenario

The baseline emissions represent emissions that would have occurred in the absence of the project.

The baseline scenario is directly associated with the CO_2 capture or the source of CO_2 from the capture installations and transported to the geological CO_2 storage site for solubility trapping and in-situ carbon mineralization. Therefore, the baseline scenario is determined at the CO_2 capture step and at the project level according to Appendix 4 or according to Appendix 5.

For the baseline emissions two approaches are applicable, i.e. baseline for DAC and baseline for other sources.

- DAC Baseline: No other capture activities are present in the absence of projects and their activities, and no other emissions involved other than anthropogenic emissions who are outside of the project's boundary.
- Other baseline emissions: Baseline emissions are derived directly from the primary processes. The CO_2 capture may be less than emissions being emitted from the primary processes and the proportion of the captured CO_2 relative to the baseline demonstrates the efficiency of the capture installations.

Baseline Scenario			
Source	GHGs	Amount	Justification/Explanation
	CO_2	Yes	CO_2 is the only GHG being captured thus other GHG are excluded.
	CH_4	No	Baseline scenario based on the CO_2 capture and all identified sources
	N_2O	No	within the boundary, i.e., the gas stream which is captured from the primary process.

A5.3.2. Project Scenario

The procedure for calculation of the CO_2 capture involves all emission sources, demarcated within the boundary of the CO_2 capture installations and its auxiliary equipment with the installation of any capture and compression systems. The boundary of the CO_2 capture site extends towards the input of the CO_2 transport site/installations (Figure 12).

Includes:

1. All facilities capturing CO_2
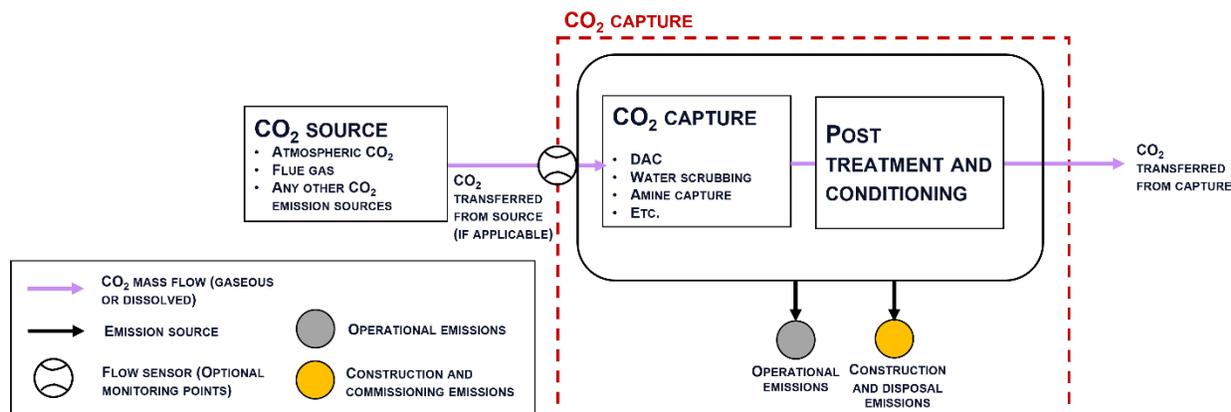2. All/any treatment facilities

Figure 12: CO_2 Capture Project Boundary.

All significant emission type shall be defined at the project assessment level and include but not limited to:

- embodied emission from construction and disposal of the capture facilities and associated facilities
- stationary combustion, and/or
- use of thermal energy and/or
- electric auxiliary installations, and/or
- Consumption of consumables

Emissions associated depend on location and configuration of installations. Electricity and thermal energy purchased shall primarily be from renewable production where available and emission from fuel usage shall be preferably from low carbon fuel.

Project Scenario			
Source	GHGs	Amount	Justification/Explanation
mCO2,capture,operation	CO_2	Yes	May be an emission source. If contributing as a source CO_2 is always included. Other GHG may be excluded if demonstrated they are negligible. Direct or indirect emissions to operate the CO_2 Capture facilities. This include but not limited to emissions from energy and consumables consumption. If Renewable energy is used certificate of origin, renewable energy certificate or local statement of origin shall be accompanied the electricity consumption.
	CH_4	Yes	
	N_2O	Yes	
mCO2,capture,emboddied	CO_2	Yes	May be an emission source. If contributing as a source CO_2 is always included. Other GHG may be excluded if demonstrated they are negligible.
	CH_4	Yes	
	N_2O	Yes	

			Emissions due to construction and disposal of the capture and treatment facility. Must be calculated for each individual process step. and distributed over the crediting period.

A5.4. Baseline Emissions

As the methodology is site specific, the project scenario is the counterbalance to the baseline scenario i.e. the methodology is applied at the project level. If CO_2 capture is performed at an existing point-source of CO_2 emissions, the point-source without CO_2 capture represent the baseline scenario CO_2.

- For DAC facilities, baseline emission is 0.
- For other capturing facilities the baseline emissions shall be calculated as follows:

$BE_y = \sum BE_{PP,y} = \sum(m_{PP,y} \cdot Elem_{CO2,y})$			Equation 9
Where			
BE_y	=	Baseline emissions in period y	tonne (tCO$_2$)
$BE_{PP,y}$		Baseline emissions from Primary process i.e., fossil fuel combustion, electricity consumption, fugitive emissions, biogas, industrial processes from the CO_2 capture in year y.	
$m_{PP,y}$	=	Amount of emission from primary processes *PP*.	tonne (t)
$Elem_{CO2,y}$		Elemental composition of the CO_2 stream from primary processes *PP*.	Vol% (for gas streams)

A5.5. Project Emissions

A.5.5.1 Emission from Project operation — $mCO_{2eq,\text{capture,operation}}$

A project-based assessment of all emission sources shall be conducted, and all significant emission source shall be included in the calculation of the project operational emissions according to Equation 4.

- Significant emissions shall account for usage intensity ($I_{type\ of\ emission}$) and associated emission factors associated ($ef_{type\ of\ emission}$).
- All emission factors shall be derived from IPCC except for electricity/thermal usage which shall be derived from nationally determined emission factors and/or information provided by the energy supplier.
- Significant emissions are defined as those that amount to more than 0.5% of $mCO_{2eq,\text{project,operation},y}$. All emission sources that are less than 0.5% of $mCO_{2eq,\text{project,operation},y}$ individually can be assumed negligible and therefore not significant if the sum of all negligible emissions sources is less than 5% of $mCO_{2eq,\text{project,operation},y}$.

A.5.5.2 Emission from Project operation — $mCO_{2eq,\text{capture,emboddied}}$

GHG annual emissions associated with the construction and disposal of facilities are to be quantified based on case specific assessments of the facilities constructed and can be based on the following. In all cases, the minimal scope of the assessment of construction emissions shall be the cradle to grave GHG emissions from materials used, including embodied emissions. Construction emissions can be calculated according to an assessment before the start of operations and should be for a specific plant. Construction emissions only need to be accounted for once. If a plant gets reused or if its operational lifetime is expanded beyond

what was assumed in the ex-ante estimate, the yearly accounting for construction emissions shall cease to zero once the entire amount has cumulatively been accounted for (i.e. similar to full depreciation of the value of a good at the end of its planned lifetime in financial accounting).

Embodied emissions for the project shall be scaled to yearly values, so that all construction emissions will be accounted for over the lifespan of the installation. In addition, provided that the embodied emissions are fully accounted for during the project lifetime, embodied emissions may be excluded during periods of ramp-up and decommissioning.

A5.6 CO_2 capture equations and parameters

According to section 10 and below:

Parameter	$\dot{m}_{PP,y}$
Parameter type	Measured or calculated
Data unit	t
Description	Mass of emission from primary process *PP*.
Equations	Equation 9
Source of data	On-site measurement
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	Recalibration according to manufacturer's specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	Baseline emission
Comments	

Parameter	$Elem_{CO2,PP}$
Parameter type	Measured
Data unit	Volume %
Description	Elemental composition of the CO_2 stream from primary process *PP*.
Equations	Equation 9
Source of data	On-site sampling and on-or-off-site analysis.
Calculation method/equations	NA

Description of measurement methods and procedures to be applied	Sampling and subsequent analysis annually.
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	Analytical equipment shall be calibrated according to manufacturer's specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	Baseline emission
Comments	-

Appendix 6 – General requirements for CO_2 Transport

Here are outlined the general requirement for other methodologies or if no other methodology is available the minimum requirement in the project assessment of CO_2 Transport.

A6.1. Applicability

This methodology applies to CO_2 Transport project and operation activities that meet all the following conditions:

- Eligible CO_2 transport options which include without limitation transportation of CO_2 from the CO_2 capture to the geological injection Site via:
    o pipelines
    o modular transportation e.g., cargo ship, rail, truck.
- do no net environmental or social harm.
- Installations shall be installed according to national best practices and national statutory requirements.
- All installations shall be approved by local authorities and hold relevant permits for the CO_2 transport.
- Transparent and rigorous accounting of the CO_2 reduction or removal avoiding any double counting.
- All measurement devices shall be calibrated according to the manufacturer's recommended procedures or best practice consensus standard to an accuracy of 5%. All calibration records shall be maintained and documented.

A6.2. Boundary

Quantification of CO_2 transport includes full pipeline system from the delivery of CO_2 from the CO_2 capture to a delivery point at the CO_2 storage site.

The procedure for calculation of the CO_2 Transport involves all emission sources, demarcated within the boundary of the CO_2 Transport installations and its auxiliary equipment with the installation of any transport and compression systems. The boundary of the CO_2 Transport site extends towards the input of the CO_2 Storage site/installations. Further, it can involve transportation with containers e.g. cargo ship, rail or truck and storage until injected (Figure 13).

Includes emissions from:

1. All facilities transporting CO_2
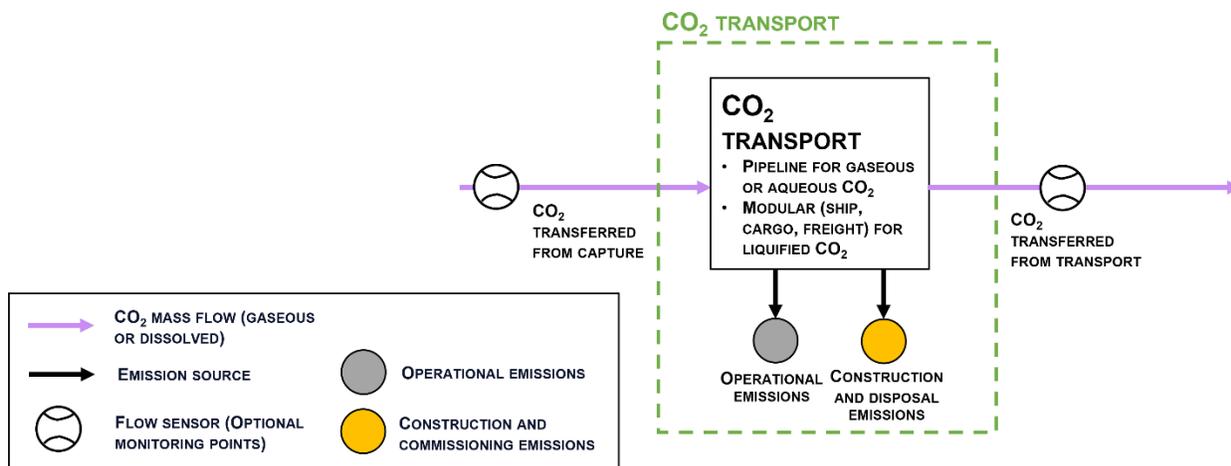2. All/any treatment facilities

Figure 13: CO$_2$ transport project boundary

All significant emission type shall be defined at the project assessment level and include but not limited to:

- embodied emission from construction and disposal of the transport facilities and associated facilities
- stationary combustion, and/or
- use of thermal energy and/or
- electric auxiliary installations, and/or
- Consumption of consumables
- etc.

Emissions associated depend on location and configuration of installations. Electricity and thermal energy purchased shall primarily be from renewable production where available and emission from fuel usage shall be preferably from low carbon fuel.

Installations which include stationary combustion in order to operate and maintain the pipeline system must be included in the CO$_2$ transport project emissions.

Modular transport of CO$_2$ shall be included in the project emissions and account for all combustion emissions derived due to the transportation using the appropriate emission factor for each mode of transport and fuel used.

- Modular equipment used for transportation and/or

- Pipeline transportation equipment/installations

- Reception facilities and/or tanks at the capture and/or injection site

Project Scenario			
Source	**GHGs**	**Amount**	**Justification/Explanation**
mCO$_{2,capture,operation}$	CO$_2$	Yes	May be an emission source. If contributing as a source
	CH$_4$	Yes	CO$_2$ is always included. Other GHG may be excluded if
	N$_2$O	Yes	demonstrated they are negligible.

			Direct or indirect emissions to operate the CO_2 Capture facilities. This include but not limited to emissions from energy and consumables consumption. If Renewable energy is used certificate of origin, renewable energy certificate or local statement of origin shall be accompanied the electricity consumption.
mCO$_{2,capture,emboddied}$	CO_2	Yes	May be an emission source. If contributing as a source CO_2 is always included. Other GHG may be excluded if demonstrated they are negligible.
	CH_4	Yes	Emissions due to construction and disposal of the capture and treatment facility. Must be calculated for each individual process step. and distributed over the crediting period.
	N_2O	Yes	

A6.3. Project Emissions

A.6.3.1 Emission from Project operation — $mCO_{2eq,transport,operation}$

A project-based assessment of all emission source shall be conducted and all significant emission source shall be included in the calculation of the project operational emissions according to Equation 4.

- Significant emissions shall account for usage intensity ($I_{type\ of\ emission}$) and associated emission factors associated ($ef_{type\ of\ emission}$).
- All emission factors shall be derived from IPCC except for electricity/thermal usage which shall be derived from nationally determined emission factors and/or information provided by the energy supplier.
- Significant emissions are defined as those that amount to more than 0.5% of $mCO_{2eq,project,operation,y}$. All emission sources that are less than 0.5% of $mCO_{2eq,project,operation,y}$ individually can be assumed negligible and therefore not significant if the sum of all negligible emissions sources is less than 5% of $mCO_{2eq,project,operation,y}$.

A.6.3.2 Emission from Project operation — $mCO_{2eq,transport,emboddied}$

GHG annual emissions associated with the construction and disposal of facilities are to be quantified on the basis of case specific assessments of the facilities constructed and can be based on the following. In all cases, the minimal scope of the assessment of construction emissions shall be the cradle to grave GHG emissions from materials used, including embodied emissions. Construction emissions can be calculated according to an assessment before the start of operations and should be for a specific plant. Construction emissions only need to be accounted for once. If a plant gets reused or if its operational lifetime is expanded beyond what was assumed in the ex-ante estimate, the yearly accounting for construction emissions shall cease to zero once the entire amount has cumulatively been accounted for (i.e. similar to full depreciation of the value of a good at the end of its planned lifetime in financial accounting).

Embodied emissions for the project shall be scaled to yearly values, so that all construction emissions will be accounted for over the lifespan of the installation. In addition, provided that the embodied emissions

are fully accounted for during the project lifetime, embodied emissions may be excluded during periods of ramp-up and decommissioning.

A6.4 CO_2 transport equations and parameters

According to section 10.

Appendix 7 – Multi-CO$_2$ Stream projects: Emission Mitigation and Carbon Dioxide Removal

A7.1 General case

For multi-source projects, there may be only one geological storage reservoir.

Where additional CO$_2$ streams enter and potentially leave thereafter the project boundary at one or multiple points at capture, transport or storage of the CCS activity the project is defined as a multi-source project (Figure 14). For such projects special provisions shall be followed to make clear distinction between the CO$_2$ Stream.

- If the project activity shares facilities with any additional CO$_2$ streams, project proponent must monitor the amount of CO$_2$ from each CO$_2$ entering and leaving the project boundary at any point in the capture, transport, or storage facilities. Project proponents must assure that CO$_2$ captured following one of the applicable capture modules is monitored at appropriate locations to allow a clear differentiation of the CO$_2$ streams.
- Project emission including CO$_2$ release from the Storage Site shall be attributed in proportion to relative CO$_2$ contribution to the injection stream.
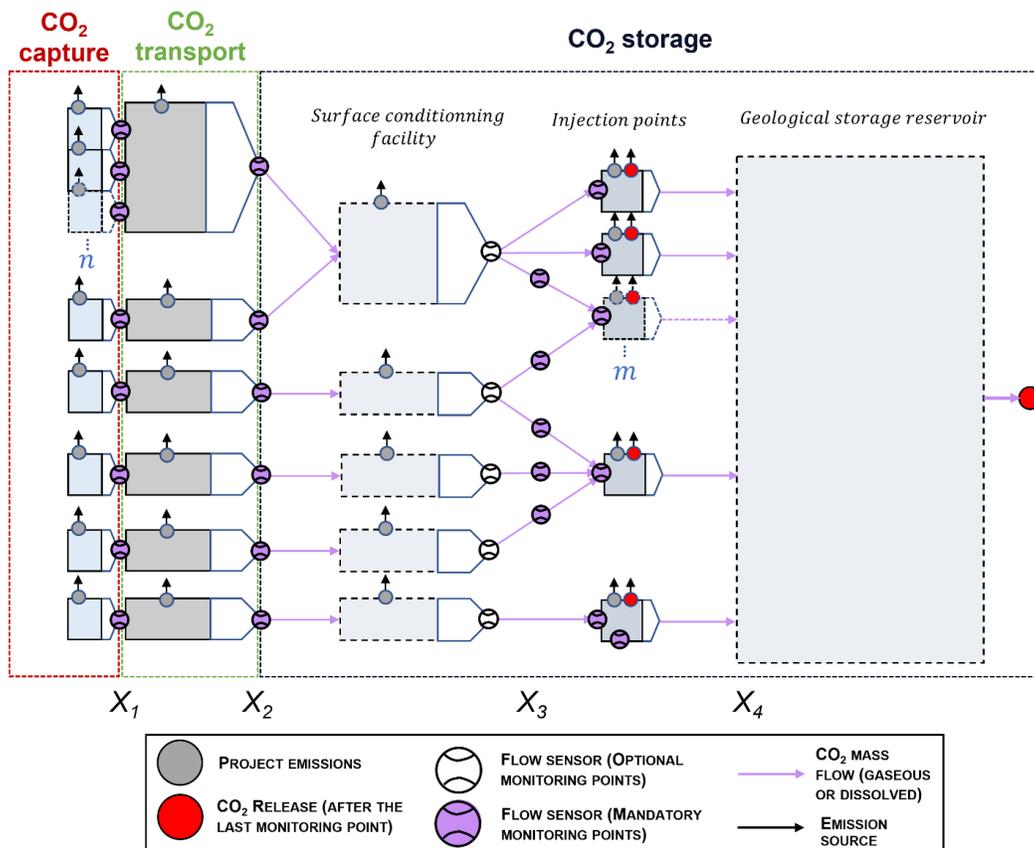

Figure 14: Multi-source project CO$_2$ streams and mandatory monitoring points.

				Equation 1a
$m_{CO2,credited,n,y}$ $= mCO_{2,injected,n,y} - mCO_{2,released,n,y}$ $- \sum_{p}^{P} X_{n,p,y} \cdot (mCO_{2eq,p,operation,y} + mCO_{2eq,p,embodied,y})$				
Where				
$mCO_{2,credited,n,y}$	=	total amount of CO_2 credited in own accounting or sold/transacted to third parties from source n in period y.		tonne (tCO_2)
$mCO_{2,injected,n,y}$	=	Total amount of CO_2 injected at the storage site from source n in period y, determined at the last monitoring point on the injection system.		tonne (tCO_2)
$mCO_{2,released,n,y}$	=	Total amount of CO_2 released at the storage site from source n downstream of the last monitoring point on the injection system in period y.		tonne (tCO_2)
$mCO_{2eq,operation,p,y}$	=	Total GHG emissions due to project operations of the CCS/CDR value chain (CO_2 Capture, Transport, and Storage) in period y.		tonne ($tCO_{2)}$
$mCO_{2eq,embodied,y}$	=	Total GHG emissions due to construction and disposal of the CCS/CDR value chain (CO_2 Capture, Transport, and Storage) scheduled for monitoring period y.		tonne (tCO_2)
$X_{i,p,y}$	=	proportion of the CO_2 stream from source n entering the process step p relative to the total amount of CO_2 entering the same process step in period y.		unitless
n	=	Represents the CO_2 Capture source.		unitless
p	=	Process Steps, these include the capture, transport, and storage steps in the CCS/CDR chain. If mixing of CO_2 stream occurs within the storage step, the storage can be further divided into the surface conditioning and injection facility steps.		unitless
y	=	Monitoring period during which credits are produced.		days

The amount of CO_2 injected from each Project n into the geological storage reservoir must be measured or calculated at the geological injection site for each injection well.

$mCO_{2,injected,y}$ shall be calculated as:

			Equation 2a
$mCO_{2,injected,n,y} = \sum_{i} X_{n,i,y} \cdot mCO_{2,i,y}$			
Where			
$mCO_{2,injected,n,y}$	=	total amount of CO_2 injected in the geological storage from source n in period y, determined at the last monitoring point.	tonne (tCO_2)

$mCO_{2,i,y}$	=	Mass of CO_2 injected at each injection well i in period y, determined at the last monitoring point on the injection system.	tonne (tCO_2)
$X_{n,i,y}$	=	Proportion of the CO_2 stream from source n entering the injection system i relative to the total amount of CO_2 entering the same process step in period y.	unitless
i	=	Injection well(s).	unitless
y	=	Monitoring period during which credits are produced.	days

$mCO_{2,i,y}$ shall be calculated according to Equation 3.

$mCO_{2eq, operation,p, y}$ shall be calculated according to Equation 4.

$mCO_{2eq, embodied, y}$ shall be calculated according to Equation 5.

		Equation 6b
$$\begin{aligned} mCO_{2,released,n,y} &= mCO_{2,released,injection\ system,n,y} \\ &+ mCO_{2,released,geological\ storage,n,y} \\ &= \sum_{j} (X_{i,j,n,y} \cdot mCO_{2,release,injection\ system,j}) + X_{n,y} \\ &\cdot \sum_{k} mCO_{2,release\ event,injection\ system,k} \end{aligned}$$		
Where		
$mCO_{2,released,n,y}$	=	Total amount of CO_2 released at the storage site from source n downstream of the last monitoring point on the injection system in period y.	tonne (tCO_2)
$mCO_{2,released,injection\ system,n,y}$	=	Amount of CO_2 released at the storage site from the injection system from source n downstream of the last monitoring point on the injection system in period y.	tonne (tCO_2)
$mCO_{2,released,geological\ storage,n,y}$	=	Amount of CO_2 released at the storage site from the geological storage from source n downstream of the last monitoring point on the injection system in period y.	tonne (tCO_2)
$mCO_{2,release\ event,injection\ system,j}$	=	Mass of CO_2 released intentionally or unintentionally from the injection system downstream of the last monitoring point on the injection system during event j.	tonne (tCO_2)
$mCO_{2,release\ event,injection\ system,j}$	=	Mass of CO_2 released intentionally or unintentionally from the geological storage reservoir during event k.	tonne (tCO_2)

$X_{i,j,n,y}$	=	Proportion of the CO_2 stream from source n injected into the injection well i relative to total amount of CO_2 injected into the injection well i during release event j in period y.	unitless
$X_{n,y}$	=	Proportion of the CO_2 stream from source n injected into the injection system relative to total amount of CO_2 injected into the geological storage reservoir in period y.	Unitless
j	=	CO_2 release event from the injection system.	unitless
k		CO_2 release event from the geological storage reservoir.	unitless
y	=	Monitoring period during which credits are produced.	days

A7.2 Multi-Source Project

This is an example of a multi-source project consisting of three CO_2 capture steps, two CO_2 transport steps, two CO_2 surface conditioning steps, one injection point, and one geological storage reservoir (Figure 15).

$$X_{1,1} = 0.2 \qquad X_{1\text{-}2,2} = 1 \qquad X_{1\text{-}2,3} = 0,6 \qquad X_{1\text{-}3,4} = 1$$
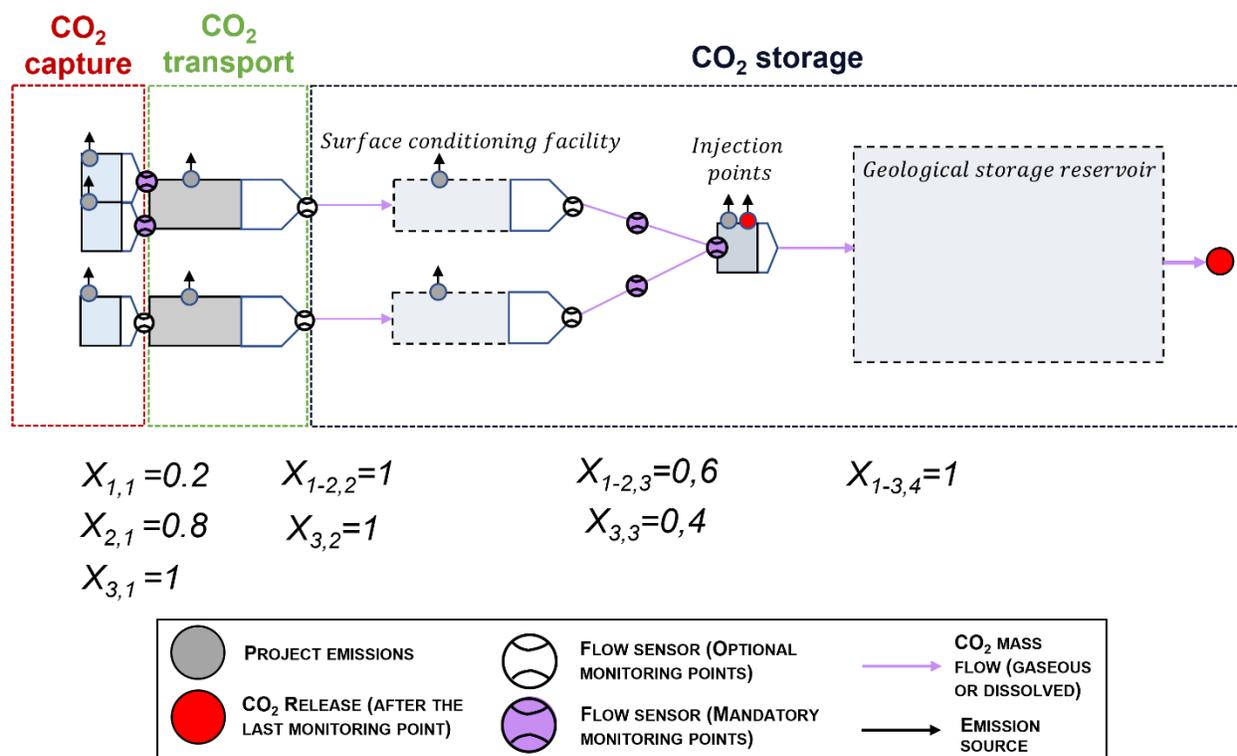$$X_{2,1} = 0.8 \qquad X_{3,2} = 1 \qquad X_{3,3} = 0,4$$
$$X_{3,1} = 1$$

Figure 15: Example of a multi-source project

Project 1:

The Amount of GHG that can be credited in own accounting or sold/transacted to third parties for Project 1 shall be calculated as follow:

$m_{CO2,\,credited,1,y}$

$$= mCO_{2,\,injected,1,y} - mCO_{2,\,released,1,y} - (mCO_{2eq,\,capture,operation,\,y} + X_{1,1}$$
$$\cdot mCO_{2eq,\,transport,operation,\,y} + X_{1,1} \cdot mCO_{2eq,\,conditioning,operation,\,y} + X_{1,1}X_{1-2,3}$$
$$\cdot mCO_{2eq,\,injection,operation,\,y} + X_{1,1}X_{1-2,3} \cdot mCO_{2eq,\,transport,operation,\,y})$$

where:

$$mCO_{2,injected,1,y} = (X_{1-2,3} \cdot X_{1,1}) \cdot mCO_{2,i,\,y}$$

$mCO_{2,released,1,y}$

$$= \sum_{j}(X_{1-2,3} \cdot X_{1,1}) \cdot mCO_{2,release,injection\ system,j}) + (X_{1-2,3} \cdot X_{1,1})$$
$$\cdot \sum_{k} mCO_{2,\,release\ event,injection\ system,k}$$

$m_{CO2,\,credited,1,y}$

$$= (0.6 \cdot 0.2) \cdot mCO_{2,i,\,y} - (\sum_{j}(0.6 \cdot 0.2) \cdot mCO_{2,release,injection\ system,j}) + (0.6 \cdot 0.2)$$
$$\cdot \sum_{k} mCO_{2,\,release\ event,injection\ system,k}) - (mCO_{2eq,\,capture,operation,\,y} + 0.2$$
$$\cdot mCO_{2eq,\,transport,operation,\,y} + 0.2 \cdot mCO_{2eq,\,conditioning,operation,\,y} + 0.6 \cdot 0.2$$
$$\cdot mCO_{2eq,\,injection,operation,\,y} + 0.6 \cdot 0.2 \cdot mCO_{2eq,\,storage,operation,\,y})$$

Project 2:

The Amount of GHG that can be credited in own accounting or sold/transacted to third parties for Project 2 shall be calculated as follow:

$m_{CO2,\,credited,2,y}$

$$= mCO_{2,\,injected,2,y} - mCO_{2,\,released,2,y} - (mCO_{2eq,\,capture,operation,\,y}$$
$$+ mCO_{2eq,\,transport,operation,\,y} + X_{2,1} \cdot mCO_{2eq,\,conditioning,operation,\,y} + X_{2,1}X_{1-2,3}$$
$$\cdot mCO_{2eq,\,injection,operation,\,y} + X_{2,1}X_{1-2,3} \cdot mCO_{2eq,\,transport,operation,\,y})$$

where:

$$mCO_{2,injected,2,y} = (X_{1-2,3} \cdot X_{2,1}) \cdot mCO_{2,i,\,y}$$

$mCO_{2,released,2,y}$

$$= \sum_{j}(X_{1-2,3} \cdot X_{2,1}) \cdot mCO_{2,release,injection\ system,j}) + (X_{1-2,3} \cdot X_{2,1})$$
$$\cdot \sum_{k} mCO_{2,\,release\ event,injection\ system,k}$$

$m_{CO2,\,credited,2,y}$

$$= (0.6 \cdot 0.8) \cdot mCO_{2,i,\,y} - (\sum_{j}(0.6 \cdot 0.8) \cdot mCO_{2,release,injection\,system,j}) + (0.6 \cdot 0.8)$$

$$\cdot \sum_{k} mCO_{2,\,release\,event,injection\,system,k}) - (mCO_{2eq,\,capture,operation,\,y}$$

$$+ mCO_{2eq,\,transport,operation,\,y} + 0.8 \cdot mCO_{2eq,\,conditioning,operation,\,y} + 0.8 \cdot 0.6$$

$$\cdot mCO_{2eq,\,injection,operation,\,y} + 0.8 \cdot 0.6 \cdot mCO_{2eq,\,transport,operation,\,y})$$

Project 3:

The Amount of GHG that can be credited in own accounting or sold/transacted to third parties for Project 3 shall be calculated as follow:

$m_{CO2,\,credited,3,y}$

$$= mCO_{2,\,injected,3,y} - mCO_{2,\,released,3,y} - (mCO_{2eq,\,capture,operation,\,y} + X_{3,3}$$

$$\cdot mCO_{2eq,\,transport,operation,\,y} + X_{3,3} \cdot mCO_{2eq,\,conditioning,operation,\,y} + X_{3,3}$$

$$\cdot mCO_{2eq,\,injection,operation,\,y} + X_{3,3} \cdot mCO_{2eq,\,transport,operation,\,y})$$

where:

$$mCO_{2,injected,3,y} = (X_{3,3}) \cdot mCO_{2,i,\,y}$$

$mCO_{2,released,3,y}$

$$= \sum_{j}(X_{3,3}) \cdot mCO_{2,release,injection\,system,j}) + (X_{3,3})$$

$$\cdot \sum_{k} mCO_{2,\,release\,event,injection\,system,k}$$

$m_{CO2,\,credited,3,y}$

$$= (0.4) \cdot mCO_{2,i,\,y} - (\sum_{j}(0.4) \cdot mCO_{2,release,injection\,system,j}) + (0.4)$$

$$\cdot \sum_{k} mCO_{2,\,release\,event,injection\,system,k}) - (mCO_{2eq,\,capture,operation,\,y}$$

$$+ mCO_{2eq,\,transport,operation,\,y} + mCO_{2eq,\,conditioning,operation,\,y} + 0.4$$

$$\cdot mCO_{2eq,\,injection,operation,\,y} + 0.4 \cdot mCO_{2eq,\,transport,operation,\,y})$$

A7.3 Multi-Source Project equations and parameters

A7.3.1 Equation 1a: CO$_2$ credited during monitoring period

$$m_{CO2,\,credited,n,y} = mCO_{2,\,injected,n,y} - mCO_{2,\,released,n,y} - \sum_{p}^{P} X_{n,p,y} \cdot (mCO_{2eq,\,p,operation,\,y} + mCO_{2eq,p,\,embodied,y})$$

Parameter	$mCO_{2,credited,n,y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total amount of CO$_2$ credited in own accounting or sold/transacted to third parties from source n in period y.
Equations	Equation 1a
Source of data	NA
Calculation method/equations	Equation 1a
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited
Comments	-

Parameter	$mCO_{2,injected,n,y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total amount of CO$_2$ injected at the storage site from source n in period y, determined at the last monitoring point on the injection system.
Equations	Equation 1a and 2a
Source of data	NA
Calculation method/equations	Equation 2a
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	NA

Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited
Comments	-

Parameter	$mCO_{2,\text{released},n,y}$
Parameter type	Calculated
Data unit	tonne (tCO_2)
Description	Total amount of CO_2 released at the storage site from source n downstream of the last monitoring point on the injection system in period y.
Equations	Equation 1a
Source of data	NA
Calculation method/equations	Equation 3
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited.
Comments	-

Parameter	$mCO_{2eq,p,\text{operation},y}$
Parameter type	Calculated
Data unit	tonne (tCO_2)
Description	Total GHG emissions due to the multi-source project operations of the CCS/CDR value chain (CO_2 Capture, Transport, and Storage) in period y.
Equations	Equation 1a
Source of data	NA
Calculation method/equations	Equation 4
Description of measurement methods and	NA

procedures to be applied	
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited.
Comments	-

Parameter	$mCO_{2eq,p,embodied,y}$
Parameter type	Calculated
Data unit	tonne (tCO$_2$)
Description	Total GHG emissions due to construction and disposal of the CCS/CDR value chain of the multi-source project (CO$_2$ Capture, Transport, and Storage) scheduled for monitoring period *y*.
Equations	Equation 1a
Source of data	NA
Calculation method/equations	Equation 5
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	GHG reduction or CDR credited.
Comments	Embodied emissions from capture total 841 tCO$_2$ over the project life. LCA for transport and storage is pending and will be added to this amount.

Parameter	n
Parameter type	NA
Data unit	unitless
Description	CO$_2$ source from project proponent *n*.

Equations	Equation 1a
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

Parameter	p
Parameter type	NA
Data unit	unitless
Description	Process steps. These include the capture, transport, and storage steps in the CCS/CDR chain. If mixing of CO_2 stream occurs within the storage step, the storage can be further divided into the surface conditioning and injection facility steps.
Equations	Equation 1a
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA

Comments	NA

Parameter	y
Parameter type	NA
Data unit	days
Description	Monitoring period during which credits are produced.
Equations	Equation 1a and 2a
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

A7.3.2 Equation 2a: CO₂ credited during monitoring period

$$mCO_{2,injected,n,y} = \sum_i x_{n,i,y} \cdot mCO_{2,i,y}$$

Parameter	$mCO_{2,i,y}$
Parameter type	Calculated
Data unit	tonne (tCO₂)
Description	Mass of CO₂ injected at each injection well i in period y, determined at the last monitoring point on the injection system.
Equations	Equation 2a
Source of data	NA
Calculation method/equations	Equation 3
Description of measurement methods and procedures to be applied	NA

Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	-

Parameter	$X_{n,i,y}$
Parameter type	Calculated
Data unit	unitless
Description	Proportion of the CO_2 stream from source n entering the injection system i relative to the total amount of CO_2 entering the same process step in period y.
Equations	Equation 2a
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	-

Parameter	i
Parameter type	NA
Data unit	unitless
Description	Injection well(s)
Equations	Equation 2a and 6b
Source of data	NA

Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

A7.3.3 Equation 3: CO$_2$ credited during monitoring period
According to Equation 3.

A7.3.4 Equation 4: CO$_2$ credited during monitoring period
According to Equation 4.

A7.3.5 Equation 5: CO$_2$ credited during monitoring period
According to Equation 5.

A7.3.6 Equation 6b: CO$_2$ credited during monitoring period

$$mCO_{2,released,n,y} = mCO_{2,released,injection\ system,n,y} + mCO_{2,released,geological\ storage,n,y}$$

$$= \sum_j \left(X_{i,j,n,y} \cdot mCO_{2,release,injection\ system,j} \right) + X_{n,y}$$

$$\cdot \sum_k mCO_{2,\ release\ event,injection\ system,k}$$

Parameter	$mCO_{2,\ release\ event,injection\ system,j}$
Parameter type	Measured
Data unit	tonne (tCO$_2$)
Description	Mass of CO$_2$ released intentionally or unintentionally from the injection system downstream of the last monitoring point on the injection system during event *j*.
Equations	Equation 6b
Source of data	Quantification based on type of event.
Calculation method/equations	NA
Description of measurement methods and	The project proponent must show the amount released is negligible or quantify this amount based on type of event.

procedures to be applied	Any active injection well shall be fitted with a CO_2 sensor at its wellhead.
	For any occasion of $P_{BubblePoint}$ exceeding its limits, the injected mass of CO_2 leading to $P_{BubblePoint}$ exceeding its limits shall be attributed to this parameter.
Frequency of monitoring	At least monthly.
QA/QC procedures to be applied	Recalibration of any measurement equipment used for detection or quantification according to manufacturer specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 release
Comments	-

Parameter	$mCO_{2,\,release\,event,geological\,storage,k}$
Parameter type	Measured
Data unit	tonne (tCO_2)
Description	Mass of CO_2 released intentionally or unintentionally from the geological storage reservoir during event k.
Equations	Equation 6b
Source of data	Quantification based on type of event.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	The project proponent must show the amount released is negligible or quantify this amount based on type of event.
	Atmospheric or CO_2 surface flux measurements shall be carried out around the injection site. Any monitoring well producing significant volumes of water will be fitted with a CO_2 sensor.
	Any monitoring well producing significant volumes of water shall be fitted with a CO_2 sensor at its wellhead.
Frequency of monitoring	At least annually.
QA/QC procedures to be applied	Recalibration of any measurement equipment used for detection or quantification according to manufacturer specifications. If not available, according to industry best practice.
Justification of choice of data source	NA
Purpose of data	CO_2 release
Comments	-

Parameter	$X_{i,j,n,y}$
Parameter type	Calculated

Data unit	unitless
Description	Proportion of the CO_2 stream from source n injected into the injection well i relative to total amount of CO_2 injected into the injection well i during release event j in period y.
Equations	Equation 6b
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	-

Parameter	$X_{n,y}$
Parameter type	Calculated
Data unit	unitless
Description	Proportion of the CO_2 stream from source n injected into the injection system relative to total amount of CO_2 injected into the geological storage reservoir in period y.
Equations	Equation 6b
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	NA

Justification of choice of data source	NA
Purpose of data	CO_2 injection
Comments	-

Parameter	j
Parameter type	NA
Data unit	unitless
Description	CO_2 release event from the injection system.
Equations	Equation 6b
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA

Parameter	k
Parameter type	NA
Data unit	unitless
Description	CO_2 release event from the geological storage reservoir.
Equations	Equation 6b
Source of data	NA
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA

Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of data	NA
Comments	NA