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Geologically Stored Carbon

Methodology for CO_2 Removal

Puro Standard

2024

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Edition 2024 v. 1

Puro Standard
June, 2024

Contents

Glossary

> **REMARK:** This glossary provides only the most important definitions for the current methodology. Please note that further definitions are listed in the Puro Standard General Rules.

CO_2 Plume The extent of an underground injected CO_2 Stream, in three dimensions. More specifically, this refers to the CO_2 in the free phase, excluding e.g. CO_2 fully dissolved in water, or otherwise transformed through chemical reactions.

CO_2 Stream Carbon dioxide that has been captured either directly from the atmosphere or from an eligible biogenic source, together with incidental associated substances derived from the source materials and the capture process, or added to the stream to enable or improve the injection process. However, water added to the CO_2 for dissolution before or during injection is not considered as a part of the CO_2 stream (see also CO_2 *charged water*).

CO_2 Charged water Aqueous (water-dissolved) CO_2. In particular, this refers to CO_2 injected within its solubility trapping phase, i.e. when the CO_2 Stream is dissolved in water immediately before or during injection. As the CO_2 charged water is transported into the storage reservoir, the concentration of aqueous CO_2 decreases (e.g. due to mixing and chemical reactions) until an equilibrium with background reservoir water is reached. At this point, the water cannot be considered CO_2 charged anymore, delimiting the extent of underground CO_2 charged water in three dimensions.

Activity A practice or ensemble of practices that take place on a delineated area resulting in emissions or removals taking place. For example, a geological storage activity refers to all operations within the activity boundary of a particular geological CO_2 Removal project. An eligible activity is an activity that meets the qualification criteria in a given certification methodology or protocol.

Biomass Organic matter recently derived from the biosphere, including crops, waste of crops, organic municipal waste, organic waste from paper and alcohol/ethanol production, and other similar materials.

Bubble point pressure The pressure at which the first bubble of gas appears in a liquid at a specific temperature, particularly in the context of bubbles of gas (including CO_2) formed during the potential depressurization of water-dissolved CO_2 injected into the subsurface.

Equation of state An analytical expression relating the pressure, volume, and temperature of a pure substance or mixture, commonly utilized to describe the volumetric behavior, vapor/liquid equilibria, and thermal properties of substances in different conditions. Several different equations of state are commonly utilized in reservoir engineering, depending on the use case (e.g. thermodynamic properties modeled and type of reservoir fluids). Examples include the Soave-Redlich-Kwong (SRK) and Peng-Robinson (PR) equations of state.

External operator Any party (such as the capture site operator, the logistics operators, or the storage site operator), operating on behalf and at the direction of the CO_2 Removal Supplier for provision of services relating to the geological storage activity (however, not including the CO_2 Removal Supplier itself).

Geological Storage The permanent (at least 1000 years) containment of a gaseous, liquid, supercritical, or water-dissolved CO_2 Stream in subsurface geologic formations.

Geological Storage activity See *Activity*.

Output Volume of CO_2 Removal within a certain Monitoring Period which is eligible to receive CORCs. CORCs are always Issued for Net Carbon Dioxide Removal in the production process, which means that the total volume of Output is determined by subtracting the CO_2 emissions volume (generated directly or indirectly due to the production process or materials used, according to the applicable Methodology) from the CO_2 Removal volume.

Point source A specific, identifiable source of pollution or emissions that can be pinpointed to a single location or a limited, well-defined area.

Reversal event Any event which results in CO_2 or other greenhouse gases, or other substances defined in this methodology being either i) no longer securely stored in the storage reservoir (i.e. breach of permanent storage, such as leakage from the storage reservoir to underground sources of drinking water), or ii) released from the storage reservoir into the atmosphere (i.e. re-emission, such as intentional venting due to wellbore maintenance, or unintentional emissions through transmissive faults or fissures, or improperly sealed legacy wells).

Storage area The overall geological system comprising the geological storage reservoir(s) together with any overlying geological formations, covering the defined vertical and lateral limits of the CO_2 storage project.

Storage reservoir An underground geological formation, group of formations, or part of a formation, suitable for Geological Storage of CO_2.

Storage site The storage reservoir together with the surface and subsurface facilities required for the operation of the CO_2 storage project.

Sustainable biomass Biomass that has been sourced according to the sustainability requirements of this methodology and other Puro Standard Requirements.

Tonne (t) A unit of mass equivalent to 1000 kg, also known as 'metric tonne'. In this methodology, the word 'tonne' always refers to metric tonnes.

Acronyms

BECCS Bioenergy with Carbon Capture and Storage

Bio-CCS Biomass Conversion with Carbon Dioxide Capture and Storage[1]

CCS Carbon Dioxide Capture and Storage

CDR Carbon Dioxide Removal

CORSIA Carbon Offsetting and Reduction Scheme for International Aviation

DAC Direct Air Capture

DACCS Direct Air Carbon Capture and Storage

GHG Greenhouse Gas

GSC Geologically Stored Carbon

IPCC Intergovernmental Panel of Climate Change

NDC Nationally Determined Contribution

tCO_2e Tonnes of CO_2 Equivalents

Chemical species

CH_4 Methane

${CO_3}^{2-}$ Carbonate

H_2 Hydrogen

H_2O Water

H_2S Hydrogen sulfide

${HCO_3}^-$ Hydrogen carbonate, also known as bicarbonate

N_2 Nitrogen

N_2O Dinitrogen monoxide, also known as nitrous oxide

O_2 Oxygen

SO_2 Sulfur dioxide

SO_x Sulfur oxides in general

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[1] Note that technically, bio-CCS is broader than BECCS, because it also includes processes that do not generate exclusively bioenergy, but also biomaterials, food and feed products. However, BECCS and bio-CCS are in the context of this methodology used interchangeably.

Note to the reader

REMARK: This methodology provides general information as well as actual requirements which must be met by all projects seeking certification under the Puro Standard. Across the entire methodology, the requirements correspond to numbered rules with formatting conforming to the below example.

0.0.1 This is an example of a numbered rule. The requirements set within numbered rules must be followed by all projects seeking certification under the Puro Standard.

Please note that in addition to the requirements of this methodology document, all projects seeking certification under the Puro Standard must also comply with the Puro Standard General Rules and other Standard Requirements, as well as any applicable local laws, regulations, and other binding obligations.

For Puro Standard documents, see the Puro Standard documents library.

1

Introduction

1.1 Overview

This methodology sets the requirements for eligibility and quantification of the net CO_2 removal achieved over one thousand (1000)[2] years by storing eligible CO_2 streams in suitable geological storage sites, such as deep geological formations.

In this methodology, Geological Storage of Carbon (GSC) refers to the overall process of storing an eligible carbon dioxide (CO_2) stream in underground geological formations for the purpose of permanent CO_2 removal. However, the overall concept of 'geological storage' is not entirely uniform, but presents several potential variations in scope depending on various factors, such as:

- Type and origin of the stored CO_2 stream.
- Type and characteristics of the storage site.
- Type and mechanics of the injection process.

1.2 Scope

In broad terms, the scope of this methodology includes the following fundamental components: *capture*, *transport*, and *injection and storage* of eligible biogenic CO_2 streams, or CO_2 streams from direct air capture (DAC). All of the process steps (capture, transport, injection and storage) allow several different variations, which are summarized here and elaborated in further detail in section 3.

The capture of CO_2 can occur directly from the ambient atmosphere (Direct Air Carbon Capture and Storage, DACCS), as well as from the production of bioenergy utilizing eligible biomass (Bioenergy with Carbon Capture and Storage, BECCS). Furthermore, this methodology includes certain other (sub)types of carbon capture, such as CO_2 captured from the oxidation or fermentation of biogenic materials in industrial processes. In this methodology, carbon dioxide from fossil sources is not eligible (e.g. point source capture from a coal power plant), but mixed sources (e.g. waste + CCS) can be utilized as long as the non-eligible fraction is reliably quantified and accounted for.

The capture of the CO_2 stream rarely occurs at the storage site, and therefore needs to be transported from the capture site (e.g. a BECCS facility) to the location of the storage reservoir (e.g. a deep saline aquifer). Several potential methods with varying costs and capacity exist for the transport of CO_2 [1]. For small quantities, transport by truck or rail can be utilized. For larger quantities, transport by ship can be a feasible alternative for many regions in the world,[3] but often the *most efficient method* is via pipelines [2]. Pipelines to transport CO_2 are fairly

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[2] CO_2 must be sequestered (on a net basis) for *at least* 1000 years.

[3] Thus far, transportation of CO_2 by ship has been mainly used in the food and brewery industries [1], but can be utilized for GSC projects as well, as exemplified by the Northern Lights project, where a key component is the transport of CO_2 by ship to an offshore geological storage site.

common—although thus far heavily concentrated in the United States—and the development of many new pipelines around the world is underway or expected in the future [3]. Carbon dioxide is non-flammable and non-toxic, and generally safe to transport via pipelines (in proper conditions, e.g. adequately dehydrated to manage corrosion risks), as evidenced by low accident rates [2, 4].

As with the capture and transport, the injection and geological storage of CO_2 can be achieved through several means. For example, CO_2 can be injected into porous rock formations in geological basins, or into other suitable geological storage reservoirs. Dissolved carbon dioxide can also be injected into subsurface mafic and ultramafic formations for relatively rapid mineralization. Prior to injection, CO_2 gas is often pressurized into a liquid or supercritical fluid,[4] or dissolved in water [6, 7].

In general, there are several types of geological formations potentially capable of permanently storing CO_2, such as:

- Deep saline aquifers
- Depleted hydrocarbon reservoirs
- Mafic or ultramafic rocks (e.g. basaltic rocks)
- Unmineable coal seams
- Organic-rich shales

Out of the types listed above, the first three (deep saline aquifers, depleted hydrocarbon reservoirs, and mafic and ultramafic rocks) are considered as having the *most significant potential*, as all of them show vast storage capacity[5] and are abundantly present worldwide [6, 11, 12].

1.3 Examples of geological storage

Geological storage of CO_2 is not a new concept. In fact, carbon dioxide capture and storage (CCS) facilities have been deployed around the globe since at least 1971, and have thus far collectively captured and stored around 300 Mt of CO_2 [13]. The idea of utilizing geological formations in engineered greenhouse gas removal first surfaced in the late 1970s [14], although even before that, subterranean injections of CO_2 had been employed in the context of enhanced oil recovery [13, 15].

Further examples of early utilization of geological storage sites include CO_2 injection into a deep saline aquifer at the Sleipner gas field since 1996 [16], and injection of acid gas[6] into depleted hydrocarbon reservoirs in the Alberta basin in Canada, operationalized in 1990 [17].[7]

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[4] A supercritical fluid is a particular state of matter, which exhibits characteristics from both the gaseous and liquid phases, such as the generally low viscosity of a gas and the high density of a liquid [5]. Carbon dioxide becomes a supercritical fluid above its critical pressure and temperature (roughly 73 atm and 31 °C). Besides geological storage, supercritical CO_2 is commonly used e.g. in oil and gas industry applications (such as enhanced oil recovery), and as an industrial solvent.

[5] Although there is significant uncertainty in the estimations of global geological CO_2 storage capacity [8, 9], it is clear that the technically accessible CO_2 storage resources far exceed projections of aggregate demand for CO_2 storage capacity [8, 10].

[6] Acid gas is a mixture of CO_2 and H_2S (hydrogen sulfide) with minor traces of hydrocarbons. It is produced from certain oil and gas fields and must be removed before the product is sent to market.

[7] It should be noted that while both examples (the Sleipner gas field and acid gas injection) demonstrate utilization of geological CO_2 storage, they do not constitute as carbon removal as understood in this methodology due to the fossil origin of the injected CO_2. Furthermore, despite containing significant amounts of CO_2, the injection of acid gas was in fact originally motivated by the challenge of reducing atmospheric emissions of H_2S [17].

More recent years have seen the operationalization of several industrial scale CCS projects [13], such as the Archer-Daniels-Midland (ADM) ethanol production facility in Illinois, US [18, 19]. Since 2012, CO_2 dissolved in water has been injected into reactive basaltic rock formations for subsurface mineralization at Hellisheiði in Iceland [12].

Besides being a viable option for engineered greenhouse gas removal, GSC is also a natural phenomenon in the Earth's upper crust, which has been a part of the carbon cycle for hundreds of millions of years. Carbon-containing substances and CO_2 derived from chemical, biological or volcanic activities can naturally accumulate in subsurface environments and persist for extended periods of time in various forms. The subsurface is in fact by far the *largest carbon reservoir on Earth*, storing vast quantities of carbon in coals, oil, gas, organic-rich shales and carbonate rocks [20].

1.4 Operational principles

A CO_2 capture and storage process usually consists of the fundamental components introduced in section 1.2. For example, in a typical underground storage operation, CO_2 is captured, liquefied and transported to the storage site where it is pumped from a surface facility into a saline aquifer or other suitable deep host formation. The increased temperature and pressure on the way down the borehole will then cause the CO_2 to become a supercritical fluid, which is initially stored as a free phase within the host formation. Another possibility is that CO_2 and water are simultaneously pumped down, and carbon dioxide enters the host formation in a dissolved state.

It is important that the storage reservoir is located deep enough underground to ensure efficient and secure storage. The elevated temperature and pressure deep underground increase the density of CO_2, leading to efficient utilization of the underground storage space, and prevent e.g. the degassing of any dissolved CO_2. For the injection of pure (undissolved) CO_2, the pressure and temperature inside the storage reservoir *should be* high enough to maintain any injected CO_2 in a liquid or supercritical state.[8] The precise depth will depend on site specific factors such as the geothermal gradient (rate of temperature increase with depth), but suitable formations are usually found at depths greater than about 800 meters, where the natural temperature and fluid pressures are generally high enough for any injected CO_2 to reach a supercritical state [20]. When the CO_2 is dissolved in water prior to injection (for rapid mineralization), the reservoir pressure needs to be high enough to ensure efficient mineralization and prevent degassing, and slightly shallower (500–900 m) reservoirs have been utilized in this approach [12].

The maximum storage depth is mainly limited by cost and efficiency, as very deep sedimentary formations often lack sufficient porosity for large storage capacity, and sufficient permeability for high flow rates without overly high injection pressure [21, 22]. Some studies have suggested an optimal depth window of around 800–2500 m [21, 23–25], although CO_2 can be stored at depths greater than 4000 m if favorable reservoir conditions exist [26].

To mitigate climate impacts, it is critical that the injected CO_2 remains safely stored underground, and is not re-emitted back to the atmosphere. Once underground, the injected CO_2 can undergo a host of chemical and physical processes that affect its storage permanence, and it is therefore important that proper precautions are taken to guarantee safe and permanent geological storage. For example, a comprehensive characterization of the storage site[9] and careful screening via pilot

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[8] Note that storage is also possible at shallower depths as long as phase related considerations are properly addressed.

[9] Relevant characteristics include factors such as local geological, hydrogeological, and fluid chemical conditions, as well as any fractures, faults or inadequately plugged legacy boreholes where leaks might occur.

and simulated experimental trials [27, 28] are paramount in ensuring the *physical confinement* of the injected CO_2 and predicting how it will behave and migrate in the host formation over time.

In general, CO_2 is a fairly reactive substance, and its injection into the subsurface will result in a chemical disequilibrium and initiate multiple reactions which may help or hinder its *chemical confinement* [7, 29]. These reactions can be divided into several categories, such as reactions with the minerals in the geological host formation or the naturally occurring fluids within it, the caprock, the borehole materials, etc. The various CO_2–water–rock chemical reactions often help in trapping CO_2 securely for geologically important timescales (see section 1.5), but can in some instances also be deleterious, and aid the migration of CO_2. For example, reactions with basaltic rocks in the host formation can cause CO_2 to be trapped as solid carbonate minerals for geological timescales, but excessive precipitation might also block flow pathways needed to maintain high injection rates [30, 31]. Furthermore, mineral dissolution reactions might also open new flow pathways for CO_2 migration [6, 7]. In general, the types and rates of reactions that will occur depend upon various factors, such as the mineralogical composition of the surrounding rock, chemistry of the naturally occurring fluids, groundwater flow rates, and in-situ pressure and temperature [7].

1.5 CO_2 trapping mechanisms

Trapping of CO_2 refers to the processes through which it is retained underground in porous formations after injection. Effective trapping is fundamental to prevent leakages from the storage site and re-emission of greenhouse gases. There are multiple physical and geochemical mechanisms responsible for trapping CO_2 in geological storage sites. Four main types of trapping mechanisms are often discussed in the scientific literature [15]:

- **Structural trapping**: confinement of the mobile CO_2 phase due to changes in lithology or stratigraphy of the reservoir rock, such as local variations in rock type, porosity, or permeability. In practice, the mechanism refers to e.g. trapping of CO_2 under low-permeability caprocks. The related term known as *stratigraphic trapping*[10] is sometimes used in addition to structural trapping, but for the purposes of this methodology, the two can be treated together.
- **Residual trapping**: confinement in porous media as an immobile CO_2 phase by surface tension (capillary force). During injection and subsequent migration, CO_2 invades the pore matrix of the geological formation, and a considerable volume of CO_2 becomes trapped in small and narrow pore spaces where it remains permanently immobilized by capillary forces. Residual trapping separates the large continuous CO_2 plume into multiple tiny pockets with increased ratio of surface area to volume, thus encouraging e.g. the chemical reactions that improve long-term trapping security [32]. This mechanism has significant trapping potential in the short to mid-term timeframes (see figure 1), and is a dominant trapping mechanism in e.g. sedimentary formations [33, 34].
- **Solubility trapping**: confinement through the *in situ* dissolution of CO_2 into the naturally occurring fluids (such as oil, gas, or water) contained within the geological formation, i.e. the *formation fluid*. The primary benefit of solubility trapping is that the dissolved CO_2 is no longer driven upwards by the buoyant forces that affect CO_2 when it exists as a separate phase. Instead, the migration of dissolved CO_2 is controlled by the relatively slow deep groundwater flow patterns [7]. Furthermore, the dissolved CO_2 can undergo various chemical reactions that increase the stability of the stored carbon, such as the

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[10] Technically, structural traps are formed by tectonic deformation such as arching or faulting, while stratigraphic traps are caused by depositional differences between adjacent rock types. However, in many cases, traps cannot be clearly classified as either purely structural or stratigraphic, but rather a combination of the two.

formation of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions (i.e. *ionic trapping*), or solid carbonate minerals (*mineral trapping*).

- **Mineral trapping**: conversion of CO_2 to solid carbonate minerals through chemical reactions between CO_2 and the surrounding minerals. Mineral trapping of CO_2 is often considered the most secure and permanent form of trapping [20, 35, 36]. Many of the precipitation reactions have very slow kinetics, and significant mineralization often requires a long time to occur, in the order of thousands of years or more. However, under certain conditions mineral carbonation can be promoted by injecting dissolved CO_2 into reactive ultramafic, mafic, intermediate or silicic rock formations, achieving mineral trapping within as little as two years [12, 37].

In addition to these main trapping categories, several other mechanisms can be defined. These can be e.g. variations or subtypes of the ones listed above, or mechanisms relevant in certain particular conditions. Examples of such additional trapping mechanisms include:

- **Migration assisted trapping**: effective confinement due to very long travel times of the CO_2 fluid to the surface following injection, and the resulting sequestration due to e.g. residual or solubility trapping along the migration pathway (also referred to as hydrodynamic trapping) [38, 39]. The term is used to describe CO_2 that moves in the subsurface, as it finds its way from an injector to a structural trap. This mechanism is particularly relevant in laterally unconfined sedimentary basins with limited structural traps, but with large-scale flow systems and low groundwater and fluid flow rates [40]. Migration assisted trapping / hydrodynamic trapping is sometimes considered together with (or as a component of) structural trapping.
- **Adsorption trapping**: confinement resulting from the preferential adsorption of CO_2 molecules onto microporous surfaces, such as coal seams or organic-rich shales. This trapping mechanism is relevant in e.g. the enhanced production of coal bed methane due to the coal's higher adsorption preference for CO_2 relative to CH_4 [41].

The relative importance of the various trapping mechanisms varies with time and other factors such as reservoir type and injection mechanism (see figure 1). The *most important mechanism* in the short term is usually structural trapping, and it is often a prerequisite for a storage site because it prevents the leakage of CO_2 through the caprock during the time required for other trapping mechanisms to gradually come into effect. However, other mechanisms such as residual and solubility trapping can also provide significant contributions to short term trapping. In fact, certain types of reservoirs and/or injection practices might even render structural trapping unnecessary, such as when CO_2 is injected within its solubility trapping phase (i.e. CO_2 is fully dissolved in water immediately before or during injection, and the reservoir pressure is high enough to prevent outgassing).

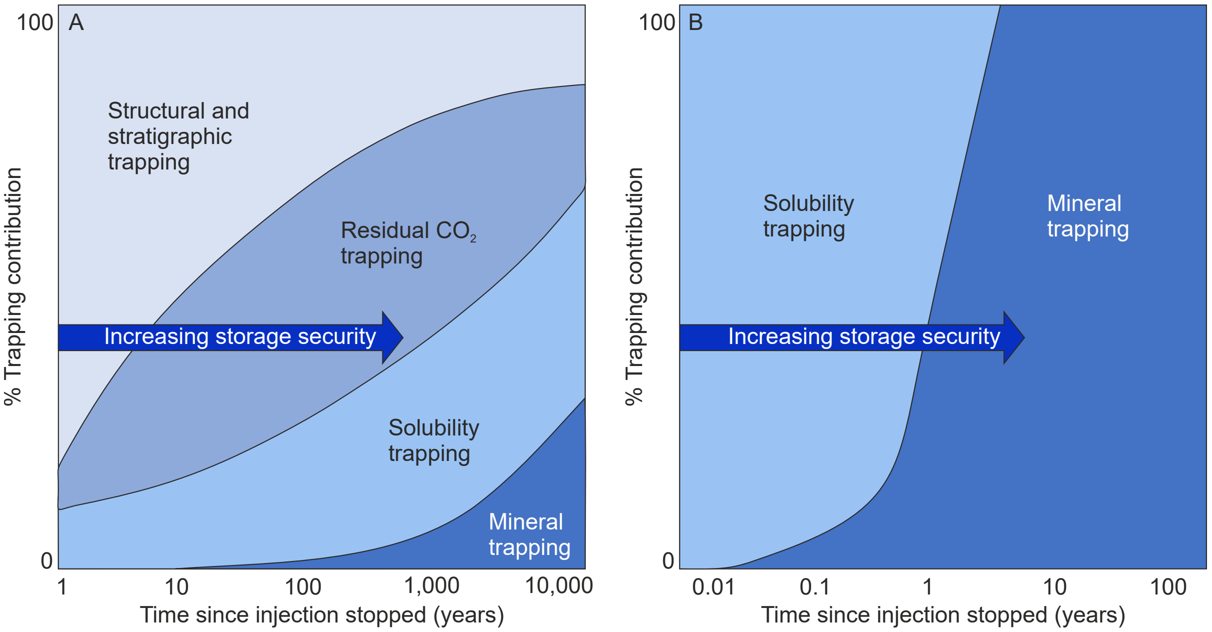

Figure 1: Various CO_2 trapping mechanisms with associated timescales and security of storage (after [12]). Part **A** (left) describes the injection of pure supercritical CO_2 into sedimentary basins, and part **B** (right) the injection of water-dissolved CO_2 for mineralization.

2

Point of creation of the CO_2 Removal Certificate (CORC)

2.1 CO_2 Removal Supplier

2.1.1 The CO_2 Removal Supplier is the party contractually authorized to represent the participants necessary to perform the end-to-end activities associated with a geological storage activity seeking certification under this methodology (see also section 3.3). Examples of entities commonly identified as the CO_2 Removal Supplier include but are not limited to the following:

- The operator of the carbon capture system.
- The owner of the carbon capture system.
- The owner of the captured CO_2.

In particular, the CO_2 Removal Supplier does not need to be the operator of the process creating the CO_2 to be captured (e.g. a biogas or bioenergy producer, or a waste treatment facility operator).

2.2 Production Facility and Crediting Period

2.2.1 The Production Facility is the ensemble of physical assets necessary to perform the end-to-end activities associated with a geological storage activity, and subject to the Production Facility Audit.[11] For the purposes of this methodology, a Production Facility comprises one or several capture sites, a logistic chain for carbon dioxide transport, and one or several storage sites, as further detailed in subrules a-c.

(a) All capture sites registered under the same Production Facility shall be similar in nature (e.g. feedstock, capture technology, CO_2 Removal Supplier), located in the same jurisdiction, and operational at the time of the Facility Audit.

(b) All storage sites registered under the same Production Facility shall be operational at the time of the Facility Audit.

(c) Any change in the definition of the Production Facility requested by the CO_2 Removal Supplier during the Crediting Period will require an update of the Production Facility Audit.

Note that in most cases, the Production Facility is composed of a single capture site, logistic chain, and storage site.

2.2.2 The Crediting Period in this methodology is 15 years starting from the first date of the first monitoring period (see rule 4.2.1). The Crediting Period can be renewed twice by successfully undergoing a new Production Facility Audit. The Crediting Period shall not overlap with another Crediting Period.

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[11] For more information regarding auditing, please see the Puro Standard General Rules, available in the Puro Standard documents library.

2.3 Point of creation

2.3.1 The point of creation of the CO_2 Removal Certificate (CORCs) is defined as the earliest point in the CO_2 Removal process when CORCs can be claimed. For this methodology, the point of creation of the CO_2 Removal Certificate (CORC) is the moment when the CO_2 Stream has been injected into the geological storage reservoir during the course of an eligible activity (see rule 3.2.1), and the data records thereof can be verified.[12]

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[12] Time of injection is here defined as the point when a complete data trail is available for verification of the end-to-end quantities captured and stored.

3

Eligibility Requirements

3.1 Overall principles

In broad terms, an eligible activity is capable of permanently increasing the geological carbon stock by safely and durably storing CO_2 captured directly from the atmosphere or from sustainable biogenic sources. In practice, the CO_2 Removal is achieved by injecting a CO_2 Stream into a geological storage reservoir (see figure 2).

It is important that the requirements for geological storage activities ensure permanent, robustly quantifiable CO_2 Removal, conducted in a manner which leads to no net harm[13] to the environment (e.g. deforestation or loss of biodiversity), or to society (through e.g. loss of arable land, decreased food security, chemical emissions, or health risks).

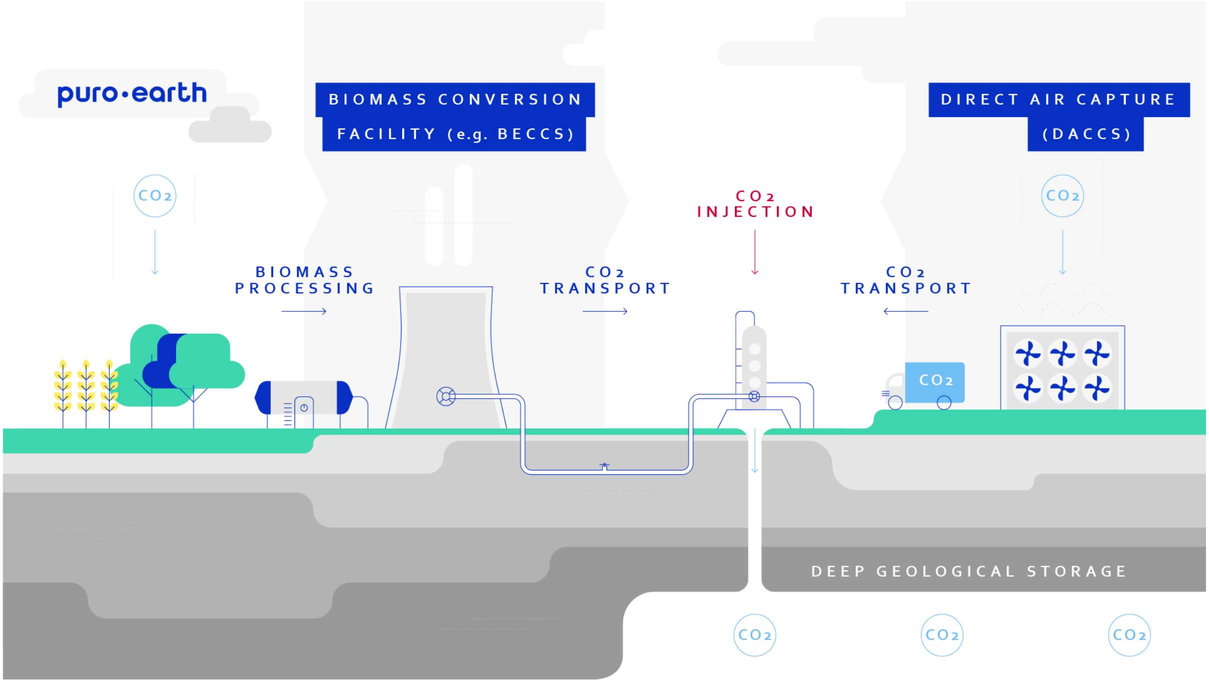

Figure 2: Schematic examples of CO_2 Removal activities within the scope of this methodology.

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[13] While the capture and geological storage of CO_2 has significant potential to help mitigate the global effects of climate change, it is paramount that the capture and storage activities are conducted in a manner such that the benefits outweigh the disadvantages.

3.2 Requirements for general eligibility

3.2.1 An **eligible activity** is an activity where an eligible CO_2 Stream (see rule 3.2.2) is sourced and subsequently injected into a suitable underground geological storage reservoir (see rule 3.2.6) under conditions which ensure the safe and durable storage of CO_2, preventing its re-emission back to the atmosphere for at least 1000 years (see also rule 8.5.3). The eligibility of the geological storage activity shall be determined during the Production Facility Audit.

3.2.2 An **eligible CO_2 Stream** shall consist overwhelmingly (at least 95% by volume) of carbon dioxide. In addition, the overall chemical composition of the CO_2 Stream (i.e. including CO_2 as well as any impurities and other substances) shall comply with all applicable local laws, regulations, and other statutory requirements, as well as all requirements imposed by relevant *external operators* (e.g. the storage site or pipeline operator, see section 3.3). The CO_2 Stream may furthermore contain:

- Incidental associated substances from the source, capture or injection process.
- Trace substances added to assist in monitoring and verifying CO_2 migration.
- Substances added to the stream to enable or improve the injection process.

The CO_2 Stream may also be dissolved in water or seawater immediately prior to or during injection, for the purpose of injecting CO_2 within its solubility trapping phase.

Note that the CO_2 Stream may contain carbon dioxide from both eligible and ineligible sources (see rule 3.2.3), but only the eligible fraction can be credited as CORCs (see rule 3.2.5).

3.2.3 The CO_2 injected into the geological storage reservoir shall be captured *directly from the atmosphere* or from a *sustainable biogenic source* as further detailed in subrules a and b (see also rules 3.2.4 and 3.2.5).

(a) The following are considered **eligible sources of CO_2** (insofar as subrule b is not violated):

- CO_2 from Direct Air Capture (DAC).
- Biogenic CO_2 from the thermochemical treatment (e.g. combustion, gasification, or pyrolysis) of biomass, bioliquids or biogas (e.g. BECCS, bio-CCS).
- Biogenic CO_2 from the incineration of biomass mixed with other substances (e.g. waste + CCS).
- Biogenic CO_2 from biological treatment of biomass (e.g. anaerobic digestion for biogas + CCS, alcoholic fermentation for ethanol + CCS).
- Biogenic CO_2 from other industrial processes (e.g. oxidation of biogenic materials).

(b) The following are considered **ineligible sources of CO_2**:

- Any CO_2 from fossil sources (i.e. any non-biogenic CO_2).[14]

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[14] Note that the presence of CO_2 from fossil sources (e.g. in the context of waste + CCS, or resulting from utilization of fossil start-up fuels or other ancillary fuels during biomass processing) in the captured CO_2 Stream does not *in general* disqualify the entire stream as long as the ineligible fraction is properly accounted for (see rules 3.2.5 and 4.4.5). However, biogenic CO_2 captured from activities relating to coal-fired electricity generation is not eligible (see below).

- Any CO_2 (even biogenic) captured from activities relating to coal-fired electricity generation (e.g. a BECCS facility which co-fires biomass with coal).

3.2.4 In the case where CO_2 is captured from a biogenic source, the CO_2 Removal Supplier shall demonstrate that the **biomass is sourced sustainably** in accordance with local regulations and other requirements detailed in this methodology (see section 3.7) or the Puro Standard.

3.2.5 Carbon dioxide captured from eligible, non-eligible, or mixed sources may be alternatingly or simultaneously injected into the same geological storage reservoir provided that the **ineligible fraction** of injected CO_2 is *reliably quantified* and *deducted* from the reported Output volume (see also rule 4.4.5).[15]

3.2.6 The CO_2 Stream shall be injected into an underground geological storage reservoir under conditions which ensure the safe and durable storage of CO_2, preventing its re-emission back to the atmosphere for at least 1000 years.[16]

The following general types of geological storage are eligible under this methodology:

- **Injection of pure CO_2**: Direct injection of a CO_2 Stream (see rule 3.2.2) into deep geological formations such as deep saline aquifers, salt caverns, or depleted hydrocarbon reservoirs (see rule 3.2.7). For increased storage efficiency and security, the temperature and pressure in the storage reservoir *should be* sufficient to maintain any injected CO_2 in a liquid or supercritical phase (see subrule 8.5.3 (a)).[17]
- **Injection of dissolved CO_2**: Injection of a CO_2 Stream (see rule 3.2.2) dissolved in water or seawater (i.e CO_2 charged water) into subsurface igneous (ultramafic, mafic, intermediate, or silicic) rock formations suitable for rapid mineralization. The injection of a dissolved CO_2 Stream shall occur in a manner which ensures immediate solubility trapping. Specifically, the pressure at the point of entry to the storage reservoir shall be greater than the bubble point pressure[18] of the injected liquid (see also rule 7.3.5). The temperature and pressure in the storage reservoir shall be sufficient to prevent degassing of CO_2.

The geological storage reservoir may be located either onshore or offshore. However, the CO_2 Stream must be injected into the Earth's crust, and shall not be stored in the water column (i.e. any body of water above the Earth's surface, such as the deep ocean), nor using any form of man-made buried container.

3.2.7 A **depleted hydrocarbon reservoir** may be utilized as a geological storage reservoir

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[15] For example, CO_2 from mixed sources (e.g. from exhaust or flue gases containing both fossil and biogenic sources of CO_2) can be injected to a geological storage reservoir, but only the biogenic fraction of CO_2 is eligible and can be credited as CO_2 Removal Certificates (CORCs).

[16] An extensive nonpermeable geological formation (e.g. caprock or salt dome) overlying the storage reservoir is a typical (but not ubiquitous) geological characteristic associated with storage reservoirs suitable for permanent CO_2 storage. For example, a caprock or similar is not necessary when a dissolved CO_2 Stream is injected under conditions which ensure immediate solubility trapping.

[17] The precise depth to maintain injected CO_2 in a liquid or supercritical phase depends on site specific parameters, but is usually greater than approximately 800 m (see section 1.4). Note that geological storage in reservoirs shallower than the aforementioned is possible (although not as efficient in terms of pore space utilization) provided that additional phase related risks are properly considered and addressed (see subrule 8.5.3 (a)).

[18] The *Bubble point pressure* is the pressure at which the first bubble of gas appears in a liquid at a specific temperature.

under conditions further detailed in subrules a and b.

(a) The CO_2 Removal Supplier shall evidence, to the satisfaction of Puro.earth, that no further hydrocarbon recovery from the storage reservoir will take place. For example, such evidence might include records of hydrocarbons previously produced, or proof that all existing hydrocarbon wells have been either plugged and abandoned, or converted into CO_2 injection wells and disconnected from any production systems (such as oil and gas separators).

(b) The reservoir pressure shall not exceed the original pressure of the reservoir except locally around injectors during injection and well stimulation, unless explicitly permitted in the applicable local legislative or regulatory requirements (such as operational limits specified in the storage permit or similar regulatory control document).

3.2.8 All **geological storage sites** shall be approved by the competent local authority or regulatory body and hold relevant permits for the injection and geological storage of CO_2.

3.2.9 All **installations and operations** relating to the geological storage activity shall comply with all applicable local laws, regulations, and other statutory requirements (including, but not limited to requirements for storage site characterization, injection operations, monitoring and reporting, as well as environmental, ecological, and social requirements).

3.2.10 All capture, transport, and storage **equipment** shall be constructed or installed according to national best practices and in compliance with statutory requirements. All installations shall be approved by local authorities and hold relevant permits for their operation.

3.2.11 The injection of a CO_2 Stream into a geological storage reservoir shall only take place in jurisdictions with a **robust legal framework** for the environmentally safe geological storage of carbon dioxide. The specific requirements for eligible jurisdictions are laid out in subrules a–c.

(a) The applicable legislation does not prohibit the geological storage of carbon dioxide.

(b) All the following jurisdictions are *a priori* considered as having a robust legal framework for the environmentally safe geological storage of carbon dioxide, provided that they fulfill subrule a:

- The United States of America
- Any member state of the European Economic Area (EEA) Agreement[19]
- The United Kingdom of Great Britain and Northern Ireland
- Canada, provided that the CO_2 storage site falls under the jurisdiction of at least one of the following provinces:[20]

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[19] The current members of the EEA Agreement are the member states of the European Union together with Iceland, Norway, and Liechtenstein. Note that currently (Nov 2023) certain member states of the EEA Agreement do not allow the geological storage of CO_2.

[20] Provinces in Canada own their subsurface resources (including the underground pore space where CO_2 is stored) and hold primary responsibility for regulating carbon management activities such as monitoring and oversight of CO_2 geological storage. Although there are federal responsibilities for certain aspects, such as cross-border (interprovincial and international) CO_2 transport by pipeline, Canada does not currently have a comprehensive

- Alberta
- Saskatchewan
- British Columbia

Note that this requirement relates specifically to the regulations governing operations at the storage site, and does not preclude e.g. the CO_2 capture facility from being located in another province.

(c) For any other jurisdiction fulfilling subrule a, except the ones explicitly mentioned in subrule b, the CO_2 Removal Supplier shall show that the applicable legal framework fulfills *all requirements* listed in table 1. Furthermore, Puro.earth reserves the right to determine the eligibility of a legal framework within the purview of subrule c based on evidence presented by the CO_2 Removal Supplier. The evidence shall be verified by the Facility Auditor.

Table 1: Requirements for a robust legal framework for the environmentally safe geological storage of carbon dioxide

Requirement	**EU CCS directive example**[a b]	**US CFR example**[a c]
The legal framework is designed for **permanent storage** of CO_2	Article 1.2	146.81(b)
The legal framework requires a **permit**, authorization, license, or equivalent regulatory control document for the operation of the storage site.	Article 6.1	144.11
The legal framework requires storage **site characterization** or other similar determination of minimum criteria of suitability for geological storage	Article 4.3	146.83
The legal framework includes a characterization of an **eligible CO_2 stream**	Article 12.1	146.81(d)
The legal framework requires appropriate **monitoring** of the injection facilities, the storage complex and the surrounding environment to ensure that the geologic storage project is operating as permitted and is not causing significant adverse effects.	Article 13	146.90
The legal framework requires at least periodical **reporting** to a competent authority to ensure that the geological storage project complies with storage permit conditions	Article 14	146.91
The legal framework includes requirements for **emergency and remedial response** in case of leakage or other significant irregularities	Article 16	146.94, 146.88(f)
The legal framework includes requirements for storage **site closure and post-closure site management**	Article 17	146.92, 146.93

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regulatory framework specific to CO_2 storage in areas of federal jurisdiction (i.e. federal lands and offshore) [42].

Table 1: Requirements for a robust legal framework for the environmentally safe geological storage of carbon dioxide (Continued)

Requirement	EU CCS directive example[a] [b]	US CFR example[a] [c]
The legal framework includes requirements for **financial responsibility** or other comparable mechanisms (e.g. transfer of responsibility to a competent authority) to ensure that the obligations arising under the issued geological storage permit can be met	Article 18, Article 19, Article 20	146.85

[a] The regulatory examples provided are not exhaustive and intended for information and clarification purposes only.
[b] Directive 2009/31/EC of the European Parliament and of the Council
[c] United States Code of Federal Regulations 40 CFR parts 144, and 146

3.2.12 The injected CO_2 Stream shall **not be utilized** for purposes other than permanent storage, including but not limited to:

- Injection for the purpose of current or future fossil fuel production (e.g. secondary hydrocarbon recovery and/or enhanced hydrocarbon recovery[21]). This includes both CO_2 injected during the actual hydrocarbon extraction phase as well as CO_2 injected before the extraction phase (e.g. for pressure maintenance) for the purpose of future hydrocarbon recovery.
- Injection for the purpose of recovering the stored CO_2 Stream for any reason, in full or in part, at any point in the future (i.e. temporary storage).

Note that the use of shared infrastructure is allowed to the extent laid out in rule 3.2.13.

3.2.13 The CO_2 Removal Supplier may utilize **shared infrastructure** for CO_2 transport, injection, or storage. Further requirements for the utilization of shared infrastructure is given in subrules a–c.

(a) Shared infrastructure may be utilized even if such infrastructure is also utilized for non-eligible activities. However, the geological storage reservoir itself shall not be utilized for enhanced hydrocarbon recovery or any other activities in violation of rule 3.2.12.[22]

(b) In cases where a part of the overall CO_2 Stream is utilized for non-eligible activities, the CO_2 Removal Supplier shall provide evidence that their CO_2 is intended for permanent storage in eligible storage sites. Such evidence shall be provided in the form of a contract or other binding arrangement.

(c) The CO_2 Removal Supplier shall provide evidence of the amount of CO_2 injected into an eligible storage reservoir. Such evidence shall be provided in the form of mass balance data from the infrastructure provider.

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[21] Enhanced hydrocarbon recovery refers to the practice of injecting substances such as CO_2, water, steam, or other chemicals into a storage reservoir for the purpose of recovering hydrocarbons additional to those produced by conventional methods of extraction. Enhanced hydrocarbon recovery covers such subtypes as enhanced oil recovery and enhanced coal bed methane recovery.

[22] For example, the CO_2 Removal Supplier may transport CO_2 along a pipeline which also serves an enhanced oil recovery site, but may not inject CO_2 into a reservoir from which oil is recovered.

3.3 Requirements for the CO_2 Removal Supplier

The activities associated with a particular geological storage project can involve multiple site operators collaborating within the project boundary. While the CO_2 Removal Supplier can act as the capture site operator, logistics operator and the storage site operator, the responsibility of these operations may also be transferred to *external operators* (see rule 3.3.2) by contractual agreements.

3.3.1 The CO_2 Removal Supplier shall provide a certified trade registry extract or similar official document stating that it is validly existing and in compliance with the legislation of the host jurisdiction.

3.3.2 The CO_2 Removal Supplier shall clearly establish and demonstrate the ownership of the CO_2 Removal project through either proof of direct ownership (in the form of contracts, authorization documents, or similar legally enforceable documents), or through contracts with external operators[23] where relevant. The CO_2 Removal Supplier shall retain its sole ownership of the permanently stored CO_2, except in cases where the transfer of ownership (e.g. to the storage site operator) is required by local regulations. However, the CO_2 Removal Supplier shall in all cases retain the sole right to the carbon removal resulting from the geological storage activity, in accordance with rule 3.6.1.

3.3.3 The CO_2 Removal Supplier shall provide, where applicable, evidence of valid permits, authorizations, licenses, or other equivalent regulatory control documents to operate any industrial facilities within the activity boundary, including but not limited to the storage site (see also rule 7.5.1). The CO_2 Removal Supplier shall furthermore provide evidence of possessing the rights to allow for appropriate monitoring at any stage within the activity boundary.

3.3.4 Where any part of the geological storage activity is contracted to an external operator, the CO_2 Removal Supplier shall establish a clear division of responsibilities and liabilities between the CO_2 Removal Supplier and the external operator, which shall at least address:

- Conducting the required monitoring activities, such as measuring device set-up, maintenance, and the monitoring of individual parameters.
- Preventive and corrective measures taken in case of a leakage, reversal or re-emission.
- Closure and post-closure requirements and expenses until the transfer of responsibility.

3.3.5 Where any part of the geological storage activity is contracted to an external operator, the CO_2 Removal Supplier shall provide the contractual information necessary for assessing compliance with this methodology, the Puro Standard General Rules and other Standard Requirements, as well as any applicable local laws, regulations, or other binding obligations. This information shall at least include:

- Certified trade registry extracts or similar official documents stating that any and all external operators are validly existing and in compliance with the legislation of the host jurisdiction.

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[23] For the purposes of this methodology, an external operator is defined as any party (such as the capture site operator, the logistics operators, or the storage site operator) operating on behalf and at the direction of the CO_2 Removal Supplier for provision of services relating to the geological storage activity.

- Documentation that the CO_2 Removal Supplier is in contractual agreement with the external operator for the purpose of achieving permanent CO_2 Removal.
- In the case of an external storage site operator, documentation establishing that the captured CO_2 Stream received by the storage site operator will be injected and permanently stored into an eligible geological reservoir.
- Proof of ownership to the CO_2 captured, transported or stored (see rule 3.3.2), and attestation of no claim where necessary as per rule 3.6.1.
- Documentation establishing the right to audit the relevant documents and equipment belonging to the external operator for the purposes of CORC Issuance.

3.3.6 The CO_2 Removal Supplier is responsible for ensuring that sufficient data is available and accessible for auditing and verification that the geological storage activity is compliant with the requirements of this methodology and other applicable Puro Standard Requirements, as well as any applicable local laws, regulations, and other binding obligations. This includes but is not limited to delivering the necessary data to assess the eligibility of the activities, and quantify the predicted net carbon removal. In particular, the CO_2 Removal Supplier shall provide all calculation functions and parameters utilized for the quantification of net CO_2 Removal in a clear and consistent manner.

3.4 Requirement for baseline demonstration

The baseline is a conservative scenario of what likely would have happened without the geological storage activity, and revenues from carbon finance. The baseline affects the determination of additionality (see section 3.5), leakage (see section 6), as well as certain supply-chain and land use change emissions (see section 5.2). This section defines a set of baseline scenarios for various different removal pathways.

For geological storage activities, the baseline scenario can be split to describe the three main process stages (i.e. capture, transport logistics, and storage). The common situations for each of the stages, which can have different implications for the certification of the activity, are described below:

- **Baseline for capture**: the capture facility can either be a newly built facility, or a retrofit of an existing facility (with several possible retrofit variants, such as feedstock conversion, capacity expansion, or increased operating hours).
- **Baseline for transport logistics**: the transport infrastructure can either be newly built specifically for CO_2 transport, or repurposed for CO_2 transport based on an existing asset. In practice, the transport infrastructure will often be shared among multiple suppliers of CO_2 and over time, more and more CO_2 capture facilities will be connected to such shared transport networks.
- **Baseline for storage**: similarly to transport logistics, the storage infrastructure can either be newly built specifically for CO_2 storage or repurposed for CO_2 storage based on an existing asset.

Among the three stages, the capture stage is the primary differentiator between activity types, and the corresponding baseline scenario has the most significant consequences for determination of leakage (see section 6). The other components of the baseline (transport logistics, and storage) primarily affect the manner in which supply-chain project emissions have to be addressed—in particular, the amortization of embodied emissions and direct land use change emissions (see section 5.2), as well as some components of leakage (ecological leakage, see section 6).

3.4.1 The CO_2 Removal Supplier shall select the applicable baseline scenario among the ones listed in rules 3.4.2 and 3.4.3 (see also rule 3.4.4). The CO_2 Removal Supplier shall furthermore demonstrate eligibility for the selected baseline where applicable (i.e. for baselines defined in rule 3.4.3).

3.4.2 For projects utilizing direct air capture with geological storage of carbon dioxide (i.e. DACCS projects), the CO_2 Removal Supplier shall select the unique baseline called **DACCS New built**. In this baseline, it is assumed that the carbon capture facility is not built, and the land meant for construction remains in its historic state (pre-project land use).

The CO_2 Removal Supplier shall specify whether the i) infrastructure for CO_2 transport, and ii) the infrastructure for the storage site are newly built specifically for CO_2, or repurposed for CO_2 based on an existing asset.

3.4.3 For all other projects besides those within the purview of rule 3.4.2 (i.e. bio-CCS projects including waste-CCS, see eligible sources of biogenic CO_2 in rule 3.2.3), a baseline shall be selected (and eligibility thereof demonstrated) among the ones listed in subrules a and b.

(a) **Retrofitting of an existing biomass conversion facility**. In this baseline, called **bio-CCS Retrofit**, it is assumed that:

- The biomass conversion facility already exists (and generates useful bioproducts, while CO_2 is emitted to the atmosphere), but it is not yet equipped with a carbon dioxide capture unit.
- The land where the biomass conversion facility is built is already converted, while other land meant for construction remains in its historic state (pre-project land use).
- The biomass use or land use from where biomass is sourced (if applicable) remains unchanged.

The CO_2 Removal Supplier shall specify whether the i) infrastructure for CO_2 transport, and ii) the infrastructure for the storage site are newly built specifically for CO_2, or repurposed for CO_2 based on an existing asset.

(b) **Construction of a new biomass conversion facility**. In this baseline, called **bio-CCS New built**, it is assumed that:

- Neither the biomass conversion facility nor the carbon capture facility are built.
- The land meant for construction remains in its historic state (pre-project land use).

For the determination of leakage (see section 6), the CO_2 Removal Supplier shall specify, on a project basis and where applicable:

- The previous use of the land where biomass is sourced from (e.g. biomass from forest land or agricultural land)
- The previous use of the biomass (i.e. biomass from recycling streams, e.g. manure, industrial wastes, food waste).

The CO_2 Removal Supplier shall furthermore specify whether the i) infrastructure for CO_2 transport, and ii) the infrastructure for the storage site are newly built or repurposed specifically for CO_2 removal activity based on an existing asset.

3.4.4 For a bio-CCS project to use the **bio-CCS New built** baseline, the CO_2 Removal Supplier shall demonstrate that the carbon capture unit has been installed within 48 months of the operational start of the biomass conversion facility. The operational start is defined as the initial commissioning date of the facility. Otherwise, the bio-CCS project must use the **bio-CCS Retrofit** baseline. Further requirements for special cases are given in subrules a and b.

(a) In the special case of energy facilities that have recently been converted from fossil fuel to biomass (100% conversion), the operational start of the facility is defined as the initial commissioning date of the converted facility.

(b) In the special case of biomass conversion facilities undergoing an expansion of their capacity (i.e. increased biomass consumption), while simultaneously installing a carbon capture unit, a case-by-case analysis shall be performed by the CO_2 Removal Supplier and the Issuing Body to select the appropriate baseline scenario.

3.5 Requirements for additionality

3.5.1 To demonstrate additionality, the CO_2 Removal Supplier shall demonstrate that the geological storage activity is not required by existing laws, regulations, or other binding obligations. Further, the CO_2 Removal Supplier must convincingly demonstrate that the CO_2 removals are a result of carbon finance, as further detailed in the Puro Additionality Assessment Requirements.[24]

3.6 Requirements for prevention of double counting

3.6.1 The CO_2 Removal Supplier shall ensure that the CO_2 removal is not double-counted in a manner which would infringe the Puro Standard General Rules. In particular, the General Rules entail that:

(a) The CO_2 Removal Supplier shall evidence that it has the sole right to claim CORCs from the CO_2 placed in storage, and that other parties involved in the supply chain have no such right. This can be evidenced by contracts or attestations exhibiting the relation between the involved parties.

(b) The CO_2 Removal Supplier or any party involved in the supply chain shall not associate any CO_2 removal claim (whether a marketing, branding, or footprint claim) to any other products or services delivered by the CO_2 Removal Supplier or involved party (including other types of environmental products, such as renewable energy certificates), unless the issued CORCs have been explicitly retired for this purpose.

(c) The CO_2 Removal Supplier or any party involved in the supply chain may still report their direct emissions and removals in other sectoral GHG inventories (e.g. mandatory national reporting for UNFCCC, or voluntary corporate reporting), making adequate disclosures regarding the issuance of CORCs.

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[24] Available in the Puro Standard documents library.

3.6.2 The CO_2 Removal Supplier shall evaluate whether the geological storage activity falls within the Nationally Determined Contributions (NDCs) commitments, or other net-zero plans of the host country[25] relevant to Article 6 of the Paris Agreement.[26]

In the case that the geological storage activity falls within the aforementioned net-zero plans of the host country, the CO_2 Removal Supplier shall request *authorization of use* for trading CORCs within the Article 6 of the Paris Agreement from the corresponding designated authority. To this end, the CO_2 Removal Supplier shall follow the Puro Standard Article 6 Procedures[27] to ensure proper reporting of the issuance, transfer, and retirement of CORCs, and to avoid double counting between national emission balances and other international mitigation purposes such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), or other entities operating in the voluntary carbon market.

3.7 Requirements for biomass sustainability and traceability of origin

3.7.1 For all bio-CCS projects, including waste-CCS (see eligible sources of biogenic CO_2 in rule 3.2.3), the CO_2 Removal Supplier shall demonstrate and keep records (i.e. traceability, chain of custody) of the **origin and type** of the biomass feedstock in order for the resulting CO_2 to be considered eligible. Any share of biomass feedstock for which origin or type cannot be demonstrated will not be eligible, and thereby its share of CO_2 will be excluded from the quantification of CORCs (see section 4.4, term F_{eligible}). Demonstration of biomass feedstock origin applies regardless of the baseline scenario (see section 3.4). The CO_2 Removal Supplier shall demonstrate the origin and type of the biomass feedstock processed in accordance with the latest version of the *Puro Biomass Sourcing Criteria*.[28]

3.7.2 For all bio-CCS projects, including waste-CCS (see eligible sources of biogenic CO_2 in rule 3.2.3), the CO_2 Removal Supplier shall demonstrate and keep records of the **sustainability** of the biomass feedstock in order for the resulting CO_2 to be considered eligible. Any share of biomass feedstock for which sustainability cannot be demonstrated will not be eligible, and thereby its share of CO_2 will be excluded from the quantification of CORCs (see section 4.4, term F_{eligible}). Demonstration of biomass feedstock sustainability applies regardless of the baseline scenario (see section 3.4). The CO_2 Removal Supplier shall demonstrate the **sustainability** of the biomass feedstock processed in accordance with the latest version of the *Puro Biomass Sourcing Criteria*.[29]

3.7.3 For all bio-CCS projects, including waste-CCS, the CO_2 Removal Supplier shall categorize the biomass feedstock utilized for the geological storage activity into one or several of the categories described in subrules a-o.

(a) The non-sorted organic fraction of mixed solid waste, from normal municipal waste collection service, from collection of assimilated waste from e.g. offices, companies, hospitals, as well as refuse derived fuel and assimilated

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[25] The host country is defined as the country under whose jurisdiction the CO_2 Removal project operates and issues mitigation outcomes (i.e. CORCs).

[26] Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Addendum. Part two: Action taken by the Conference of the Parties at its twenty-first session (a.k.a the Paris agreement). FCCC/CP/2015/10/Add.1

[27] Available in the Puro Standard documents library.

[28] Available in the Puro Standard documents library.

[29] Available in the Puro Standard documents library.

industrial waste. This feedstock category is typically processed in solid waste incinerators.

(b) Post-consumer source-separated food waste, post-production food waste, expired food, residues from food processing, other industrial food-related biowaste (e.g. sugar molasses, cooking oils), or other farm-level food-related waste (e.g. spoiled food or feed harvest, expired seeds).

(c) Post-consumer end-of-life paper, end-of-life textile, end-of-life wood materials (of different grades, e.g. untreated and treated), and assimilated biomaterials, from source-separated waste collection.

(d) Non-hazardous municipal green waste from urban or rural areas (e.g. park and garden green waste, urban tree cuttings, river debris), including any fractions (e.g. foliage, roots, branches).

(e) Abattoir waste and animal manure (typically processed via biological treatment, anaerobic digestion or fermentation) and its derivatives (e.g. digestate from manure and abattoir waste).

(f) Sewage sludge and biosolids from municipal wastewater treatment.

(g) Forest biomass, including any primary feedstock (harvested from forest land) or secondary feedstock (generated during processing of primary feedstock).

(h) Pulp and paper mill sludge and black liquor, derived from processing of virgin fibers, recycled fibers or combination of sources.

(i) Agricultural crops that are neither food nor feed crop (e.g. energy crops, biomaterial crops), cultivated on agricultural land.

(j) Agricultural crops that are food or feed crops, whether or not used in such applications (e.g. corn or wheat fermented for biofuel, cereals fermented for beverage production), cultivated on agricultural land.

(k) In-field agricultural residues, originating from the cultivation of a food or feed crop, e.g. cereal straw, rice straw, maize straw, stalks, pruning residues (trees, bushes).

(l) Non-field agricultural residues, originating from the primary processing of a food crop in a factory, e.g. rice husk, maize cob, nut shell and husk, peels, fruit seeds, bagasse, coffee husk, cocoa pods.

(m) Any biomass from palm tree plantations (which are not considered forests but agricultural plantations), e.g. palm oil and its fractions, empty fruit bunches, nuts and kernels, cakes, or other side-streams.

(n) Invasive species whether on land, in freshwater, or in coastal areas, as well as any biomass from landscape management for conservation purposes of protected areas or assimilated, including forest wildfire mitigation.

(o) Cultivated or harvested water-based plants or algae, and associated derivatives.

The list above is derived from the *Puro Biomass Sourcing Criteria,* in which type, origin and sustainability criteria are further defined. Note that the biomass sourcing criteria only address the *eligibility of the feedstock*, and that the methodology imposes further requirements for eligibility, and other aspects related to the feedstock (e.g. baseline and leakage).

REMARK ON THE *PURO BIOMASS SOURCING CRITERIA*: The Puro Biomass Sourcing Criteria are issued alongside the GSC methodology, but are meant to be ultimately applicable across all biomass-based CDR methodologies within the Puro Standard. The criteria will be refined and extended over time and the latest version of those criteria shall always be used when reporting CORCs.

The criteria distinguish (at time of publishing) between 15 categories of biomass feedstocks. For each feedstock category, the document details:

- Required feedstock origin and type disclosures (traceability),
- Required feedstock sustainability criteria,
- Options to evidence the sustainability criteria.

For certain feedstocks (e.g. post-consumer waste streams), the rules are limited to origin and type disclosures. For other feedstocks, such as forest biomass or purpose-grown biomass of different kinds, strict sustainability criteria apply covering both environmental and social aspects.

In practice, the CO_2 Removal Supplier must keep records of the biomass processed, alongside all information needed to demonstrate type, origin and sustainability. This information shall then be synthesized as part of the Output Audit procedures. Puro will make templates available to suppliers, to facilitate the reporting of this information.

3.8 Requirements for environmental and social safeguards

Please note that the Puro Standard General Rules contain the general requirements on environmental and social safeguards that apply to all methodologies (see also rule 3.8.1), while this section contains further details relevant to geological storage activities in particular.

3.8.1 The CO_2 Removal Supplier shall have in place, maintain, and abide by environmental and social safeguards to the extent required by this methodology, the Puro Standard General Rules, or any applicable local statutory requirements, in order to ensure that the geological storage activities do no net harm to the surrounding natural environment or local communities.

3.8.2 The CO_2 Removal Supplier shall provide all environmental permits, assessments, and other documents related to the analysis and management of environmental and social impacts of the geological storage activities that are required by the applicable local laws and regulations.

3.8.3 The CO_2 Removal Supplier shall undertake an assessment of the environmental and social impacts of the geological storage activities.

(a) The scope of the assessment shall cover all stages (capture, transport, and injection) within the activity boundary (see rule 5.2.6).

(b) The assessment shall include at least the following components:

- Description of the applicable legal and regulatory framework pertaining to the assessment and management of the environmental and social impacts of the geological storage activities.
- Description of the existing local environmental and socio-economic conditions (i.e. background information on the current environmental

and socio-economic context in which potential impacts are assessed).

- Description of the geological storage activity in detail, including construction, operation, and decommissioning of infrastructure, and other aspects affecting the assessment of environmental and social impacts.
- Description of the anticipated environmental and social impacts. For example, such impacts might include any potential negative effects to:
    - Soil, air, and water quality (e.g. hydrological cycles, physical and biogeochemical properties).
    - Flora and fauna (e.g. biodiversity, habitats).
    - Human health and safety.
    - Socio-economic factors (e.g. related to land use or water resources).
    - Local communities (e.g. due to noise, vibration, and other nuisance factors, or induced seismicity).
    - Sites of cultural significance.
- Description of the measures to mitigate the identified environmental and social impacts, including where relevant a description of the parameters and methods utilized to monitor the potential impacts.
- Description of public participation and consultation.

To address the above components partly or in full, the CO_2 Removal Supplier may utilize and refer to other documents (e.g. project description documents, stakeholder engagement reports, or legally mandated environmental and social impact assessment documents) containing the required information, provided that such additional documents are also included.

3.8.4 The CO_2 Removal Supplier shall record and disclose to the Issuing Body any negative environmental or social impacts (or claims thereof) occurred during the monitoring period, including but not limited to any legal actions and/or other written complaints filed by affected parties.

3.8.5 The CO_2 Removal Supplier shall comply with all applicable local laws and regulations relating to access and consumption of water resources. The CO_2 Removal supplier shall furthermore recognize, respect and promote the human rights to safe drinking water and sanitation[30] as well as the right to water as laid out in the General Comment No. 15 of the United Nations Committee on Economic, Social and Cultural Rights.[31] In particular, the CO_2 Removal Supplier shall not endanger the *availability*, *quality*, or *accessibility* of the local water supply, as defined in article 12 of General Comment No. 15.[32]

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[30] The human rights to safe drinking water and sanitation, G.A. Res 78/206, U.N. Doc. A/RES/78/206 (Dec. 22, 2023).

[31] General Comment No. 15 (2002), The right to water (arts. 11 and 12 of the International Covenant on Economic, Social and Cultural Rights), U.N. Doc. E/C.12/2002/11 (Jan. 20, 2003).

[32] Ibid., p. 5.

3.8.6 The CO_2 Removal Supplier shall prepare and abide by a plan to assess and mitigate exposure to harmful chemicals (including but not limited to CO_2). The plan shall contain at least the following elements related to environmental risks and human health risks:

(a) Identification and listing of any potentially harmful chemical compounds, such as sorbents and solvents (e.g. amines), used at any stage within the activity boundary.

(b) Risk assessment and mitigation measures for chemical injuries (for example, due to inhalation, ingestion, or skin contact) considering all relevant exposure pathways (see also section 8.5 for general requirements on risk management).

(c) Based on the local statutory requirements, a determination of threshold exposure values and/or other limit values to prevent chemically induced diseases (whether through direct exposure, or indirect exposure such as through environmental contamination where relevant), and a description of the measures to limit and monitor the exposure to harmful chemicals.

(d) Identification of any potential pathways for chemical spills or leakages, and a description of the measures to prevent leakages and mitigate any harm to the environment or human health.

(e) Emergency preparedness plan, including appropriate response procedures in case a chemical spill, leakage, or other release event has occurred. The plan shall at least address:

- How to prevent any further damage.
- Equipment and methods for cleanup.
- Evacuation zones and procedures.
- First-aid procedures.

3.9 Requirements for positive sustainable development goals impacts

Please note that the Puro Standard General Rules and the associated SDG Assessment Requirements[33] contain the general requirements related to describing and evidencing positive impacts on Sustainable Development Goals (SDGs)[34] that apply to all methodologies. For example, in the context of geologically stored carbon, positive SDG impacts might be related to targets such as increased renewable energy production (SDG target 7.2); improved sustainability of industries (SDG target 9.4); or reduced adverse environmental impact of cities (SDG target 11.6).[35]

3.9.1 The CO_2 Removal Supplier shall provide descriptions, evidence, and information on the positive impacts of the geological storage activity on Sustainable Development Goals in accordance with the Puro Standard General Rules and other Standard Requirements

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[33] Available in the Puro Standard documents library.

[34] Resolution adopted by the General Assembly on Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development, G.A. Res 78/206, U.N. Doc. A/RES/71/313 (Jul. 6, 2017). Note that this original SDG indicator framework is subject to regular updates, and has since been revised several times.

[35] For a list of currently up to date SDG targets, see the current official SDG indicator list hosted at the United Nations Statistics Division website. Furthermore, the United Nations Department of Economic and Social Affairs website provides a browsable SDG indicator list.

(in particular, the SDG Assessment Requirements). Specifically, the Puro Standard General Rules entail that:

(a) The CO_2 Removal Supplier shall provide **qualitative descriptions** of expected positive impacts on Sustainable Development Goals (SDGs) before the Production Facility Audit.

(b) The CO_2 Removal Supplier shall provide **qualitative and quantitative evidence** of positive impacts on SDGs for the Output Audit based on the SDG Assessment Requirements provided by the Issuing Body.

(c) The CO_2 Removal Supplier shall, where feasible, provide **information** on how the geological storage activity is consistent with the relevant SDG objectives of the host country.

4

Quantification of CO_2 Removal Certificates (CORCs)

4.1 General principles

In general, a CORC represents net 1 tonne CO_2e removed from the atmosphere. In the specific case of geologically stored carbon, the CO_2 removal results either from the physical removal of existing CO_2 from the atmosphere (DACCS), or from the interruption of a short-term carbon cycle by preventing CO_2 emissions from biomass decomposition (BECCS and other biogenic CCS approaches).

The overall principle of the CORC calculation (see figure 3) is that the CO_2 Removal Supplier first determines the gross amount (in metric tonnes) of CO_2 injected into the geological storage reservoir over a given monitoring period. Various deductions are then made, such as supply chain *emissions*, any potential *re-emissions*, and the effect of any unmitigated negative ecological, market, and activity-shifting *leakage*. The resulting net amount of carbon sequestered is converted to CO_2 equivalents and credited as CORCs. More details on the method of calculation are given in this section. For ease of reference, a summary of the variables utilized in this section can be found in table 2 at the end of this section.

$$\underbrace{\text{CORCs}} = \underbrace{C_{\text{stored}}} - \underbrace{E_{\text{project}}} - \underbrace{E_{\text{leakage}}} - \underbrace{E_{\text{reversal}}}$$

	CORCs	C_{stored}	E_{project}	E_{leakage}	E_{reversal}
Description	Net amount of CO_2 equivalents removed by the geological storage activity.	Gross amount of eligible CO_2 stored into the geological storage reservoir.	Total life cycle emissions arising from the whole supply chain of the geological storage activity.	Total GHG emissions due to unmitigated negative ecological, market, and activity-shifting leakage.	Total GHG emissions from the geological storage reservoir, if any.
Units	Tonnes of CO_2e	Tonnes of CO_2	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e

Figure 3: The CORC calculation equation.

4.2 Requirements for robust quantification of carbon removal and net-negativity

4.2.1 The length of the monitoring period can be decided by the CO_2 Removal Supplier, but shall *not exceed* one (1) year.

4.2.2 The CO_2 Removal Supplier shall follow robust and auditable measurement practices and protocols for the data needed for the calculation of the quantity of CORCs resulting from the geological storage activity.

4.2.3 The CO_2 Removal Supplier shall provide a life cycle assessment (LCA) quantifying the greenhouse gas emissions related to the geological storage activity, as per the scope and system boundaries defined in section 5, and following the general LCA guidelines described in the ISO 14040/44 standards.[36]

4.2.4 The CO_2 Removal Supplier shall calculate the amount of sequestered carbon in the form of CO_2 Removal Certificates (CORCs) for each monitoring period, as per the requirements detailed in section 4 (see especially rule 4.3.1).

4.2.5 The CO_2 Removal Supplier shall have in place, maintain, and utilize an information system to keep records of any events affecting the amount of CORCs resulting from the geological storage activity.[37] These records shall include time stamped, quantitative information such that their effect on the Output volume of the monitoring period can be quantified. These records shall be available to the Auditor for the Production Facility Audit and Output Audits.

4.2.6 The CO_2 Removal Supplier shall explicitly show, through comparison of data records, that the amount of CORCs (i.e. the total net amount of CO_2 removed, see rule 4.3.1) during a monitoring period does not exceed the amount (in tCO_2) of eligible CO_2 captured during the same monitoring period.

4.2.7 The CO_2 Removal Supplier shall ensure that any instrumentation used for data collection is in place and adequately calibrated at all times (see also rule 7.2.8). The data records shall be kept in a reliable data system (see also rule 4.2.5).

4.3 Overall equation

4.3.1 The overall number of CORCs (i.e. the total net amount of CO_2 removed) during a monitoring period shall be calculated as follows (see also figure 3 for an illustration):

$$\text{CORCs} = C_{\text{stored}} - E_{\text{project}} - E_{\text{leakage}} - E_{\text{reversal}} \tag{1}$$

Variable	Description	Unit
CORCs	Net amount of CO_2 equivalents removed by the geological storage activity.	tCO_2e
C_{stored}	Gross amount of eligible CO_2 stored into the geological reservoir. Further requirements on the calculation of this term are given in section 4.4.	tCO_2
E_{project}	Total life cycle emissions arising from the whole supply chain of the geological storage activity. Further requirements on the calculation of this term are given in section 4.5.	tCO_2e
E_{leakage}	Total GHG emissions due to unmitigated negative ecological, market, and activity-shifting leakage resulting from the geological storage activity. Further requirements on the calculation of this term are given in section 4.6.	tCO_2e
E_{reversal}	Total GHG emissions from the geological storage reservoir, if any. Further requirements on the calculation of this term are given in section 4.7.	tCO_2e

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[36] ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework and ISO 14044:2006 Environmental Management - Life cycle assessment - Requirements and guidelines

[37] Examples of such events include any injection or re-emission events, as well as the construction or replacement of any facilities, machinery or equipment (which would affect overall supply chain emissions).

4.4 Carbon dioxide stored (C_{stored})

4.4.1 The gross amount of eligible CO_2 stored into the geological reservoir (C_{stored}) shall be calculated as follows

$$C_{\text{stored}} = (C_{\text{injected}} - E_{\text{released}}) \times F_{\text{eligible}} \times F_{\text{supplier}} \tag{2}$$

Variable	Description	Unit
C_{stored}	Gross amount of eligible CO_2 stored into the geological reservoir.	tCO_2
C_{injected}	Total amount of CO_2 injected at the storage site determined at the last monitoring point on the injection system.	tCO_2
E_{released}	Total amount GHGs released from the injection system downstream of the last monitoring point, but prior to final geological storage (i.e. injection leaks, such as accidental CO_2 leaks due to equipment failure, or other fugitive emissions during injection).	tCO_2e
F_{eligible}	Fraction of eligible CO_2 in the CO_2 Stream of the CO_2 Removal Supplier.	% mass
F_{supplier}	Fraction of the total gross amount of injected CO_2 attributed to the CO_2 Removal Supplier (e.g. when CO_2 Streams from several different operators are simultaneously injected into the same storage reservoir).	% mass

4.4.2 The CO_2 Removal Supplier shall quantify the total amount of CO_2 injected into the storage reservoir (C_{injected}) through direct measurements of the flow (either mass or volumetric flow, see subrule 4.4.7 (a)) and composition of the injected CO_2 Stream.

(a) In case mass flow measurements are utilized, C_{injected} shall be calculated as

$$C_{\text{injected}} = m_{\text{fluid}} \times F_{CO_2} \tag{3}$$

(b) In case volumetric flow measurements are utilized, C_{injected} shall be calculated as

$$C_{\text{injected}} = V_{\text{fluid}} \times Q_{CO_2} \times \rho_{CO_2} \tag{4}$$

Variable	Description	Unit
C_{injected}	Total amount of CO_2 injected at the storage site, determined at the last monitoring point on the injection system.	tCO_2
m_{fluid}	Total mass of fluid injected at the storage site determined at the last monitoring point on the injection system.	tonnes
F_{CO_2}	Mass fraction of CO_2 in the injected fluid.	% mass
V_{fluid}	Total volume of fluid injected at the storage site, determined at the last monitoring point on the injection system, and at the CO_2 Removal Supplier's chosen reference conditions (see subrule 4.4.7 (b)).	m^3

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Variable	Description	Unit
Q_{CO_2}	Volume fraction of CO_2 in the injected fluid at the CO_2 Removal Supplier's chosen reference conditions (see subrule 4.4.7 (b)).	% vol
ρ_{CO_2}	Density of CO_2 at the CO_2 Removal Supplier's chosen reference conditions (see subrule 4.4.7 (b)).	tCO_2/m^3

4.4.3 The CO_2 Removal Supplier shall quantify the mass or volume fraction of CO_2 in the injected fluid (F_{CO_2} or Q_{CO_2}, see rule 4.4.2) through direct measurement of the CO_2 concentration of the CO_2 Stream in accordance with rule 7.3.4.

4.4.4 The CO_2 Removal Supplier shall quantify any injection leaks ($E_{released}$). The term E_{released} is defined as the amount of greenhouse gases attributable to the CO_2 Removal Supplier (in tCO_2e) released from the injection system downstream of the last monitoring point (i.e. from equipment located *on the surface* between the flow meter used to measure injection quantity and the injection wellhead).[38]

(a) In cases where the flow meter measuring injection is placed directly on the injection wellhead(s), the value $E_{\text{released}} = 0\,tCO_2e$ shall be utilized.

(b) In all other cases besides those within the purview of subrule a, the value of E_{released} shall be calculated as

$$E_{\text{released}} = F_{\text{supplier}} \times E_{\text{total released}} \tag{5}$$

(c) In all other cases besides those within the purview of subrule a, the CO_2 Removal Supplier shall determine the value of $E_{\text{total released}}$ in accordance with applicable local regulations[39] or, if no such regulations exist, by any of the following methods:

- Documentation from the storage site operator quantifying the value of $E_{\text{total released}}$ and specifying the method of quantification.
- Direct measurement (e.g. if the injection wellhead and other infrastructure after the last monitoring point are located in an enclosed space, where gas sensors can effectively detect release).
- Conservative estimation (e.g. via component specific emission factors for potentially leaking equipment).

(d) The term E_{released} **shall not include** emissions from the geological storage reservoir itself (e.g. through fissures or inadequately plugged legacy injection wells), which are classified as reversals, and quantified in the term E_{reversal} (see section 4.7).

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[38] Examples of injection leaks include unintentional leaks from equipment such as fittings, flanges, valves, connectors, or meters (e.g. due to equipment failure), as well as any vented CO_2 (e.g. for safety reasons from a pressure release device), and other fugitive emissions during injection.

[39] For example, a geological storage project in the United States might fall under the reporting requirements of 40 CFR 98.443(f)(2), which further references 40 CFR Part 98 Subpart W for determination of equipment leaks and vented emissions.

Variable	Description	Unit
E_{released}	The amount of greenhouse gases attributable to the CO_2 Removal Supplier released from the injection system downstream of the last monitoring point.	tCO_2e
F_{supplier}	Fraction of the total gross amount of injected CO_2 attributed to the CO_2 Removal Supplier (see rule 4.4.6)	% mass
$E_{\text{total released}}$	The amount of total greenhouse gases released from the injection system downstream of the last monitoring point.	tCO_2e

4.4.5 The CO_2 Removal Supplier shall quantify the mass fraction of eligible CO_2 in the captured CO_2 Stream (F_{eligible}, see also rule 3.2.5) based on the eligibility of the CO_2 source (see rule 3.2.3) as well as the eligibility of any biomass feedstocks utilized (see rules rules 3.7.1 and 3.7.2), as further detailed in subrules a–d.

(a) For CO_2 Streams captured directly from the atmosphere (DAC), the value of F_{eligible} shall be determined as

$$F_{\text{eligible}} = F_{\text{eligible source}} \tag{6}$$

(b) For all other CO_2 Streams besides those captured directly from the atmosphere, the value of F_{eligible} shall calculated as

$$F_{\text{eligible}} = F_{\text{eligible source}} \times F_{\text{eligible biomass}} \tag{7}$$

(c) The CO_2 Removal Supplier shall determine the mass fraction of CO_2 from eligible sources (in the sense of rule 3.2.3) in the captured stream ($F_{\text{eligible source}}$) as detailed below:

- For CO_2 Streams which do not include CO_2 from fossil fuels or feedstocks derived from fossil fuels (i.e. for CO_2 captured directly from the atmosphere or from purely biogenic sources), the CO_2 Removal Supplier may utilize the value of $F_{\text{eligible source}} = 100\%$ provided that the CO_2 Removal Supplier provides operational data records that rule out ineligible sources of CO_2 in the captured stream.[40]
- In cases where the CO_2 Stream is captured in a manner where, during the capture process, a minor and accurately quantifiable amount of fossil CO_2 is mixed with CO_2 of otherwise purely biogenic origin (e.g. due to utilization of fossil start-up fuels, or other ancillary fuels in the capture process), the CO_2 Removal Supplier may determine the value of $F_{\text{eligible source}}$ based on operational data records on the quantity of fossil fuels utilized, provided that the CO_2 Removal Supplier also provides further operational data records that rule out any other ineligible sources of CO_2 in the captured stream.

  Note that in the special case of CO_2 captured from activities relating to coal-fired electricity generation, $F_{\text{eligible source}} = 0\%$ as per subrule 3.2.3 (b).

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[40] For example, such data records might include records to show that 100% of feedstock is biogenic, capture plant design documents to show that e.g. CO_2 from fossil fuel combustion processes is not mixed with the captured CO_2 stream, or comparisons between mass of captured CO_2 and directly measured plant performance (for DAC). See also rule 4.2.6.

- In all other cases besides the aforementioned (e.g. for CO_2 from waste + CCS and other mixed sources, or if the required data records to rule out fossil sources of CO_2 in the captured stream are not provided), the CO_2 Removal Supplier shall determine the value of $F_{\text{eligible source}}$ via measurement of biogenic CO_2 in the stream through radiocarbon (^{14}C) analysis following either the ISO 13833 or the ASTM D6866 standard test methods.[41]

(d) For CO_2 Streams containing CO_2 captured from biomass feedstocks (i.e. bio-CCS, including waste-CCS and other mixed sources), the CO_2 Removal Supplier shall determine the mass fraction of processed biomass feedstock, which is eligible in the sense of rules 3.7.1 and 3.7.2 ($F_{\text{eligible biomass}}$) based on operational data records on the origin, type, and sustainability of the biomass feedstock (see rules 3.7.1 and 3.7.2).

Variable	Description	Unit
F_{eligible}	Total mass fraction of eligible CO_2 in the CO_2 Stream.	% mass
$F_{\text{eligible source}}$	Mass fraction of CO_2 from eligible sources (in the sense of rule 3.2.3) in the captured stream.	% mass
$F_{\text{eligible biomass}}$	The mass fraction of processed biomass feedstock, which is eligible in the sense of rules 3.7.1 and 3.7.2.	% mass

4.4.6 The CO_2 Removal Supplier shall quantify the fraction of the total gross amount of injected CO_2 attributed to the CO_2 Removal Supplier (F_{supplier}). The fraction F_{supplier} is defined as

$$F_{\text{supplier}} = m_{\text{supplier } CO_2} / m_{\text{total } CO_2} \tag{8}$$

(a) The value $F_{\text{supplier}} = 100\%$ shall be utilized if the CO_2 Stream of the CO_2 Removal Supplier is not mixed with other CO_2 Streams prior to injection (e.g. if the CO_2 Removal Supplier is the sole user of the geological storage reservoir or if CO_2 Streams from different users are not simultaneously injected).

(b) In all other cases besides those within the purview of subrule a, the CO_2 Removal Supplier shall provide documentation from the storage site operator certifying the fraction of the total gross amount of injected CO_2 attributed to the CO_2 Removal Supplier (F_{supplier}, see also subrule 3.2.13 (c)).

The values of $m_{\text{supplier } CO_2}$ and $m_{\text{total } CO_2}$ shall be determined in accordance with applicable local regulations or, if no such regulations exist, through any of the following methods:

- Direct measurement of the flow and composition of the delivered CO_2 Streams (similar to rule 4.4.2). In cases where CO_2 is delivered in containers, the mass may also be determined by weight measurement (e.g. via load cells or weighbridges). The measurements shall take

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[41] ISO 13833:2013 Stationary source emissions — Determination of the ratio of biomass (biogenic) and fossil-derived carbon dioxide — Radiocarbon sampling and determination, or ASTM D6866 Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis. Note that with radiocarbon analysis, the accuracy of the % biobased carbon content calculation might be reduced in cases where the analyzed biomass contains significant quantities of long-lived renewable carbon, such as wood or wood residues stemming from the core part of a tree. In such cases, critical assessment of the results (according to the provisions of the utilized standard) might be necessary.

place prior to any subsequent processing operations at the storage site (e.g. at a receiving custody transfer meter or similar).

- Documentation of delivered masses of CO_2 from shipping invoices, manifests, sales contracts or similar records.

Variable	Description	Unit
F_{supplier}	Fraction of the total gross amount of injected CO_2 attributed to the CO_2 Removal Supplier	% mass
$m_{\text{supplier CO}_2}$	Total mass of CO_2 delivered to the storage site by the CO_2 Removal Supplier during the monitoring period.	tCO_2
$m_{\text{total CO}_2}$	Total mass of all CO_2 delivered to the storage site during the monitoring period.	tCO_2

4.4.7 The CO_2 Removal Supplier shall monitor either i) the mass or ii) the volume and density of all captured and injected CO_2 Streams through direct measurement.

(a) Any fluid flow measurements shall be performed using commercially available mass or volumetric flow meters. All flow meters shall be operated continuously (i.e. one measurement every 15 minutes or less) except as necessary for maintenance and calibration.

(b) Any measurements of volume or other quantities derived from volume (e.g. density, volume fraction) shall be reported at the CO_2 Removal Supplier's chosen standard reference temperature (T_{ref}) and pressure (p_{ref}). The same reference values shall be used for all relevant quantities.[42]

Where necessary, volumes in non-standard conditions (T, p) shall be converted into volumes in standard conditions $(T_{\text{ref}}, p_{\text{ref}})$ via

$$V(T_{\text{ref}}, p_{\text{ref}}) = V(T, p) \times \rho(T, p)/\rho(T_{\text{ref}}, p_{\text{ref}}) \quad (9)$$

The values of $\rho(T, p)$ and $\rho(T_{\text{ref}}, p_{\text{ref}})$ shall be determined by measurement, or sourced from publicly available data.[43]

Variable	Description	Unit
$V(T_{\text{ref}}, p_{\text{ref}})$	Volume of the fluid at the CO_2 Removal Supplier's chosen reference temperature T_{ref} and pressure p_{ref}.	m^3

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[42] Definitions of standard reference conditions vary somewhat between different standards and jurisdictions. For example, the US mandatory greenhouse gas reporting regulations for the geologic sequestration of carbon dioxide require reporting of measured volumes of CO_2 at 60 °F and 1 atm (15.56 °C and 101.325 kPa) (40 CFR 98.444(f)(2)), while EU regulations use 0 °C and 1 atm (2018/2066 Article 3(52)). For the purposes of this methodology, the different definitions are not significant, as long as the CO_2 Removal Supplier consistently utilizes the same reference conditions for all relevant parameters.

[43] In general, density can be calculated e.g. from an equation of state or from an empirical correlation formula. Easily accessible sources of data for carbon dioxide in conditions relevant for geological storage applications include the NIST Thermophysical Properties database [43] or an empirical correlation formula by Ouyang [44].

(Continued)

Variable	Description	Unit
$V(T, p)$	Volume of the fluid at some non-standard temperature T and pressure p.	m^3
$\rho(T, p)$	Density of the fluid at some non-standard temperature T and pressure p.	$\mathrm{t\,m^{-3}}$
$\rho(T_{\mathrm{ref}}, p_{\mathrm{ref}})$	Density of the fluid at the CO_2 Removal Supplier's chosen reference temperature T_{ref} and pressure p_{ref}.	$\mathrm{t\,m^{-3}}$

4.5 Project emissions (E_{project})

4.5.1 The total life cycle emissions arising from the whole supply chain of the geological storage activity (project emissions, E_{project}) shall be calculated as follows.

$$E_{\mathrm{project}} = E_{\mathrm{capture}} + E_{\mathrm{transport}} + E_{\mathrm{injection}} \tag{10}$$

Variable	Description	Unit
E_{project}	Total life cycle emissions arising from the whole supply chain of the geological storage activity.	tCO_2e
E_{capture}	Total life cycle emissions arising from the capture of the CO_2 Stream (see subrule 5.2.6 (a)).	tCO_2e
$E_{\mathrm{transport}}$	Total life cycle emissions arising from the transport of the CO_2 Stream (see subrule 5.2.6 (b)).	tCO_2e
$E_{\mathrm{injection}}$	Total life cycle emissions arising from the injection of the CO_2 Stream (see subrule 5.2.6 (c)).	tCO_2e

4.5.2 The CO_2 Removal Supplier shall quantify the project emissions (E_{project}) based on a life cycle assessment of the geological storage activity, according to the requirements and system boundaries defined in section 5 of this methodology.

The term E_{project} **shall not include** any emissions or removals already accounted for in the terms C_{stored}, E_{leakage} and E_{reversal}.

4.5.3 The project emissions (E_{project}) shall be updated in each monitoring period with actual measured and recorded activity data (such as transport distances as well as fuel, energy, and material consumption).

4.6 Ecological, market, and activity-shifting leakage (E_{leakage})

4.6.1 The total greenhouse gas emissions due to negative ecological, market, and activity-shifting leakage resulting from the geological storage activity shall be calculated as follows.

$$E_{\mathrm{leakage}} = E_{\mathrm{ECO}} + E_{\mathrm{MA}} \tag{11}$$

Variable	Description	Unit
E_{leakage}	Total GHG emissions due to unmitigated negative leakage resulting from the geological storage activity.	tCO_2e
E_{ECO}	Total GHG emissions due to unmitigated negative ecological leakage resulting from the geological storage activity (see section 6).	tCO_2e
E_{MA}	Total GHG emissions due to unmitigated negative market and activity shifting leakage resulting from the geological storage activity (see section 6).	tCO_2e

4.6.2 The CO_2 Removal Supplier shall quantify the total GHG emissions due to unmitigated negative leakage (E_{leakage}) based on an assessment of leakage due to the geological storage activity, in accordance with the requirements defined in section 6 of this methodology.

The term E_{leakage} **shall not include** any emissions or removals already accounted for in the terms C_{stored}, E_{project} and E_{reversal}.

4.7 Reversals (E_{reversal})

4.7.1 The CO_2 Removal Supplier shall monitor and quantify any reversal events (see also section 7.6). For the purposes of this methodology, a reversal event is defined as any event which results in *any of the following substances* being either no longer securely stored in the storage reservoir,[44] or released from the storage reservoir into the atmosphere:[45]

- CO_2 or other greenhouse gases
- Fossil fuels and other hydrocarbons
- Any previously stored carbon-containing substances (e.g. bio-oils or slurries)

4.7.2 The total greenhouse gas emissions due to reversal (E_{reversal}) shall be calculated as follows.

$$E_{\text{reversal}} = \sum_{i=1}^{n} \text{mCO}_2\text{e}_i \tag{12}$$

In case of reversals from a shared storage reservoir (i.e. a geological storage reservoir utilized to store CO_2 from several different operators), the Issuing Body may decide to adjust the value of E_{reversal} by a suitable attribution factor based on the nature of the reversal event, and evidence provided by the CO_2 Removal Supplier.

Variable	Description	Unit
E_{reversal}	Total mass of GHGs emissions due to reversal events from the subsurface storage reservoir.	tCO_2e

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[44] i.e. breach of permanent storage, such as leakage from the storage reservoir to underground sources of drinking water.

[45] i.e. re-emission, such as intentional venting due to wellbore maintenance, or unintentional emissions through transmissive faults or fissures, or improperly sealed legacy wells.

(Continued)

Variable	Description	Unit
mCO_2e_i	Total mass of GHGs emitted during reversal event i.	tCO_2e
i	Enumeration of reversal events, see also rule 4.7.3.	unitless
n	Total number of reversal events.	unitless

4.7.3 The CO_2 Removal Supplier shall quantify the total amount of CO_2 released during each reversal event (mCO_2e_i, see rule 4.7.2) through direct measurement or conservative estimation. Where the quantification of emissions from release events through direct measurement is unfeasible or impossible, the CO_2 Removal Supplier shall conservatively estimate the released amount based on the duration of the reversal event (ΔT_i) and estimated average flux of GHGs released (R_i) as follows.

$$mCO_2e_i = R_i \times \Delta T_i = R_i \times (T_{i,\text{ end}} - T_{i,\text{ start}}) \tag{13}$$

(a) The average flux from a reversal event (R_i) shall be quantified through measurement and/or other relevant operational data.

(b) The duration of a reversal event (ΔT_i) is defined as the number of days between the start date ($T_{i,\text{ start}}$) and end date ($T_{i,\text{ end}}$) of the event (both dates included).

(c) The start date ($T_{i,\text{ start}}$) of a reversal event is defined as the last date for which evidence of no reversal (related to event i) is available. If no such evidence is available, the start date is defined as the start date of the first Crediting Period.

(d) The end date ($T_{i,\text{ end}}$) of a reversal event is defined as the date by which appropriate remedial measures have been undertaken to such an extent that reversal can no longer be detected.

(e) Instead of estimating the total amount of CO_2 released during a reversal event (mCO_2e_i by utilizing equation (13), the CO_2 Removal Supplier may, where possible, quantify mCO_2e_idirectly through measurement (e.g. in the context of intentional reversal during maintenance or monitoring operations, such as when pumping small amounts of fluids from the storage reservoir for monitoring purposes without re-injection).

Variable	Description	Unit
mCO_2e_i	Total mass of GHGs emitted during reversal event i.	tCO_2e
R_i	Estimated average flux of GHGs released during reversal event i.	tCO_2e/day
ΔT_i	The duration or estimated duration of reversal event i.	days
$T_{i,\text{ end}}$	The date by which remedial measures have been undertaken to such an extent that reversal can no longer be detected.	days

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Variable	Description	Unit
$T_{i,\text{ start}}$	One of the following dates: • The last date when evidence of no reversal was identified from the site monitoring. • The date the CO_2 injection started as part of the activity credited under this methodology, if no available evidence exists to show that no reversal has been previously detected.	days

4.8 Quantification uncertainty assessment

Besides being able to quantify the amount of CO_2 Removal achieved in a project, it is also important to be able to estimate the uncertainty in the quantified value to ensure that the CO_2 Removal issued as CORCs is not overstated. This subsection considers uncertainty in the sense of quantification error, i.e. the difference between a measured/calculated value of a quantity and its unknown 'true' value (uncertainty in a more general sense is further considered in section 8). Additional guidance on the expression of uncertainty in measurement can be found, for example, in the ISO/IEC Guide 98 suite of documents.[46]

4.8.1 The CO_2 Removal Supplier shall use conservative assumptions, values, and procedures to ensure that the CO_2 Removal issued as CORCs is not overstated.

4.8.2 The CO_2 Removal Supplier shall identify and report all material sources of uncertainty in the Output volume, considering at least the following common sources of material uncertainty:

- Representativeness of the parameters utilized (e.g. the statistical dispersion in the value utilized for the mass fraction of eligible CO_2 in the captured CO_2 Stream)
- Measurement errors (e.g. the measurement/calibration error of the flow meter utilized for quantification of the injected CO_2)
- Assumptions or estimations utilized by the CO_2 Removal Supplier (e.g. typical/estimated uncertainties of reference data sourced by the CO_2 Removal supplier, such as the density of CO_2 at reference conditions).

A material source of uncertainty is here defined as any source of uncertainty, whose effect to the total Output volume during the monitoring period is, or can be reasonably assumed to be, 1% or greater (see also rule 4.8.3).

4.8.3 For the purposes of this methodology, uncertainties associated with the emission factors utilized for the determination of greenhouse gas emissions are considered non-material (and therefore need not be considered), provided that the emission factors originate from LCA databases, local regulations, or other official sources (e.g. governmental, intergovernmental), and that those factors include upstream and

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[46] ISO/IEC Guide 98 suite of documents currently available:
ISO/IEC Guide 98-1:2024 Guide to the expression of uncertainty measurement — Part 1: Introduction;
ISO/IEC Guide 98-3:2008 Uncertainty of measurement — Part 3, Guide to the expression of uncertainty in measurement; ISO/IEC Guide 98-4:2008 Uncertainty of measurement — Part 4, Role of measurement uncertainty in conformity assessment; and
ISO/IEC Guide 98-6:2021 Uncertainty of measurement — Part 6, Developing and using measurement models.

downstream contributions as required in section 5. For emission factors originating from other sources, a flat uncertainty of 20% of the value of the emission factor shall be assumed, unless an uncertainty has been determined by the publisher of the emission factor (in which case the determined value shall be used).

4.8.4 The CO_2 Removal Supplier shall quantify the uncertainties in the Output volume as detailed in subrules a-c.

(a) The CO_2 Removal Supplier shall quantify each identified material uncertainty (see rule 4.8.2) following the procedure in subrule b.

(b) The CO_2 Removal Supplier shall directly quantify uncertainties (e.g. via calibration records, or statistical methods based on project data) where possible. Uncertainty estimations from external sources (such as peer-reviewed scientific literature or local regulations) or expert judgment may be utilized when necessary.

(c) The CO_2 Removal Supplier shall calculate the overall uncertainty (i.e. estimated standard deviation) in the Output volume utilizing a quantitative, scientifically justifiable method for the propagation of uncertainty such as the variance propagation formula, or Monte Carlo simulations.

4.8.5 The CO_2 Removal Supplier shall conduct the uncertainty assessment before the 1st Output Audit, and thereafter update it at least annually.

Table 2: Summary of parameters utilized in this section, in order of appearance.

Variable	Description	Unit	Reference
$CORCs$	Net amount of CO_2 equivalents removed by the geological storage activity.	tCO_2e	rule 4.3.1
C_{stored}	Gross amount of eligible CO_2 stored into the geological reservoir.	tCO_2	rule 4.3.1 rule 4.4.1
E_{project}	Total life cycle emissions arising from the whole supply chain of the geological storage activity.	tCO_2e	rule 4.3.1
E_{leakage}	Total GHG emissions due to unmitigated negative leakage resulting from the geological storage activity.	tCO_2e	rule 4.3.1 rule 4.6.1
E_{reversal}	Total mass of GHGs emissions due to reversal events from the subsurface storage reservoir.	tCO_2e	rule 4.3.1 rule 4.7.2
C_{injected}	Total amount of CO_2 injected at the storage site, determined at the last monitoring point on the injection system.	tCO_2	rule 4.4.1 rule 4.4.2
E_{released}	The amount of greenhouse gases attributable to the CO_2 Removal Supplier released from the injection system downstream of the last monitoring point.	tCO_2e	rule 4.4.1 rule 4.4.3
F_{eligible}	Fraction of eligible CO_2 in the CO_2 Stream of the CO_2 Removal Supplier.	% mass	rule 4.4.1 rule 4.4.5

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Table 2: Summary of parameters utilized in this section, in order of appearance. (Continued)

Variable	Description	Unit	Reference
F_{supplier}	Fraction of the total gross amount of injected CO_2 attributed to the CO_2 Removal Supplier.	% mass	rule 4.4.1 rule 4.4.4 rule 4.4.6
m_{fluid}	Total mass of fluid injected at the storage site determined at the last monitoring point on the injection system.	t	rule 4.4.2
F_{CO_2}	Mass fraction of CO_2 in the injected fluid.	% mass	rule 4.4.2 rule 4.4.3
V_{fluid}	Total volume of fluid injected at the storage site, determined at the last monitoring point on the injection system, and at the CO_2 Removal Supplier's chosen reference conditions.	m^3	rule 4.4.2
Q_{CO_2}	Volume fraction of CO_2 in the injected fluid at the CO_2 Removal Supplier's chosen reference conditions.	% vol	rule 4.4.2 rule 4.4.3
ρ_{CO_2}	Density of CO_2 at the CO_2 Removal Supplier's chosen reference conditions.	tCO_2/m^3	rule 4.4.2
$E_{\text{total released}}$	The amount of total greenhouse gases released from the injection system downstream of the last monitoring point.	tCO_2e	rule 4.4.3
$F_{\text{eligible source}}$	Mass fraction of CO_2 from eligible sources (in the sense of rule 3.2.3) in the captured stream.	% mass	rule 4.4.5
$F_{\text{eligible biomass}}$	The mass fraction of processed biomass feedstock, which is eligible in the sense of rules 3.7.1 and 3.7.2.	% mass	rule 4.4.5
$m_{\text{supplier } CO_2}$	Total mass of CO_2 delivered to the storage site by the CO_2 Removal Supplier during the monitoring period.	tCO_2	rule 4.4.6
$m_{\text{total } CO_2}$	Total mass of all CO_2 delivered to the storage site during the monitoring period.	tCO_2	rule 4.4.6
$V(T_{\text{ref}}, p_{\text{ref}})$	Volume of the fluid at the CO_2 Removal Supplier's chosen reference temperature T_{ref} and pressure p_{ref}.	m^3	rule 4.4.7
$V(T, p)$	Volume of the fluid at some non-standard temperature T and pressure p.	m^3	rule 4.4.7
$\rho(T, p)$	Density of the fluid at some non-standard temperature T and pressure p.	$t\,m^{-3}$	rule 4.4.7
$\rho(T_{\text{ref}}, p_{\text{ref}})$	Density of the fluid at some non-standard temperature T and pressure p.	$t\,m^{-3}$	rule 4.4.7
E_{project}	Total life cycle emissions arising from the whole supply chain of the geological storage activity.	tCO_2e	rule 4.5.1

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Table 2: Summary of parameters utilized in this section, in order of appearance. (Continued)

Variable	Description	Unit	Reference
E_{capture}	Total life cycle emissions arising from the capture of the CO_2 Stream.	tCO_2e	rule 4.5.1
$E_{\text{transport}}$	Total life cycle emissions arising from the transport of the CO_2 Stream.	tCO_2e	rule 4.5.1
$E_{\text{injection}}$	Total life cycle emissions arising from the injection of the CO_2 Stream.	tCO_2e	rule 4.5.1
E_{ECO}	Total GHG emissions due to unmitigated negative ecological leakage resulting from the geological storage activity.	tCO_2e	rule 4.6.1
E_{MA}	Total GHG emissions due to unmitigated negative market and activity shifting leakage resulting from the geological storage activity.	tCO_2e	rule 4.6.1
mCO_2e_i	Total mass of GHG emitted during reversal event i.	tCO_2e	rule 4.7.2 rule 4.7.3
i	Enumeration of reversal events.	unitless	rule 4.7.2
n	Total number of reversal events	unitless	rule 4.7.2
R_i	Estimated average flux of GHGs released during reversal event i.	tCO_2e/day	rule 4.7.3
ΔT_i	The duration or estimated duration of reversal event i.	days	rule 4.7.3
$T_{i,\text{ end}}$	The date by which remedial measures have been undertaken to such an extent that reversal can no longer be detected.	days	rule 4.7.3
$T_{i,\text{ start}}$	One of the following dates: • The last date when evidence of no reversal was identified from the site monitoring • The date of the first Crediting Period, if no available evidence exists to show that no reversal has been previously detected.	days	rule 4.7.3

5

Assessment of life cycle greenhouse gas emissions

5.1 General life cycle assessment requirements

5.1.1 The CO_2 Removal Supplier shall conduct a life cycle assessment (LCA) for the geological storage activity. The LCA shall follow the general principles defined in ISO 14040/44 and the scope defined in sections 4 and 5 of this methodology.

5.1.2 The LCA shall include a report which explains and justifies the data and modeling choices made, as well as all supporting calculation files which will be used for calculation of CORCs.

5.1.3 The LCA shall calculate the climate change impact of the activity, characterized using 100-year global warming potentials (GWP_{100}) from the latest version available. Other environmental impact categories may be included but are not required.

5.1.4 The emission factors used in the LCA shall at least include the contribution of major greenhouse gases (fossil CO_2, biogenic non-renewable CO_2, CH_4, N_2O). The emission factors used in the LCA shall include a full-scope of emissions (i.e. including upstream and downstream emissions, or so-called supply chain emissions, as opposed to emission factors used for greenhouse gas inventory purposes).

5.1.5 For transparency, interpretability and auditing purposes (i.e. verification of claims), the climate change impact calculated in the LCA shall be presented in a disaggregated way exhibiting the contributions of the different life cycle stages described in figure 4 and table 3, as well as the contributions of major greenhouse gases (i.e. providing the total in tCO_2e but also the specific contributions of CO_2, CH_4, N_2O and other greenhouse gases to this total climate impact). In case any of the contributions defined in figure 4 or table 3 are deemed to be null or irrelevant, the CO_2 Removal Supplier shall provide an explicit justification thereof in the LCA report and calculation files.

5.1.6 Publicly available LCA results in the Puro Registry (i.e. the verified LCA results after audit) may be aggregated to a level sufficient to protect sensitive information or licensed LCA data, as agreed with the Issuing Body. However, the aggregation shall at least disclose the level 1 and level 2 contributions, as well as certain level 3 contributions (e.g. direct land use change emissions) as further defined in table 3 (see also see subrule 5.2.7 (b)).

5.1.7 In the event that waste, recycled or secondary resources are used as input to the activity (e.g. recycled steel or plastic), it is permissible and recommended to apply the cut-off approach[47] for waste, recycled and secondary products in the LCA. Specifically, the environmental burdens from production of secondary resources may be excluded from the system boundary, but the supply, transformation and handling of the secondary resources must be included.

5.1.8 In the event that by-products *with a meaningful use outside the process boundaries* are

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[47] Description of the cut-off system model is available on the website of the ecoinvent life cycle database.

generated during the activity, an allocation of the relevant life cycle stages between the co-products may be applied. Whenever possible, the allocation procedure shall follow the stepwise process described under ISO 14044:2006, starting by determining the physical relationship as the basis for the allocation. Otherwise, an allocation based on economic value of the products may be used.

5.1.9 The CO_2 Removal Supplier shall coordinate data collection and LCA modeling with any external operators[48] to the level necessary to ensure compliance with this methodology and the Puro Standard requirements.

5.2 Methodology-specific life cycle assessment requirements

5.2.1 The **functional unit** of the LCA shall be "the capture, transport, and storage of 1 metric tonne of carbon dioxide" in a specific geological reservoir. Results of the LCA are expressed per dry metric tonne of carbon dioxide captured, transported, and stored.

5.2.2 The **spatial boundaries** of the LCA must be defined. This includes: the areas from which biomass is sourced (for any biomass-based capture activity), locations in the upstream supply chain (e.g. biomass processing sites and transport routes), the location of the capture site(s), the main transport routes, as well as the location of the storage site(s).

5.2.3 The **time boundaries** of the LCA must be defined. This includes specifying the planned duration of the carbon capture activities, carbon injection activities (until site closure), storage site monitoring activities (until liability transfer to national entity or equivalent), and the planned lifetime of key infrastructure (e.g. facilities, pipelines). It is required to disclose in the LCA both technical design lifetimes, as well as any useful lifetimes, because useful lifetimes may be shorter than technical design lifetimes. Those lifetimes may affect how embodied emissions are amortized (see below).

5.2.4 The **activity boundaries** that must be included in the LCA to represent the carbon capture and storage activity are defined in figure 4, from capture of the carbon stream to injection of the carbon stream. The LCA report must include a project-specific process-flow diagram that details each of the main stages defined in figure 4. These **stages** are also called **unit processes** for the purpose of defining the scope and completeness of life cycle inventories. See also rule 5.2.21.

5.2.5 Each stage included in the **activity boundaries** includes both embedded emissions (e.g. infrastructure and machinery) and operational emissions (e.g. energy and material use). These two types of emissions shall be specified and accounted for in the LCA ,as detailed in subrules a and b.

(a) **Embedded or embodied emissions** of infrastructure and/or equipment represent the carbon emitted in the land-use conversion (when applicable) and the fabrication, construction, maintenance, and demolition of these assets. These emissions shall be calculated and amortized against the gross carbon captured according to rules 5.2.14–5.2.17.

The embodied emissions of *pre-existing facilities* shall not be accounted for in the project's emissions. However, embodied emissions associated with the retrofit and maintenance of retrofitted facilities for project operation shall be taken into account.

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[48] Data required for performing the LCA of a geological storage activity originates from multiple parties, and most importantly from the capture site operator, the logistics operators, and the storage site operator.

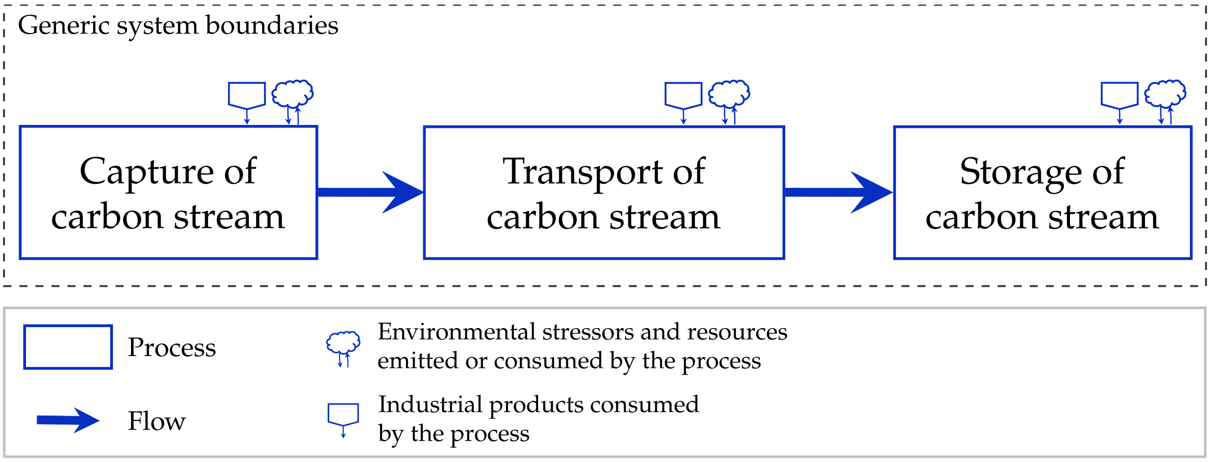

Figure 4: Process boundaries for the life cycle assessment (LCA) of a GSC activity.

The embodied emissions of *shared facilities* shall be allocated to the participating users. Whenever possible, the allocation procedure shall follow the stepwise process described under ISO 14044:2006, starting by determining the physical relationship as the basis for the allocation. Otherwise, an allocation based on economic value of the products may be used. See rule 5.2.21 for a numerical example of this rule.

(b) **Operational emissions** of facilities or other types of infrastructure and machinery include the energy used to operate these assets, and the material inputs necessary for their operation (e.g. biomass supply, solvents). These emissions are subtracted from the gross carbon captured.

5.2.6 Each stage included in the **activity boundaries** must represent a complete life cycle, for which the full scope of emissions must be included. A full scope of emissions implies that infrastructure and equipment requirements, material and energy consumption, as well as treatment of waste materials must be included (i.e. upstream and downstream activities). The three main stages are briefly described in subrules a-c, and further detailed in the following rules.

(a) **Capture of carbon stream** refers to all activities required for sourcing, capturing and processing the carbon stream at the capture facility. Depending on the specific capture pathway, this stage may also include activities related to biomass production and sourcing (see rules 5.2.8 and 5.2.9). This stage terminates with the *carbon stream captured and ready for transport*. LCA data for this stage is expected to originate mainly from the *capture site operator*. Emission types within this stage include:

- *Embodied emissions*: this includes emissions related to the construction, maintenance and disposal of any equipment (buildings, machines) needed for sourcing, capturing and processing the carbon stream at the capture facility.
- *Operational emissions*: this includes the use of energy, materials and chemicals (e.g. sorbents) in the capture process and any further processing of the carbon stream (e.g. dehydration, liquefaction), as well as the treatment of any waste arising during operations.

- *Biomass supply emissions*: this includes, when applicable, biomass production and sourcing (see rules 5.2.8 and 5.2.9).

(b) **Transport of carbon stream** refers to all activities required for transporting the carbon stream from the capture site to the storage site, whether by pipeline, rail, road, shipping, or a combination of transportation modes, regardless of whether or not the stream is mixed with other carbon streams. It also includes any transfer steps, intermediary storage steps and processing of the carbon stream, as well as any potential carbon losses during those steps. This stage terminates with the *carbon stream delivered to the storage site.* LCA data for this stage is expected to originate mainly from the *logistic operators*. Emission types within this stage include:

- *Embodied emissions*: this includes emissions related to construction, maintenance, and disposal of any infrastructure and equipment (i.e. buildings, machines, pipelines). Excluded from embodied GHG emissions calculations are the processes for the production of vehicles and transport or transshipment devices, in alignment with the GLEC Framework v3.[49]
- *Operational emissions*: this includes the emissions of all transport and hub operation activities of the transport chain, and all emissions of energy provisions of those activities for all transport chain elements (TCE). This stage shall be calculated in accordance with ISO 14083:2023[50] and using the GLEC Framework v3. In addition, material and chemical use, and treatment of any waste arising during transportation *should be* included.

(c) **Injection of carbon stream** refers to all activities required for injecting the delivered carbon stream into the storage reservoir, as well as the monitoring of the storage site until liability transfer (or other similar cessation of post-closure site management obligations). This stage terminates with the *carbon stream injected at the storage site.* LCA data for this stage is expected to originate mainly from the *storage site operator*. Emission types within this stage include:

- *Embodied emissions*: this includes emissions related to the construction, maintenance and disposal of any equipment (e.g. buildings, machines) needed for the storage site,
- *Operational emissions*: this includes emissions related to i) energy use by the injection process, ii) material and chemical use by the injection process, and iii) treatment of any waste arising during operations.

5.2.7 The CO_2 Removal Supplier shall collect and organize the elements and processes that contribute to generate the overall project emissions (E_{project}, including both embodied and operational emissions) according to the levels of information described in table 3 and in subrules a and b.

(a) The LCA results must be provided in a disaggregated manner aligned with table 3, exhibiting the contributions of each main stage (level 1) and substage

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[49] Smart Freight Centre. Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting v3.0, revised and updated (2023). ISBN 978-90-833629-0-8.

[50] ISO 14083:2023 Greenhouse gases - Quantification and reporting of greenhouse gas emissions arising from transport chain operations.

(level 2). Each sub-stage can be further divided into contributions (level 3) relevant for each project type. If a contribution is deemed not relevant or equal to 0, an explicit motivation shall be provided (see rule 5.1.5).

(b) The CO_2 Removal Supplier shall publicly disclose in the Puro Registry, as part of annual Output Audit, at least the contributions marked with an asterisk (*) in table 3.

Table 3: Stages that must be included in the life cycle assessment of the removal activity (see rule 5.2.7)

Main stages Level 1	Substages Level 2	Further substages Level 3	Comment
*E_{capture}	*Operational emissions of carbon capture	Energy use (heat, electricity, fuel) Material use Waste treatment	
	*Biomass production, supply and conversion (if applicable)	Production Supply Conversion *Direct land use change (dLUC)[a]	Either fully attributed to CORCs or partly allocated to CORCs via share of internally use bioenergy.
	*Embodied emissions of carbon capture	Construction, maintenance, and disposal of infrastructure and equipment *dLUC.	Maintenance can be demonstrated to be negligible, in annual reporting.
*$E_{\text{transport}}$	*Operational emissions of carbon transport	Energy use (heat, electricity, fuel) Material use	Third-level contributions may be split in sub-stages as relevant for each supply-chain.
	*Embodied emissions of carbon transport	Construction, maintenance, and disposal of infrastructure and equipment *dLUC.	Maintenance can be demonstrated to be negligible, in annual reporting.
*$E_{\text{injection}}$	*Operational emissions of carbon injection	Energy use (heat, electricity, fuel) Material use Waste treatment	
	*Embodied emissions of injection/storage	Construction & disposal Maintenance *dLUC	Maintenance can be demonstrated to be negligible, in annual reporting.

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Table 3: Stages that must be included in the life cycle assessment of the removal activity (see rule 5.2.7) (Continued)

Main stages Level 1	Substages Level 2	Further substages Level 3	Comment
	*Storage site monitoring		Can be demonstrated to be negligible, as per rule 5.2.18.

[a] Emission contributions associated with direct land use change are described under rule 5.2.16.

*: The contributions marked with an asterisk (*) must be publicly disclosed in the Puro Registry as part of annual Output Audit (see subrule 5.2.7 (b))

5.2.8 For the stage **Capture of carbon stream** (see subrule 5.2.6 (a)), the following rule further applies to any **biomass-based capture** activity regarding **attribution of emissions** from the *production*, *supply* and *conversion* of biomass feedstock:

(a) In the case that the activity is associated with **the production of one or several biomaterial or bioenergy products**, the emissions associated with the production and supply of the biomass feedstock are *in the general case* fully attributed to those products (with exceptions detailed below). If any of those main products are then utilized in the capture process (e.g. steam or electricity used in capture process), the emissions associated with the share utilized are included in the stage *Capture of carbon stream*. For example, this general case applies to:

- **Anaerobic digestion** facilities (producing biomethane for heat and power production, upgraded biomethane for vehicle fuel or industrial fuel usage, and digestate for use as fertilizer)
- **Fermentation facilities** (producing ethanol-products, either for consumption or fuel usage)
- **Thermochemical conversion facilities** (producing heat, steam, power, fuel, biochar or a combination of these, whether via combustion, pyrolysis, gasification of biomass).

Exceptions to the general case:

- The CO_2 Removal Supplier may decide to fully attribute emissions from production, supply and conversion of biomass to the Carbon capture activity (and thereby consider the co-produced bioenergy and biomaterials as burden-free), provided that this is allowed and compatible with other greenhouse gas reporting schemes the operator is subject to. This is conservative from the perspective of CORCs, but not required.
- The Puro Standard reserves the right to issue rule clarifications for specific removal pathways in which emissions from biomass feedstock production and supply may need to be allocated in other ways between the material/energy products and the carbon stream captured. This might apply to specific pathways where the *conversion* of the biomass and the *capture and storage* of carbon dioxide take place simultaneously and cannot be dissociated.

The emission partitioning rules used to perform the allocation between co-products shall be consistent with any other accounting performed by the operator, whether voluntary or required in the jurisdiction of the project. If no such system is in place, the emission partitioning rules shall follow industry best-practice (e.g. based on GHG Protocol guidance for CHP plants[51]), or default to the general principles of allocation defined in ISO 14040/44.

The attribution of the biomass supply-chain emissions between the carbon dioxide stream and the co-products shall always be explicitly defined in the LCA report and calculation files submitted, and thereby also include the calculations of the biomass supply-chain emissions (even if not contributing to the CORC quantification).

(b) In the case that the activity is **not associated with the production of any main material or energy product**, the emissions associated with the production, supply and conversion of the biomass feedstock shall be included in the stage *Capture of carbon stream*. This applies to any activities using purpose-grown biomass, or secondary biomass streams (e.g. agricultural residues, urban biomass waste), for the sole purpose of carbon capture and storage without any co-products.

5.2.9 For the stage **Capture of carbon stream**, the following rule further applies to any **biomass-based capture** pathway regarding **quantification of emissions** from *production*, *supply* and *conversion* of biomass feedstock:

(a) For biomass **production**, the following requirements apply:

(i) In the case of purpose-grown biomass, emissions arising from all activities involved in biomass cultivation and harvesting (e.g. the use of machinery and fuel, the production of fertilizers, emissions from soils following fertilizer use, machinery manufacturing and disposal) shall be included.

(ii) In the case that the biomass production process is multi-functional such as producing different biomass fractions for different purposes (e.g. hemp cultivation producing stalks and seeds), allocation may be used, motivating the selection of an adequate partitioning rule (e.g. dry mass, carbon content, or economic value allocation partitioning, or by-product cut-off).

(iii) In the case that the biomass feedstock is residues from forestry activities for timber production (e.g. residues at final felling, residues from thinning, bark, sawdust), the production of the biomass stream is considered burden free, only its supply and conversion shall be included. Likewise, for biomass generated during processing of primary forest biomass (e.g. sawmill residues), the production of the biomass stream is considered burden free, only its supply and conversion shall be included.

(iv) In the case of post-consumer or secondary biomass streams (e.g. biomass from recycling or landscaping activities in urban areas), the production of the biomass stream is considered burden free, only its supply and conversion shall be included.

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[51] Allocation of GHG Emissions from a Combined Heat and Power (CHP) Plant. Guide to calculation worksheets (September 2006) v1.0 A WRI/WBCSD GHG Protocol Initiative calculation tool.

(v) Direct land use change due to sourcing of primary biomass from forest land or agricultural land must be demonstrated to be null, which is achieved by demonstrating that the biomass feedstock meets the sustainability criteria as per rule 3.7.2, which conditions eligibility. Further, situations of shifting biomass use, which potentially leads to indirect leakage effects, or indirect land use change must be addressed according to the requirements of section 6.

(vi) For biomass production, the CO_2 Removal Supplier may utilize national or regional average emission factors from peer-reviewed databases and literature, as long as the reported sourced volume is supported by records of purchase. Such average emissions factors shall be cradle-to-gate and include all relevant upstream and downstream emissions.

(b) Biomass **supply** shall include, as applicable:

- Harvesting of the biomass in the field or forest (e.g. farm or forest management practices).
- Transport of the biomass from the production site to the conversion facility.
- Any other processing of the biomass, anywhere along the supply chain, such as chipping or drying.
- Any significant emissions from biomass decay during storage, if relevant.

(c) Biomass **conversion** shall include, as applicable:

- Energy inputs (e.g. start-up or ancillary fuel usage, external electricity usage).
- Material inputs, such as consumables used for flue gas treatment systems (e.g. chemicals, bag filters, water).
- Disposal of waste streams (e.g. ash disposal in biomass combustion plants, disposal of other consumables from flue gas treatment systems, wastewater).
- Direct greenhouse gas emissions from the biomass conversion process (e.g. CH_4, N_2O at the facility), either derived from measurements specific to the facility, default values used for national greenhouse gas inventory reporting, or as per default conservative values provided in table 4 (if available).
- Embodied emissions of infrastructure and equipment.

Table 4: Available default factors for direct emission of CH_4 and N_2O at the biomass conversion plant, per pathway and feedstock type.[a]

Conversion pathway	Biomass feedstock	CH_4	N_2O	Unit[b]
Combustion, conventional technology[c]	Wood	100	15	kg per TJ biomass

Continued on next page

Table 4: Available default factors for direct emission of CH_4 and N_2O at the biomass conversion plant, per pathway and feedstock type.[a] (Continued)

Conversion pathway	Biomass feedstock	CH_4	N_2O	Unit[b]
	Municipal solid waste	100	15	kg per TJ biomass
	Black liquor	18	21	kg per TJ biomass
Anaerobic digestion[d]	Manure, food waste, sludge	20	Negligible	kg per dry tonne biomass

[a] Note that project and technology specific values (e.g. for fluidized bed combustion, gasification) can be used instead if supported by evidence (see subrule 5.2.9 (c)). Default values for other technologies might be added in future revisions.

[b] The emission factors are expressed in kg of greenhouse gas per TJ of biomass on a lower heating value basis, or per tonne of waste processed on a dry basis.

[c] See [45], Volume 2, Chapter 2, Table 2.2, upper values

[d] See [45], Volume 5, Chapter 4, Table 4.1, upper values

5.2.10 For the stage **Capture of carbon stream**, whether for direct air or for flue gas capture, emissions from **sorbent or solvent usage** shall include:

- Manufacturing of the sorbent, including energy inputs, material inputs, and disposal of waste arising during production (e.g. wastewater).
- Supply of the sorbent from its production site to the capture facility
- Disposal of the sorbent.

Determination of the climate footprint of such chemicals may be performed in a separate LCA study, provided it complies with the rules defined in this methodology and the calculations are made available for auditing. Further, the calculations and reporting shall also make explicit the assumed or demonstrated useful lifetime and efficiency of the sorbents or solvents.

5.2.11 For the stage **Capture of carbon stream**, the following rule further applies to any project where a fraction of the captured carbon stream is used for permanent storage (i.e. CCS) and another fraction is utilized or sold for other purposes (i.e. CCU): the emissions from the stage Capture of carbon stream may be split between the two carbon streams, based on the mass of carbon. The carbon utilized or sold for CCU applications shall be reported with a product footprint consistent with the accounting rules applied in this methodology.

NUMERICAL EXAMPLE

Assume that the stage Capture of carbon stream is associated with supply-chain emissions of 150 kg CO_2e for 1000 kg of CO_2 captured, out of which 30% is meant for CCU applications and 70% is meant for CCS. Then, 30% of the 150 kg CO_2e are attributed to the CO_2 meant for CCU (not included in LCA), while 70% are attributed to the CO_2 meant for CCS, and thereby included in the LCA.

5.2.12 For the stage **Capture of carbon stream**, the following rule further applies to any **mixed capture** activity where both non-eligible (i.e. fossil CO_2, non-eligible biogenic CO_2) and eligible carbon fractions (biogenic CO_2, atmospheric CO_2) are captured jointly, regarding the attribution of emissions between the eligible and non-eligible carbon sources: the emissions from the stage Capture of carbon stream are fully attributed to the eligible carbon fraction, regardless of the fact that the non-eligible fraction is also injected to permanent storage. This applies in particular to solid waste incinerators (waste-CCS) where fossil plastic materials and biogenic materials are combusted together.

5.2.13 For the stages **Transport of carbon stream** and **Storage of carbon stream**, the following rule further applies to any **mixed transport** or **mixed injection** activities, where eligible carbon sources from the CO_2 Removal Supplier is mixed with either i) non-eligible carbon sources from the CO_2 Removal Supplier and/or ii) carbon sources (of unknown eligibility) from other projects:

(a) The CO_2 Removal Supplier shall account for emissions for the total of its volume processed, including both eligible and non-eligible fractions, which is conservative and consistent with rule 5.2.12.

(b) The operators shall differentiate between operational and embodied emissions, which have different attribution/amortization rules.

(c) For operational emissions related to recurring energy use and material use, the operators shall attribute the emissions per gross tonne of CO_2 processed by considering the total volume of carbon dioxide processed over the monitoring period (e.g. year), regardless of the nature or eligibility of the CO_2 processed. In case of pipeline transport, this entails the energy used by pumps when the product is in transit and requires that the pipeline operator provides the emission intensity expressed in GHG emissions per tonne km of product throughput, averaged on an annual basis.

(d) For embodied emissions related to foreground infrastructure construction, maintenance activities and disposal, and to direct land use change from infrastructure construction, the operators shall amortize the embodied emissions per gross tonne of CO_2 processed as detailed in the rule 5.2.15.

5.2.14 For emissions related to infrastructure (equipment, building, machinery) at any stage in the foreground system (i.e. capture facility, transport infrastructure, and storage facility), the **inventory modeling** shall include at least the following elements:

- Production of key materials (concrete, asphalt, steel, wood).
- Transport of key materials to site.
- Energy usage during construction (fuels, electricity).
- Disposal of waste arising during construction (e.g. excavated material sent for disposal).
- Disposal of key materials at end-of-life (e.g. using default processes available in LCA databases for disposal).

For the process-based LCA calculation of whole building and infrastructure projects, the following standards are referenced as general guidance: EN 15804+A2,[52] EN

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[52] EN 15804:2012+A2:2020 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

15978,[53] and ISO 21930:2017.[54]

(a) Alternatively, recent monetary emission factors (e.g. kg CO_2e per USD spent) may be used as a proxy for estimating embodied emissions based on capital expenditure (CAPEX), provided that such factors are available in the countries where the facilities are built.[55]

(b) Further, a distinction is made between the two baselines for bio-CCS pathways (see rule 3.4.3). For bio-CCS New Built, the biomass conversion facility is part of the capture facility, and embodied emissions are calculated for both assets. For bio-CCS Retrofit, the biomass conversion facility is considered burden-free (i.e. the embodied emissions are disregarded), only emissions from the capture facility are included.

(c) For bio-CCS Retrofit, the CO_2 Removal Supplier shall account for the embodied emissions of the infrastructure for CO_2 transport, and/or the infrastructure for the storage site that are newly built or repurposed based on an existing asset specifically for the CO_2 Removal activity as included in the baseline definition of subrule 3.4.3 (a).

5.2.15 In the context of this methodology, the **amortization of the embodied emissions** of an asset (infrastructure or equipment) is the process of apportioning the embodied emissions associated with the production, maintenance, and decommissioning of the asset over a period of time in line with its expected operational life or the project's lifetime assumption.[56]

(a) The amortization period of the embodied carbon shall be equal to the first crediting period (15 years, see rule 2.2.2), or the lifetime assumption of the asset if it is shorter than the crediting period. This period starts with the first date of the first monitoring period.

(b) After the first 15 years, recurring maintenance-related emissions shall be amortized annually, if they exceed the cut-off value.

(c) In case the facility or transport infrastructure is shared with other operators outside the project boundaries, the embodied emissions shall be allocated based on the share of operation or use calculated on an annual basis within the 15-year-period. *This typically applies to shared logistic chains and shared storage sites.*

(d) In the case that unplanned maintenance or infrastructure changes are necessary for the proper operation of the facility/infrastructure, the additional accrued carbon emissions shall be added to the embodied emissions and amortized accordingly.

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[53] EN 15978:2012 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.

[54] ISO 21930:2017 Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services.

[55] Such monetary emission factors are in general more conservative.

[56] Note that the calculation of the embodied emissions depends on the project's baseline definition (whether the facility is newly built or retrofitted), see section 3.4.

NUMERICAL EXAMPLE

Assume a project that shares an infrastructure facility (e.g. storage site) with another supplier. The total embodied emissions, including the expected maintenance, are approximately 1500 tCO_2e. This amount is chosen to be equally divided across 15 years. As the use of the facility could vary amongst the different users, it was agreed that the portion of the embodied emissions will be calculated annually based on the % share of the infrastructure use (see table 5).

The "share of infrastructure use by supplier" for a pipeline or storage facility could be determined based on the ratio of supplier carbon stream divided by the total of carbon transported and/or injected in a year.

Table 5: An example of amortized infrastructure embodied emissions.

Year	Estimated embodied emissions, amortized annually (tCO_2e)	Share of infrastructure use by supplier (%)	Amortized embodied emissions allocated to given supplier (tCO_2e)
Year 1	100	45%	45
Year 2	100	40%	40
Year 3	100	50%	50
Year 4	100	65%	65
Year 5	100	70%	70
Year 6	100	60%	60
Year 7	100	60%	60
Year 8	100	55%	55
Year 9	100	55%	55
Year 10	100	60%	60
Year 11	100	60%	60
Year 12	100	60%	60
Year 13	100	55%	55
Year 14	100	55%	55
Year 15	100	60%	60
Total	**1500**	**57%**	**850**

5.2.16 For embodied emissions related to the construction of infrastructure (e.g. facilities, pipelines), the following rules apply regarding **direct land use change** (dLUC):

(a) dLUC emissions (E_{dLUC}) shall be considered and included in the LCA, as part of the emissions related to the construction of infrastructure in each relevant stage (capture, transport, injection). For instance, the construction of a pipeline for CO_2 transport may require clearing parts of forest land, which constitutes dLUC and must therefore be included. Likewise, construction of facilities on land entails land conversion.

(b) dLUC shall be assessed relative to the land area remaining in its historical state prior to the carbon removal project (new built or retrofit).

(c) dLUC shall include any loss of aboveground and belowground biogenic carbon stocks, relative to the historical state of the land. dLUC shall also include any greenhouse emissions arising during land conversion, such as emissions associated with land clearing by fire as these may include significant amounts of methane (CH_4) and dinitrogen monoxide (N_2O).

(d) These emissions shall be quantified using either the default values for land conversion available in the IPCC Guidelines for National Greenhouse Gas Inventories [45, 46] (Tier 1), or country-specific values (Tier 2), or data specific to the project (Tier 3).

(e) The dLUC emissions (E_{dLUC}) shall be calculated as follows:

$$E_{\mathrm{dLUC}} = 44/12 \times (CS_{\mathrm{B}} - CS_{\mathrm{P}}) \times A + E_{\mathrm{conversion}} \tag{14}$$

where the carbon stock per unit area is defined as

$$CS_{\mathrm{X}} = C_{VEG_{\mathrm{X}}} + C_{DOM_{\mathrm{X}}} + SOC_{\mathrm{X}} \tag{15}$$

The parameters $C_{VEG_{\mathrm{X}}}$, $C_{DOM_{\mathrm{X}}}$, and SOC_{X} should be determined using the equations presented in volume 4 of the IPCC Guidelines for National Greenhouse Gas Inventories [45, 46] and the EU Commission decision on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC[57] (see also subrule d). In addition, Puro.earth will make calculation tools and data available to CO_2 Removal Suppliers.

Variable	Description	Unit
E_{dLUC}	Absolute direct land use change associated with the construction of infrastructure.	tCO_2e
CS_{B}	Carbon stock per unit area associated with the baseline land use.	$tC\ ha^{-1}$
CS_{P}	Carbon stock per unit area associated with the project land use.	$tC\ ha^{-1}$
A	Area of land converted.	ha
$E_{\mathrm{conversion}}$	Greenhouse gas emissions associated with the land use conversion activities, e.g. fuel usage for clearing the land, direct emissions from fire.	tCO_2e
CS_{X}	Carbon stock per unit area with the project or baseline land use, where subscript X indicates the type of land use.	$tC\ ha^{-1}$
$C_{VEG_{\mathrm{X}}}$	Above and below ground living biomass carbon stock.	$tC\ ha^{-1}$
$C_{DOM_{\mathrm{X}}}$	Dead organic matter or litter biomass carbon stock.	$tC\ ha^{-1}$
SOC_{X}	Soil organic carbon stock.	$tC\ ha^{-1}$

5.2.17 For emissions related to infrastructure (equipment, building, machinery) at any stage in the foreground system (i.e. capture facility, transport infrastructure, and storage facility), the following rules apply regarding **maintenance**

(a) The CO_2 Removal Supplier or each external operator shall keep records of maintenance and repair works performed on the infrastructure, and estimate

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[57] 2010/335/: Commission Decision of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC (notified under document C(2010) 3751).

emissions associated with those works, including material production, sourcing, and energy usage. The quantification shall follow the same inventory modeling as detailed in rule 5.2.14.

(b) On an annual basis, if emissions related to infrastructure are material, i.e. larger than 5% of the total supply-chain emissions of the stage in which they occur (either Capture, Transport, or Storage), then those emissions must be reported for inclusion in CORC quantification as part of the remaining embodied emissions to be amortized.

> **REMARK ON BACKGROUND INFRASTRUCTURE EMISSIONS:** Rules 5.2.14–5.2.17 above deal with foreground infrastructure emissions, as opposed to background infrastructure emissions. Background infrastructure refers to, for instance, the infrastructure needed in production of electricity that is consumed by the project. Background infrastructure emissions are already included in the emission factors used in the LCA, with their own modeling of lifetime, maintenance etc. The CO_2 Removal Supplier does not need to modify or verify those assumptions; background emission factors can be used as-is.

5.2.18 For emissions related to monitoring and post-closure monitoring of the storage site (i.e. all activities performed to ensure the integrity of the CO_2 storage), as part of the stage **Carbon storage**, the following rules apply:

(a) The CO_2 Removal Supplier shall calculate M_s, the emissions related to monitoring and post-closure monitoring of the storage site (scaled per tonne of CO_2 injected) as follows.

$$M_s = \frac{M \times (T_o + T_m)}{C_o} \tag{16}$$

If the resulting scaled monitoring emissions (M_s) are less than 1% of the emissions of the Storage stage (per tonne of CO_2 stored), then monitoring emissions can be ignored. Otherwise, the calculated value shall be included in the quantification of CORCs.

(b) Emissions from monitoring of the storage site for 1 year (M), shall be conservatively estimated (in kg of CO_2e per year) based on best available knowledge (e.g. based on energy use or budgeted spending).

(c) The storage site operator shall determine, based on best available knowledge, an estimate for the number of years that the storage site will remain in operation (T_o), as well as the amount of carbon dioxide (in tCO_2) projected to be stored during that time (C_o). The time T_o shall cover at least the first Crediting Period (15 years, see rule 2.2.2).

(d) The storage site operator shall report T_m, the number of years of post-closure monitoring required until liability transfer to a national entity (or, if no regulations on the transfer of responsibility exist in the applicable legal framework, the number of years of post-closure monitoring required by local regulations).[58] During this time, the operator shall make provisions to cover

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[58] In general, this time frame *should cover* a post-closure monitoring period of roughly 20-50 years, depending on local regulations. The time frame might also be shorter in certain specific cases, such as in the context of projects utilizing rapid mineralization of injected CO_2.

the costs of maintenance, monitoring and control, reporting, and corrective measures to ensure safety and avoid reversals from the storage reservoir. This post-closure monitoring plan shall be in accordance with local regulations.

Variable	Description	Unit
M_s	Emissions related to monitoring and post-closure monitoring of the storage site scaled per tonne of CO_2 injected.	$kgCO_2e/tCO_2$
M	Emissions from monitoring of the storage site for 1 year.	$kgCO_2e/yr$
T_o	Number of years that the storage site will be in operation.	yr
T_m	Number of years of post-closure monitoring required until liability transfer (or, if no regulations on the transfer of responsibility exist in the applicable legal framework, the number of years of post-closure monitoring required by the local regulations).	yr
C_o	Carbon dioxide projected to be stored during operational time T_o.	tCO_2

5.2.19 Whenever external energy inputs are used along the supply chain (e.g. electricity from the grid or steam/heat from a local network), the CO_2 Removal Supplier may utilize renewable energy certificates (REC), guarantees of origin (GOO), direct purchase agreements (DPA), and similar renewable low-carbon energy supply schemes, and thereby correspondingly adjust the emission factors used in the LCA, provided that *all of the following conditions* are fulfilled:

- The purchased certificates originate from the same physical grid or network as where they are consumed (i.e. same spatial resolution).
- The purchased certificates have been issued within the same calendar year as when they are consumed (i.e. same temporal resolution).[59]
- The purchased certificates specify the energy source or mix of sources, so that a carbon footprint can be calculated and used in the LCA (i.e. non-zero value).
- The purchased certificates specify when the production capacity of the energy source or mix of sources was commissioned, and that information is then disclosed by the CO_2 Removal Supplier as part of the Output Audit. The information on the year of commissioning of the energy asset is an indicator of the additionality of the renewable energy production, allowing to distinguish between already existing assets and more recently built assets.[60]
- The amount of purchased certificates matches with the amounts of low-carbon energy declared in the LCA calculations.

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[59] Note that in line with other regulations and trends, Puro.earth envisions that in the future, temporal matching is likely to gradually shift from annual to hourly matching, but it does not yet seem feasible globally as of 2024. Suppliers who already now envision to procure certificates with hourly matching are welcome to do so, as it is also valued by various parties.

[60] Note that in line with other regulations and trends, Puro.earth encourages suppliers to purchase certificates from recently built assets (e.g. less than 3 years old), as it is also valued by various parties.

- The CO_2 Removal Supplier provides evidence of purchased certificates at each Output Audit, or alternatively reverts to using market average emission factors if certificates are no longer purchased.

5.2.20 Energy derived from fossil fuels or as a by-product of their refining (i.e. heat energy) cannot be considered to have a null climate footprint, even in situations where the energy is considered previously unvalued waste energy. Instead, a suitable footprint must be determined depending on the specificities of the process.

5.2.21 The CO_2 Removal Supplier shall endeavor to record in the inventory model approximately 100% of the project emissions associated with each of the project stages (see section 4.5). However, as the total inventory cannot be known with complete certainty, it is possible to exclude elements via the cut-off criteria detailed in subrules a-c.

(a) After a preliminary inventory model that aimed, under best judgment, to approximate 100% of the project emissions per project stage (capture, transport, storage), the CO_2 Removal Supplier shall develop a unit process data set of at least 95% completeness for both embodied and operational emissions per activity boundary.

(b) In the final project emissions calculations, the CO_2 Removal Supplier may ignore the flows or activities that individually account for less than 0.5% of the total approximated emissions of the corresponding activity boundary, provided that the total approximated emissions from all ignored flows or activities does not exceed 5% of the the corresponding activity boundary (see subrule a).

(c) The cut-off criteria shall be applied consistently to each activity boundary, and separately for embodied and operational emissions.

5.2.22 The following elements are considered non-material for the purposes of LCA modeling, and therefore need not be included therein:

- Site selection and feasibility studies.
- Monitoring activities other than storage site monitoring.
- Staff transport (e.g. business travel and employee commuting).

5.3 Activity monitoring for life cycle assessment calculations

5.3.1 The CO_2 Removal Supplier shall update its LCA calculations and report the operational emissions for each monitoring period in accordance with rule 5.2.7 and table 3. To this end, the CO_2 Removal Supplier shall collect the necessary LCA data during each monitoring period in accordance with its monitoring plan (see also rules 5.3.2 and 7.2.5–7.2.7).[61] The reported contributions will be accounted towards the project emissions (E_{project}, see section 4.5) for the monitoring period.

5.3.2 The parameters monitored by the CO_2 Removal Supplier for LCA calculations shall be described in the monitoring plan. Information to be compiled for parameters monitored shall follow the format shown in table 6. In particular, this must include a quantified error value, and how any significant uncertainties in the monitored parameter are conservatively tackled in subsequent calculations.

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[61] Note that the monitoring plan for the LCA calculations can be part of the LCA report, part of a broader monitoring plan of the activity, or a standalone document.

Table 6: Information to be compiled in the monitoring plan for each relevant parameter involved in the LCA calculations.

Parameter	Description
Parameter ID	A unique identifier of the parameter or data point
Data/Parameter	The name of the data point or parameter
Data unit	The unit of the data point or parameter
Description	A brief text describing what the parameter is about, and how it is used in calculations.
Source of data	A brief text describing where the data is sourced from.
Measurement procedures and conservativeness	A brief text describing how the data is obtained, via what measurements, and why the value selected is conservative in light of possible error or uncertainty.
Measurement error	An estimation of the error associated with the measurement, and how it is determined.
Monitoring frequency	The frequency of monitoring of the parameter or data point.
QA/QC procedures	Quality assurance and quality control procedures in place. This may include measurement instrument calibration protocols and certificates.
Comments	Free text comments.

6

Determination of leakage

As defined in the Puro Standard General Rules, leakage refers to indirect effects, associated with a removal activity and dependent on the selected baseline, which may lead to an increase or decrease in greenhouse gas emissions or removals outside of the system boundaries of the activity. Only the increase in GHG emissions or decreases in carbon stocks are quantified, and the removal activity is penalized if those effects are not avoided or mitigated. Net positive effects are not included in the quantification of CORCs.

This section defines what leakage sources are relevant to consider for bio-CCS (including BECCS and waste-CCS) and DACCS projects of different kinds, following the three-step approach defined in the Puro Standard General Rules:

1. Identify and characterize leakage sources.
2. Mitigate leakage sources.
3. Quantify unmitigated leakage sources.

6.1 Identification and characterisation of leakage sources

Scoping of leakage sources

As any infrastructure project, bio-CCS and DACCS projects might have negative effects on nearby land and ecosystems, e.g. due to land drainage for construction purposes, or deforestation as a result of enabling construction.[62] Biomass production and sourcing may also be associated with similar effects, e.g. due to land drainage to enable the use of heavy machinery for harvesting, or deforestation following construction of roads used for transporting the biomass. These types of potential negative effects to nearby land and ecosystems are here called *ecological leakage*.

Another type of leakage, known as *market and activity shifting leakage*, is related to GHG emissions resulting from project activities changing the supply/demand equilibrium, or displacing a previous activity outside the project's boundaries, causing increased emissions elsewhere. In the context of geological storage, the removal pathways are often energy intensive processes, usually due to the carbon capture step, and rely on resources available in limited amounts. In particular, the availability of renewable and low-carbon energy is an important factor for direct air carbon capture, while the availability of renewable, low-carbon and sustainable biomass is important for bio-based carbon capture. Therefore, DACCS and bio-CCS projects can potentially lead to *market and activity shifting leakage relating to bioenergy, biomaterials, renewable energy, biomass markets, or land markets.*

Dependence of leakage effects on the baseline scenario

Regardless of the category (i.e. ecological, or market and activity shifting leakage), leakage sources may materialize differently depending on the baseline scenario applicable to a given

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[62] In this context, *nearby land and ecosystems* refers to the physical areas directly surrounding the project area, but excluding the actual project area itself.

removal pathway. Therefore, the leakage sources identified in this methodology are further characterized for each possible baseline scenario and removal pathway, to specify the conditions under which they are material, and how they can be mitigated or quantified. Several distinctions are introduced for bio-CCS pathways, where two baseline scenarios exist, as well as multiple types of biomass feedstocks and conversion pathways. For DACCS pathways, the same leakage rules apply to all projects, as all capture facilities are considered new built.

> **REMARK:** The *sustainability* of any biomass feedstock must be demonstrated as per the rules in section 3.7, regardless of the baseline scenario and the leakage situations described here. The biomass sustainability criteria are meant to also minimize the situations of ecological, market and activity shifting leakage, as well as direct land use change.

6.1.1 The CO_2 Removal Supplier shall assess all sources of leakage that are identified in this methodology for the removal pathway and baseline scenario utilized by the CO_2 Removal Supplier (see rules 6.1.2–6.1.5). Each leakage source must be either mitigated according to the rules in section 6.2, or quantified according to the rules in section 6.3. Furthermore, the CO_2 Removal Supplier shall account for any unmitigated leakage in the quantification of CORCs according to the rules in section 4.6 (see also rule 4.3.1).

6.1.2 For **DACCS** pathways under the **New Built** baseline, the identified sources of leakage are:

- Ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where facilities (capture, logistics, storage facilities) are built or extended, either via land drainage or land cover change.
- Market and activity shifting leakage relating to the utilization of renewable electricity *in the capture process* in cases when electricity is from a grid.
- Market and activity shifting leakage relating to the utilization of renewable electricity *in the capture process* in cases when electricity is from an off-grid source already in-use for other productive purposes.
- Market and activity shifting leakage relating to the utilization of renewable thermal energy *in the capture process* in cases when thermal energy is from a network.
- Market and activity shifting leakage relating to the utilization of renewable thermal energy *in the capture process* in case when thermal energy is from an off-network source already in-use for other productive purposes.

Further, it is considered that the increased use of sorbents, solvents or their constituents is *not a relevant leakage source*, as the emissions related to their production are included in the supply-chain emissions, assuming new production and the capacity to increase production of said materials (non-constrained market).

6.1.3 For **bio-CCS** pathways under the **New Built** baseline, the identified sources of leakage are:

- Ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where facilities (capture, logistics, storage facilities) are built or extended, either via land drainage or land cover change.
- Ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where biomass is sourced from, either via land drainage

or land cover change (e.g. tree felling).

- Market and activity shifting leakage in the material and energy sector, relating to the use of biomass feedstocks or land that were already utilized for other productive purposes (feedstock diversion).
- Market and activity shifting leakage in the agriculture, forestry and other land use (AFOLU) sector, relating to the use of biomass feedstock or the use of land.

6.1.4 For **bio-CCS** pathways under the **Retrofit** baseline, the identified sources of leakage are:

- Ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where facilities (capture, logistics, storage facilities) are built or extended, either via land drainage or land cover change.
- Ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where biomass is sourced from, either via land drainage or land cover change (e.g. tree felling).
- Market and activity shifting leakage in the material and energy sector, relating to reduced bioenergy or biomaterial output due to retrofitting of the conversion facility (e.g. most commonly, reduced power output due to self-utilization of energy for the capture process).
- Market and activity shifting leakage in the agriculture, forestry and other land use (AFOLU) sector, relating to the use of biomass feedstock or the use of land.

6.1.5 In case the specifics of the removal activity proposed by the CO_2 Removal Supplier do not fully align with the situations described in this methodology (e.g. atypical pathways, mixed baseline), the CO_2 Removal Supplier shall re-assess potential sources of leakage in cooperation with the Issuing Body, who will in turn issue a rule clarification statement. For instance, this might apply to projects where a facility is retrofitted to both expand its biomass processing capacity and add a capture module (see rule 3.4.4), or other unforeseen situations.

6.2 Mitigation of leakage sources

The mitigation of a particular leakage source refers to the process of demonstrating that it has no significant effect in the project area. In this methodology, leakage mitigation relies on a combination of system-level measures and supplier-level measures. In other words, the CO_2 Removal Supplier may demonstrate that an identified source of leakage has no significant effect in the project area by demonstrating that certain features apply in the project area (system-level) in combination with, whenever relevant, other measures directly implemented by the supplier (supply-level). If this can be demonstrated following the rules defined below, the emissions from the corresponding leakage source can be set to zero in the CORC quantification. In some cases, the demonstrated mitigation of a leakage source is a requirement conditioning the eligibility of the project.

Mitigation of ecological leakage

6.2.1 The procedure detailed in subrules a-e shall be applied to mitigate *ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where facilities are built or extended*.

(a) The CO_2 Removal Supplier shall assess this leakage source during the design phase of the project, as part of an environmental impact assessment (EIA) study, or as a standalone assessment. For facilities that have been designed or built prior to the publication date of this methodology, a retrospective assessment shall be performed.

(b) In the assessment of this leakage source, the CO_2 Removal Supplier shall at least:

- Define the areas of land and ecosystems potentially affected (e.g. spatial extent, locations, soil types, hydrology, land cover, cultural and biodiversity values).
- Determine whether or not the planned construction works will affect the local *hydrology*.
- Determine whether or not the planned construction works will affect the *land cover*.
- Conclude whether the nearby land and ecosystems will suffer from loss of carbon stocks or from emissions of other greenhouse gases.

(c) If the assessment concludes that nearby land and ecosystems would not be negatively affected, then this leakage source is considered mitigated and can be set to zero in the quantification of CORCs. Otherwise, the project shall perform an *ex-ante* quantification of the loss of carbon stocks and emission of greenhouse gases, which shall then be included in the CORC quantification as per rule 6.3.1. The *ex-ante* quantification shall be based on either methods derived from the IPCC Guidelines for National Greenhouse Gas Inventories (as in rule 5.2.16), or site-specific quantification approaches.

(d) In case the assessment concludes that nearby land and ecosystems would be negatively affected, but that quantification is not possible, the project is **not eligible** in its current design. However, construction plans or locations may be changed for the project to become eligible.

(e) In case the assessment concludes that nearby land and ecosystems would not be negatively affected, but later events and/or grievances demonstrate otherwise, penalties shall apply retrospectively, following the Puro Standard General Rules for reversals.

6.2.2 The procedure detailed in subrules a-d shall be applied to mitigate *ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where biomass is sourced from.*

(a) The CO_2 Removal Supplier shall assess this leakage source as part of the biomass procurement planning and eligibility assessment of the biomass for each Output Audit, following the latest version of the Puro Biomass Sourcing Criteria.

(b) It is considered that the Puro Biomass Sourcing Criteria are sufficient to ensure that the sourcing of the biomass will not significantly affect the local *hydrology* nor the *land cover* of nearby lands and ecosystems surrounding the areas of sourcing. This is ensured via the sustainability criteria defined in particular for biomass feedstocks sourced from forest and agricultural land (as opposed to e.g. end-of-life feedstocks such as municipal and industrial waste, for which this leakage source is not relevant).

(c) If the biomass feedstock is demonstrated to be eligible, then this leakage source is considered mitigated and can be set to zero in the quantification.

(d) In case the assessment concluded that nearby land and ecosystems would not be negatively affected, but later events and/or grievances demonstrate otherwise, penalties shall apply retrospectively, following the Puro General Rules for reversals.

Mitigation of market and activity shifting leakage in the energy sector for DACCS

6.2.3 For projects utilizing direct air capture with geological storage of carbon dioxide (i.e. DACCS projects), the procedure detailed in subrules a and b shall be applied to mitigate *market and activity shifting leakage relating to the utilization of renewable electricity in the capture process in cases when electricity is from a grid or from an off-grid source already in-use for other productive purposes*.

(a) The CO_2 Removal Supplier shall measure and declare the amount of electricity consumed in the capture process.

(b) Leakage can be deemed mitigated, and thereby set to zero in the quantification of CORCs, if *one of the following conditions* is demonstrated by the CO_2 Removal Supplier on an on-going basis (i.e. at each Output Audit):

- The capture facility is connected to an electricity grid (as defined by the bidding zone, or national boundaries) in which the average proportion of renewable electricity (excluding nuclear power) exceeded 90% in the previous calendar year, or in which the emission intensity of electricity is lower than 18.0 gCO_2e/MJ (64.8 gCO_2e/kWh), as determined by national statistics.[63]
- The capture facility is connected to an electricity grid (as defined by the bidding zone, or national boundaries) that is part of a cap and trade mechanism for emission reductions. *The Issuing Body reserves the right to declare, prior to audit, a specific cap and trade mechanism as not sufficient in case it is deemed not stringent enough to ensure emission reduction (e.g. too many allowances).* In addition, the supplier must procure renewable or low-carbon electricity from the grid, e.g. via direct supply agreements, or purchase of certificates following the requirements specified in rule 5.2.19.
- The capture facility is consuming electricity produced off-grid that used to be sold to specific end-users (i.e. not as part of a grid, but rather an off-grid direct supply), and the CO_2 Removal Supplier can demonstrate that the previous end-users of the electricity have deployed or are planning to deploy other low-carbon means of meeting their energy demand (e.g. via energy efficiency measures, or deployment of new energy systems).

If none of the above conditions apply or can be demonstrated, then leakage remains unmitigated and must be quantified as per rule 6.3.2.

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[63] The quantitative limits in this rule are derived from the EU Commission Delegated Regulation 2023/1184 on rules for the production of renewable liquid and gaseous transport fuels of non-biological origin. The limits set here are indicative of an electricity grid largely dominated by renewable or low-carbon electricity.

6.2.4 For projects utilizing direct air capture with geological storage of carbon dioxide (i.e. DACCS projects), the procedure detailed in subrules a and b shall be applied to mitigate *market and activity shifting leakage relating to the utilization of renewable thermal energy in the capture process in cases when thermal energy is from a grid or from a network or an off-network source already in-use for other productive purposes*.

(a) The CO_2 Removal Supplier shall measure and declare the net amount of thermal energy consumed in the capture process, as well as its quality (i.e. exergy).

(b) Leakage can be deemed mitigated, and thereby set to zero in the quantification of CORCs, if *one of the following conditions* is demonstrated by the CO_2 Removal Supplier on an on-going basis (i.e. at each Output Audit):

- The capture facility is connected to a thermal energy network (e.g. district heating network) in which the average proportion of renewable thermal energy exceeded 90% in the previous calendar year (combined supply- and system-level measure).
- The capture facility is connected to a thermal energy network that is part of a cap and trade mechanism for emission reductions (system-level measure). *The Issuing Body reserves the right to declare, prior to audit, a specific cap and trade mechanism as not sufficient in case it is deemed not stringent enough to ensure emission reduction (e.g. too many allowances).* In addition, the supplier must procure renewable or low-carbon thermal energy from the network, e.g. via direct supply agreements, or purchase of certificates following the requirements specified in rule 5.2.19 (supply-level measure).
- The capture facility is consuming thermal energy produced off-network that used to be sold to specific end-users (i.e. not as part of a network, but rather direct supply), and the CO_2 Removal Supplier can demonstrate that previous end-users of the thermal energy have deployed or are planning to deploy other low-carbon means of meeting their energy demand (e.g. via energy efficiency measures or deployment of new energy systems) (combined supply- and system-level measure).

If none of the above conditions apply or can be demonstrated, then leakage remains unmitigated and must be quantified as per rule 6.3.2.

Mitigation of market and activity shifting leakage in the material and energy sector for bio-CCS

6.2.5 For projects utilizing the bio-CCS New Built scenario (see subrule 3.4.3 (b)), the procedure detailed in subrules a and b shall be applied to mitigate *market and activity shifting leakage in the material and energy sector, relating to the use of biomass feedstocks or land that were already utilized for other productive purposes* (feedstock diversion).

(a) To mitigate leakage related to the **use of nutrient rich (N, P, K) waste streams** (e.g. animal manure) from which nutrients were previously recovered (e.g. via digestate, composting, or direct land application), but which are subsequently utilized for bio-CCS **via a thermochemical conversion process** (leading to nutrient losses), the procedure detailed below shall be applied.

The CO_2 Removal Supplier shall first quantify the amount of nutrients (N, P, K) which are no-longer recycled to soils (on an annual basis, in tonnes per year). Negative leakage occurs if the feedstock diversion leads to a net decrease in nutrient recycling. However, leakage is deemed mitigated, and thereby set to zero in the quantification of CORCs, if the following condition can be demonstrated by the CO_2 Removal Supplier:

- The project area suffers from an over-supply of nutrients that has demonstrated negative effects on water resources.

If the above condition cannot be demonstrated, leakage remains unmitigated, and shall be quantified according to rule 6.3.3.

(b) To mitigate leakage related to the **use of other biomass feedstocks that were already utilized** for another **known and identified productive purpose** (i.e. not left to decay in the field or forest floor, nor sourced from a market; excluding nutrient-rich waste streams covered in subrule 6.2.5 (a)), the procedure detailed below shall be applied.

The CO_2 Removal Supplier shall first:

- Identify the previous use of the biomass.
- Characterize the change in product generation entailed by the feedstock diversion (i.e. gains and losses in material and energy products).
- Provide a written justification for why the feedstock diversion is deemed environmentally favorable in the context of the project.

Leakage is deemed mitigated or not-applicable, and thereby set to zero in the quantification of CORCs, if *one of the following conditions* can be demonstrated by the CO_2 Removal Supplier:

- Previous use is scheduled to be discontinued or phased-out (e.g. factory reaching end-of-life, regulation planning to phase-out a technology).
- Previous use and new use are of the same type (i.e. producing similar material and energy products), but the previous use is technically less efficient and thereby produces less material and/or energy products.
- Previous use is associated with significant negative direct environmental or social impacts (e.g. incomplete combustion, improper flue gas treatment, unsafe working conditions).

If none of the conditions above can be demonstrated, the leakage source shall be further assessed as in rule 6.2.6 (similar to bio-CCS retrofit) and, where unmitigated, quantified as per rule 6.3.4.

6.2.6 For projects utilizing the bio-CCS Retrofit scenario (see subrule 3.4.3 (a)), or when required by subrule 6.2.5 (b), the procedure detailed in subrules a-c shall be applied to mitigate *market and activity shifting leakage in the material and energy sector, relating to reduced bioenergy or biomaterial output due to retrofitting of the conversion facility*.

(a) The CO_2 Removal Supplier shall provide a mass and energy balance for the facility before and after retrofitting, under normal conditions. The mass and energy balance shall fulfill the following requirements:

- Quantified in annual amounts (per year).

- Scaled to the same amount of input feedstock (typically tonnes of biomass feedstock used per year).
- Quantified all inputs (e.g. biomass, external energy sources), all bioenergy or biomaterial outputs,[64] the captured CO_2 output, as well as waste streams (e.g. ashes sent for disposal). Any amount of bioenergy used internally e.g. for operating the capture process shall be excluded from the bioenergy outputs.

Note that for certain energy systems, the mass and energy balance can include net system effects on bioenergy or biomaterial outputs, in which case associated calculations and evidence must be provided. This applies, e.g. to the case of retrofitting combined heat and power plants that are connected to large district heating networks. In this case, retrofitting usually leads to an increased heat output and a decreased electricity output. However, the increased heat output can reduce electricity consumption from large-scale heat pumps in the same direct heating network, thereby partly reducing the net electricity loss to the electricity grid entailed by retrofitting.

(b) If retrofitting of the conversion facility does not lead to any decrease in bioenergy or biomaterial outputs, then no negative leakage occurs, and it can be set to zero in the quantification of CORCs. *This is typically the case for retrofitting of anaerobic digestion and alcoholic fermentation facilities.* If retrofitting leads to an increase in bioenergy or biomaterial output (without any other decrease), then positive leakage occurs, but no benefits are granted in the quantification of CORCs: leakage is also set to zero. *This might be the case when retrofitting of an existing facility also introduces new energy efficiency measures.*

(c) If retrofitting of the conversion facility leads to a decrease in one or several bioenergy or biomaterial outputs, then negative leakage occurs for those outputs. For the outputs where negative leakage occurs, leakage is deemed mitigated, and thereby set to zero in the quantification of CORCs, if *one of the following conditions* (per output type) can be demonstrated by the CO_2 Removal Supplier on an on-going basis (i.e. at each Output Audit):

(i) For reduced **electricity** output:

- The facility is connected to an electricity grid (as defined by the bidding zone, or national boundaries) in which the average proportion of renewable electricity (excluding nuclear power) exceeded 90% in the previous calendar year, or in which the emission intensity of electricity is lower than 18.0 gCO_2e/MJ (64.8 gCO_2e/kWh) as determined by national statistics (combined supply- and system-level measure).[65]
- The facility is connected to an electricity grid (as defined by the bidding zone, or national boundaries) that is part of a cap and trade mechanism for emission reductions

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[64] Depending on the facility type, bioenergy or biomaterial outputs might include e.g. electricity, heat, steam, biogas, liquid fuel, animal feed, food products, fertilizers, chemicals, and materials.

[65] The quantitative limits in this rule are derived from the EU Commission Delegated Regulation 2023/1184 on rules for the production of renewable liquid and gaseous transport fuels of non-biological origin. The limits set here are indicative of an electricity grid largely dominated by renewable or low-carbon electricity.

(system-level measure). *The Issuing Body reserves the right to declare, prior to audit, a specific cap and trade mechanism as not sufficient in case the is not deemed stringent enough to ensure emission reduction (e.g. too many allowances).* In addition, the supplier shall procure renewable or low-carbon electricity for the amounts it consumes from the grid after retrofitting (supply-level measure).

If none of the conditions above apply or if they cannot be demonstrated, then leakage remains unmitigated and must be quantified as per rule 6.3.4.

(ii) For reduced **thermal energy** (heat or steam) output:

- The facility is connected to a thermal energy network (e.g. district heating network) in which the average proportion of renewable thermal energy exceeded 90% in the previous calendar year.
- The facility is connected to a thermal energy network that is part of a cap and trade mechanism for emission reductions (system-level measure). *The Issuing Body reserves the right to declare, prior to audit, a specific cap and trade mechanism as not sufficient in case the is deemed not stringent enough to ensure emission reduction (e.g. too many allowances).* In addition, the supplier shall procure renewable or low-carbon thermal energy for the amounts it consumes from the network after retrofitting (supply-level measure).
- The facility was delivering thermal energy to specific end-users (i.e. not as part of a network, but rather direct supply), and the CO_2 Removal Supplier can demonstrate that previous end-users of the thermal energy have deployed or are planning to deploy other low-carbon means of meeting their energy demand (e.g. via energy efficiency measures or deployment of new energy systems) (combined supply- and system-level measure).

If none of the conditions above apply or if they cannot be demonstrated, then leakage remains unmitigated and must be quantified as per rule 6.3.4.

(iii) For reduced **gas** or **liquid fuel** output:

- No mitigation rules are currently defined in this methodology.[66] This leakage source must be quantified as per rule 6.3.4.

(iv) For reduced **biomaterial output** (animal feed, food product, chemicals, materials):

- No mitigation rules are currently defined in this methodology. This leakage source must be quantified as per rule 6.3.4.

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[66] Further mitigation rules might be included in future revisions.

Note: The situation described in rule 6.2.6 typically materializes when retrofitting power plants or combined heat and power plants fueled by either solid biomass (e.g. forest residues) or municipal solid waste, where a large share of the energy would be used in the carbon capture process, diminishing the amount of electricity supplied to the local grid (and often increasing the amount of heat supplied).

Mitigation of market and activity shifting leakage in the land sector for bio-CCS

6.2.7 For bio-CCS projects regardless of the scenario (whether New Built or Retrofit, see rule 3.4.3), the procedure detailed in subrules a-d shall be applied to mitigate *market and activity shifting leakage in the agriculture, forestry and other land use (AFOLU) sector, relating to the use of biomass feedstock or the use of land*.

(a) In cases where the biomass feedstock is a **post-consumer or industrial waste stream** (feedstock categories defined in subrules 3.7.3 (a)–(f)), this leakage source is considered irrelevant.

(b) In cases where the biomass feedstock originates from **agricultural or forest land**, **but is not the primary driver of the land use** and **is not a feedstock associated with high iLUC risks** (see subrule 6.2.7 (d)), this leakage source is considered mitigated provided that the biomass sourcing criteria are met.[67]

Examples of such situations include:

- Forest residues or sawmill residues originating from forest land, where the primary driver of land use is timber for material use
- Wheat straw sourced from agricultural land, where the primary driver of land use is food production.

(c) In cases where the biomass feedstock originates from **agricultural land, and is the primary driver of the land use** (food crops and energy crops), but **is not a feedstock associated with high iLUC risks** (see subrule 6.2.7 (d)), this leakage source is considered mitigated provided that the CO_2 Removal Supplier demonstrates, on an on-going basis (i.e. at each Output Audit) and for each biomass feedstock, that *one of the following conditions* is met:

- The feedstock is used in a conversion process whose primary product is a food product (e.g. distilleries for beverages)
- The feedstock is produced on agricultural land as an intermediary or cover crop.
- The feedstock is produced on marginal land, degraded or contaminated land, not suited for food or feed production.

If none of the conditions above can be demonstrated, then:

- For food crops, including starch crops, sugar crops and oil crops, the feedstock is considered eligible provided that the biomass sourcing criteria are met (see in particular criteria for categories defined in subrules 3.7.3 (i) and (j)). For eligible feedstocks, the CO_2 Removal Supplier shall quantify and account for this leakage source in accordance with rule 6.3.5.

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[67] The biomass sourcing criteria include considerations on land carbon stocks (at the level of the sourcing area) to mitigate negative effects from land use intensification or indirect effects in the sourcing area.

- For other crops, i.e. energy crops (e.g. willow grown on agricultural land that could have been used for food production), the feedstock is considered *not eligible*.

(d) In cases where the biomass feedstock originates from **agricultural or forest land and the feedstock is associated with high iLUC risks** (in the sense defined below), the feedstock is considered eligible provided that the CO_2 Removal Supplier demonstrates, on an on-going basis (i.e. at each Output Audit), that:

- The biomass sourcing criteria are met.
- The feedstock is certified by a third-party as being associated with low iLUC risks, under a voluntary certification scheme recognized under the EU RED II/III, or similar regulations or schemes approved by the Issuing Body.

For eligible feedstocks, the CO_2 Removal Supplier shall quantify and account for this leakage source in accordance with rule 6.3.5.

In this methodology, a **feedstock associated with high iLUC risks** (regardless of whether the feedstock is the primary product or a co-product of the cultivation activity) is defined as a feedstock for which a significant expansion of the production area into land with high-carbon stock is observed.[68] In this methodology, high iLUC-risk feedstocks currently include:

- Biomass from palm tree plantations.
- Biomass from soybean cultivation.

6.3 Quantification of unmitigated leakage sources

Quantification of ecological leakage

6.3.1 The CO_2 Removal Supplier shall quantify and amortize any unmitigated *ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where facilities are built or extended* as further detailed in subrules a and b. the following applies for the amortization of emissions per tonne of CO_2 processed:

(a) The CO_2 Removal Supplier shall perform an *ex-ante* quantification of any unmitigated leakage related to this leakage source in accordance with subrule 6.2.1 (c). For each facility x (where x denotes either a capture facility, a transport and logistics facility, or an injection facility), the CO_2 Removal Supplier shall determine, in absolute terms, the corresponding unmitigated leakage, denoted EL_x (in tCO_2e).

(b) For each facility x, the absolute impact EL_x (see subrule a) shall be added to the term E_{ECO} under E_{leakage} (see rule 4.6.1), and amortized following the same procedure as for embodied emissions in rule 5.2.15.

Quantification of market and activity shifting leakage for DACCS

6.3.2 The CO_2 Removal Supplier shall quantify any unmitigated *market and activity shifting leakage relating to electricity or thermal energy consumption during the capture stage* as

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[68] This definition is adopted from the Directive 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 (recast).

follows.

$$L_{\mathrm{MA}} = Q_{\mathrm{el}} \times EF_{\mathrm{el}} + Q_{\mathrm{th}} \times EF_{\mathrm{th}} \tag{17}$$

(a) By definition, the term L_{MA} is a number higher or equal to zero, and cannot be negative.

(b) The emission factors EF_{el} and EF_{th} are defined as positive numbers, which shall be determined as follows:

- For electricity, EF_{el} is the average emission factor of the grid (as defined by the bidding zone, or national boundaries) to which the facility is connected.
- For thermal energy (heat or steam), $EF_{\mathrm{th}}$is the average emission factor of the network to which the facility is connected, or the most likely non-constrained substitute off-network thermal energy source available in the area where the facility is located.

The values for the emission factors EF_{el} and EF_{th} shall be updated annually.

Variable	Description	Unit
L_{MA}	Market and activity leakage for the monitoring period (typically one year).	tCO_2e
Q_{el}	The amount of electricity consumed during the monitoring period for which leakage was not mitigated.	kWh
EF_{el}	Emission factor for electricity.	tCO_2e/kWh
Q_{th}	The amount of thermal energy consumed during the monitoring period for which leakage was not mitigated.	kWh
EF_{th}	Emission factor for thermal energy.	tCO_2e/kWh

Quantification of market and activity shifting leakage for bio-CCS New Built

6.3.3 The CO_2 Removal Supplier shall quantify any unmitigated *market and activity shifting leakage relating to decrease in nutrient (N, P, K) recycling via diversion of a nutrient-rich feedstock* as follows.

$$L_{\mathrm{MA}} = \max\left(0, \sum_{i \in S} \Delta O_i \times EF_i\right) \tag{18}$$

(a) By definition, the term L_{MA} is a number higher or equal to zero, and cannot be negative.

(b) For the nutrient i, the term $\Delta O_i$is positive in case of a net loss in nutrient recycling, and negative in case of a net gain in nutrient recycling. Within this leakage category, the CO_2 Removal Supplier may consider both gains and losses to calculate a net leakage effect.

(c) The emission factors EF_i are defined as positive numbers, which shall be derived from an LCA database. The emission factors EF_i shall be updated annually.

Variable	Description	Unit
L_{MA}	Market and activity leakage for the monitoring perio (typically one year).	tCO_2e
ΔO_{i}	Net change in nutrient recycling for the nutrient i (limited to N, P, K) following feedstock diversion	tonnes
EF_i	Emission factor representative of the production of an alternative source of nutrient i	tCO_2e/tonne
i	Summation index (an element in the set of nutrients S)	unitless
S	The set of nutrients $\{N, P, K\}$ (nitrogen, phosphorus and potassium).	unitless

Quantification of market and activity shifting leakage for bio-CCS Retrofit

6.3.4 The CO_2 Removal Supplier shall quantify any unmitigated *market and activity shifting leakage relating to reduced bioenergy or biomaterial output due to retrofitting of the conversion facility* as follows.

$$L_{\mathrm{MA}} = \max\left(0, \sum_{i \in S} \Delta O_i \times EF_i\right) \tag{19}$$

(a) By definition, the term L_{MA} is a number higher or equal to zero, and cannot be negative.

(b) For the output i, the term $\Delta O_i$is positive in case of a net loss of the output, and negative in case of a net gain of the output. Within this leakage category, the CO_2 Removal Supplier may consider both gains and losses to calculate a net leakage effect.

(c) The emission factors EF_i are defined as positive numbers, which shall be determined based on the type of output as follows:

- For **electricity**, EF_i is the average emission factor of the grid (as defined by the bidding zone, or national boundaries) to which the facility is connected.
- For **thermal energy** (heat or steam), EF_i is the average emission factor of the network to which the facility is connected or the most likely non-constrained substitute off-network thermal energy source available in the area where the facility is located.
- For **gas** or **liquid fuel**, EF_i is the most likely non-constrained substitute fuel source available in the area where the facility is located.
- For **biomaterial output** (animal feed, food product, chemicals, materials), EF_i is the most likely non-constrained substitute material available in the area where the facility is located.

The emission factors EF_i shall be updated annually.

Variable	Description	Unit
L_{MA}	Market and activity leakage for the monitoring period (typically one year).	tCO_2e
ΔO_i	Net change in bioenergy or biomaterial output i (for the monitoring period) following retrofitting.	tonnes or MJ
EF_i	Emission factor representative of the service delivered by the output i.	tCO_2e per tonne or MJ
i	Summation index (an element in the set of outputs S)	unitless
S	The set of relevant bioenergy or biomaterial outputs (e.g. electricity, thermal energy, gas or liquid fuels, and biomaterials).	unitless

Quantification of market and activity shifting leakage relating to use of biomass feedstock

6.3.5 The CO_2 Removal Supplier shall quantify any unmitigated *market and activity shifting leakage in the agriculture, forestry and other land use (AFOLU) sector, relating to the use of biomass feedstock or the use of land* as follows.

(a) The CO_2 Removal Supplier shall utilize the iLUC factors[69] listed in table 7 to calculate, for each monitoring period, an additional contribution to the market and activity shifting leakage (L_{MA}) due to land sector leakage (see rule 6.2.7). This additional contribution, denoted $iLUC$, shall be calculated as follows.

$$iLUC = \sum_{f \in F} \left(Q_f \times LHV_f \times iLUC_f \times AF\right) \tag{20}$$

(b) The value of the term $iLUC$ shall be added to the market and activity shifting leakage (L_{MA}) for the monitoring period.

(c) The value of the attribution factor AF is defined as 100% in the general case, meaning that the iLUC emissions are conservatively attributed in full to the CORCs issued.

(d) The value of the attribution factor AF can be lowered only if the CO_2 Removal Supplier can demonstrate that *both of the following conditions* apply:

- The climate footprints of the co-products (e.g. biofuel, bioenergy, biomaterials) incorporate in part or in full the iLUC emissions.
- The climate footprints of the co-products are reported as part of an governmental or intergovernmental regulatory scheme (e.g. EU RED II / III).

In cases where both of the above conditions are demonstrated by the CO_2 Removal Supplier, the value of the attribution factor AF shall be equal to the percentage share of iLUC emissions that have not been attributed to the co-products (thus not double-counting the iLUC emissions).

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[69] Reproduced from the EU RED II directive, Annex VIII: 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 (recast).

Variable	Description	Unit
$iLUC$	Indirect land use change contribution to be added to market and activity shifting leakage, for the monitoring period.	tCO_2e
Q_f	Quantity of the biomass feedstock f with high risk of indirect land use change processed during the monitoring period	dry metric tonnes
LHV_f	Lower heating value of the biomass feedstock f, expressed in GJ per dry tonnes.	GJ / dry metric tonne
$iLUC_f$	Indirect land use change factor for biomass feedstock of type f *(see values in table 7)*	kg CO_2e/MJ
AF	Attribution factor of the iLUC emissions to the CORC, varying between 0 and 100%, and set to 100% in the normal case.	unitless
f	Summation index (an element in the set of biomass feedstocks F)	unitless
F	The set of biomass feedstock processed during the reporting period that are associated with high risks of land use change, grouped as: cereals and other starch-rich crops, sugar crops, oil crops *(see values in table 7)*.	unitless

Table 7: iLUC factors for different crop types.

Crop type	iLUC factor[a]
Cereals and other starch-rich crops	0.012
Sugar crops	0.013
Oil crops	0.055

[a] The iLUC factors are derived from the EU RED II, Annex VIII, and are expressed per MJ of biomass feedstock on a dry lower heating value basis.

7

Data collection and monitoring

7.1 Overall principles

Monitoring, data collection and reporting are essential to ensure that the requirements prescribed in this methodology have been fulfilled. Due to the technical complexity of deep geological storage, as well as the substantial risks involved with a poorly chosen or managed storage site, it is paramount that a robust local legal framework is in place to regulate the geological storage operations and mitigate risks (see also section 8). This methodology only allows geological storage operations in jurisdictions where such a framework already exists (see rule 3.2.11). As a design principle, this methodology aims to rely on—rather than reduplicate—local regulations to ensure a safe and operationalizable result.

In general, abundant external resources on the design and operation of the geological storage activity are available to the CO_2 Removal Supplier. The below-listed examples of such resources contain useful information, outlines and recommendations on risk assessment, injection operations, monitoring, and other practicalities.

- Regulatory guidance documents from the US Environmental Protection Agency
    - Class VI - Wells used for Geologic Sequestration of Carbon Dioxide
    - Final Class VI Guidance Documents
    - Class VI Permit Application Templates
    - Table of EPA's Draft and Final Class VI Well Permits (see “Permit Documents”)
    - General Technical Support Document for Injection and Geologic Sequestration of Carbon Dioxide: Subparts RR and UU
- Regulatory guidance documents from the EU for the implementation of directive 2009/31/EC on the geological storage of carbon dioxide
    - CO_2 storage life cycle risk management framework
    - Characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures
    - Criteria for transfer of responsibility to the competent authority
    - Article 19 Financial Security and Article 20 Financial Mechanism
- Regulatory guidance documents from the UK North Sea Transition Authority
    - Guidance on Applications for a Carbon Storage Permit
    - Guidance on the content of an Offshore Carbon Storage Permit Applications
- ISO and national standards
    - ISO 27914:2017 Carbon dioxide capture, transportation and geological storage

  - 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
  - CSA Z741:12 (R2022) Geological storage of carbon dioxide

While adherence to the above external documents is not required in this methodology (except if/when explicitly stated in a numbered rule, or required by local regulations), they can be a useful source of background information to assist the CO_2 Removal Supplier in creating a well designed and monitored geological storage project.

In practice, the monitoring, reporting and verification procedure followed in this methodology consists of monitoring and reporting by the CO_2 Removal Supplier, verification by a recognized third-party auditor, and finally issuance of CO_2 Removal Certificates (CORCs). A key step in verifying the monitoring data consists of inspection of relevant evidence and corroborating calculations by the auditor. Depending on the requirement, the pieces of evidence themselves can take various forms, such as data records, permits, official documents, or other relevant information which demonstrate compliance with the requirements, and enable claims to be verified. If the auditor concludes, based on the evidence presented, that the carbon removal activity is compliant with the requirements of this methodology, the validated amount of CORCs is then issued to the CO_2 Removal Supplier.

Note that while this section contains several overarching requirements on the data collection, monitoring, and reporting requirements concerning the geological storage activity, additional requirements on these topics are included in other sections of this methodology as well.

7.2 General monitoring requirements

The main objectives for monitoring the geological storage activity are:

- **Confirm** the containment of CO_2.
- **Alert** to increased risk of adverse events (e.g. CO_2 leaks, environmental contamination).
- **Verify** that the injected CO_2 behaves as expected.
- **Identify** any occurring adverse events.
- **Enable** reliable quantification of stored carbon and any emissions.
- **Optimize** injection and storage operations.

It is important to note that these goals can be achieved through several routes, and multiple monitoring techniques can often be utilized for the same parameter. As different approaches might be preferred in different situations, the CO_2 Removal Supplier should always consider **site-specific needs** and choose a suite of monitoring technologies that enable the volume and location of injected CO_2 to be verified at the levels of resolution and certainly required by the applicable local regulations and this methodology.

While the resolutions or accuracies of individual tools in the monitoring suite may vary, it is the cumulative data from the monitoring approach as a whole (including e.g. reservoir modeling and careful monitoring of injection rates and other parameters) that yields the necessary level of detail to determine with a very high degree of certainty that the CO_2 is effectively stored; that groundwater, surface resources, and the environment are being protected; and that any irregularities can be detected and addressed before they escalate.

7.2.1 The CO_2 Removal Supplier shall prepare and make available to the Auditor documentation that demonstrates conformity of the geological storage activity with the requirements of this methodology, as well as the Puro Standard General Rules and other Standard Requirements.

7.2.2 The CO_2 Removal Supplier shall have in place, maintain, and utilize an **information system** to keep records of all monitoring activities associated with the geological storage activity. These records shall at least include information on the parameter or process monitored (i.e. what was monitored and how), as well as results of any measurements performed.[70] The information shall be time-stamped and quantitative (where applicable). These records shall be available to the Auditor, for the Production Facility Audit and Output Audits.

7.2.3 The terminology used in this methodology in relation to monitoring frequency shall be interpreted as detailed in subrules a and b:

(a) The following definitions apply to the description of monitoring frequency:

- **Continuous** monitoring is defined as at least once every 15 minutes.
- **Monthly** monitoring is defined as at least once per calendar month.
- **Quarterly** monitoring is defined as at least four times per calendar year (once every three months).
- **Semi-annual** monitoring is defined as at least twice per calendar year (once every six months).
- **Annual** monitoring is defined as at least once per calendar year.
- **Periodical** monitoring is defined as monitoring at predetermined, regular temporal intervals decided by the CO_2 Removal Supplier based on site-specific needs as well as any applicable regulations. The monitoring frequency and rationale thereof shall be explained in the monitoring plan.

(b) Monitoring activities with a predefined cadence (e.g. quarterly monitoring) shall be evenly distributed throughout the monitoring period (e.g. once every three months for quarterly monitoring). The CO_2 Removal Supplier may make reasonable adjustments to the monitoring schedule for reasons of necessity or practicality, but such adjustment shall not result in any undue or disproportionate delays to the monitoring activities.

7.2.4 Unless otherwise specified, all monitoring shall be based on data specific to the CO_2 Removal activity and sites of operation (e.g. capture/storage site).

7.2.5 The CO_2 Removal Supplier shall prepare, maintain, and comply with a monitoring plan for the geological storage activity, as further described in subrules a-e.[71]

(a) The monitoring plan shall be tailored to the specific characteristics and requirements of all stages (capture, transport, and injection) within the activity boundary (see rule 5.2.6).

(b) The monitoring plan shall describe procedures for measuring, calculating and analyzing data and information to ensure that the storage reservoir conforms

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[70] Note also rule 4.2.5 on keeping records of events that affect the quantification of CORCs. Note that these records are at least partly separate, as not all monitoring activities or results thereof necessarily affect the number of CORCs.

[71] Note also the requirements in section 5.3 relating to activity monitoring plans for LCA calculations, which may be incorporated in the monitoring plan described here, or in other documents (see rule 5.3.1).

to expected behavior, and that any injected CO_2 remains securely contained. To this end, the monitoring plan shall at least:

- Identify potential vulnerabilities and propose solutions to mitigate recognized vulnerabilities.
- Specify monitoring parameters and define monitoring tasks.

(c) The monitoring plan shall cover activities throughout the duration of the geological storage activity, including:

- Baseline data gathering and storage site characterization (pre-injection period).
- Performance of the storage reservoir during operations (injection period).
- Closure of the storage site and post-closure monitoring (post-injection period).

(d) The monitoring plan shall describe how the CO_2 Removal Supplier will provide monitoring data for the variables and quantities required by this methodology. This description shall at least include:

- Parameters monitored.
- Monitoring methods employed (including measurement device type and quantification accuracy where applicable) and rationale for choice of method.
- Monitoring locations and spatial sampling rationale.
- Frequency of application and temporal sampling rationale.
- Normal and alert thresholds for monitored parameters, including corresponding mitigation activities (see also rules 7.2.7 and 7.6.2).

(e) The monitoring plan shall be periodically evaluated and updated to ensure that the monitoring practices continue to be appropriate and effective. The evaluation shall include a re-assessment of the site-specific monitoring requirements and risks. For example, updates to the monitoring plan might be necessary due to:

- Monitoring and site performance data.
- New scientific knowledge.
- Improvements in best available technology.

7.2.6 The monitoring plan shall include a detailed description of at least the following aspects:

- Operational monitoring of the CO_2 Stream.
- Monitoring the CO_2 plume or CO_2 charged water.[72]
- Monitoring pathways for potential release based on risk-assessment.

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[72] The term 'CO_2 charged water' is utilized in this methodology to refer to the body of injected water-dissolved CO_2 (as opposed to 'CO_2 plume' which refers to free-phase CO_2 in the subsurface). See also glossary entries for CO_2 *charged water* and CO_2 *Plume*.

- Environmental monitoring for detection and quantification of release from the storage site.

7.2.7 The monitoring plan shall describe how the CO_2 Removal Supplier plans to respond to any significant irregularities in the performance of the monitoring or storage systems during the capture, injection and storage operations (contingency monitoring).

7.2.8 All measurement devices shall be installed, operated and calibrated according to the device manufacturer's specifications or according to an appropriate industry consensus standard.

7.2.9 All measurement devices utilized for quantification shall be calibrated to an accuracy of at least 5% (i.e. the calibration error of any measurement device shall not exceed 5%). Calibration records shall be made available for third-party verification.

This requirement does not apply to energy (heat, electricity, fuel) billing meters, provided that the energy supplier and the CO_2 Removal Supplier do not have any common owners and are not owned by subsidiaries or affiliates of the same company.

7.3 Monitoring of the CO_2 Stream and related parameters

7.3.1 The CO_2 Removal Supplier shall continuously monitor the mass flow rate of CO_2 entering the storage reservoir through direct measurement of the flow in accordance with rule 4.4.7. In the case of a geological storage activity utilizing injection of dissolved CO_2 (see rule 3.2.6), the CO_2 Removal Supplier shall also continuously monitor the mass flow rate of the water stream entering the storage reservoir through an equivalent direct measurement of the water flow.

7.3.2 The CO_2 Removal Supplier shall continuously monitor the temperature and pressure in the injection wells (for example, by means of downhole pressure and temperature gauges) to determine CO_2 phase behavior and state. Where the direct measurement of downhole temperature and pressure is not possible (e.g. due to device maintenance or calibration), the CO_2 Removal Supplier may estimate downhole conditions based on relevant operational data (e.g. well hydraulic models combined with measured flow rates, as well as temperature and pressure at the wellhead).

7.3.3 The CO_2 Removal Supplier shall at least quarterly monitor the chemical composition of the CO_2 Stream. For the purposes of this rule, 'chemical composition' refers to both the chemical constituents[73] of the CO_2 Stream as well as their concentrations.

(a) The chemical composition analysis shall be performed with a commercially available device. The analysis shall be performed with a method in accordance with applicable local regulations or, if no such regulations exist, in accordance with an appropriate standard method published by a consensus-based standards organization, or industry standard practice. Potential methods include, but are not limited to gas chromatography, mass spectrometry, and infrared spectroscopy.

(b) The sampling of the CO_2 Stream for the chemical composition analysis shall be performed as close to the injection wellhead as feasible. However, the

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[73] The CO_2 Stream consists overwhelmingly of CO_2, but depending on the capture process it might also contain other impurities and trace substances such as water (H_2O), hydrogen (H_2), hydrogen sulfide (H_2S), carbon monoxide (CO), nitrogen (N_2) and its oxides (e.g. N_2O), sulfur oxides (SO_x), oxygen (O_2), methane (CH_4), and argon (Ar), which can affect the chemical and physical properties of the CO_2 Stream and its behavior and reactions underground [47].

sampling shall be performed prior to mixing with any other CO_2 Streams (e.g. in cases where the CO_2 Stream is transported via shared infrastructure or CO_2 Streams from several different sources are mixed prior to injection into a shared geological storage reservoir).

7.3.4 The CO_2 Removal Supplier shall at least quarterly monitor the mass fraction (in % mass) or volume fraction (in % vol) of CO_2 in the injected fluid through direct measurement of the CO_2 concentration of the CO_2 Stream (i.e. the parameters F_{CO_2} or Q_{CO_2}, in accordance with the type of flow measurements utilized, see rule 4.4.2).

(a) Any of the following methods may be utilized for the determination of the CO_2 concentration of the CO_2 Stream:

- Direct measurement of the entire chemical composition of the CO_2 Stream in accordance with rule 7.3.3.
- Direct measurement of the CO_2 concentration (i.e. the CO_2 concentration alone as opposed to the entire chemical composition including impurities) with a CO_2 sensor or other suitable measurement device. The CO_2 Removal Supplier shall nevertheless follow the measurement process requirements laid out in subrules 7.3.3 (a) and (b).

(b) To ensure the representativeness of the determined values, the CO_2 Removal Supplier shall, when necessary, increase the quantification frequency based on the variability (or expected variability) of the CO_2 concentration of the CO_2 Stream due to factors specific to the geological storage activity (such as capture technology and post-capture treatment). The quantification frequency shall at least be increased whenever the absolute difference between two successive measurements of F_{CO_2} or Q_{CO_2} is one percentage point or more.

7.3.5 In the case of a geological storage activity utilizing injection of dissolved CO_2 (see rule 3.2.6), the CO_2 Removal Supplier shall at least monthly monitor the bubble point pressure of the CO_2 charged water as described in subrules a and b.

(a) The CO_2 Removal Supplier shall calculate the bubble point pressure utilizing an equation of state appropriate for the computation of gas/liquid equilibria in reservoir fluid systems, such as the Peng-Robinson equation.[74] The calculation shall be based on representative operational monitoring data (e.g. mass flow rates, temperatures, and chemical composition of the fluids entering the injection well).

(b) The CO_2 Removal Supplier shall ensure that the reservoir pressure is higher than the bubble point pressure by a safety margin of at least 5 bar (500 kPa). For any occasion where this requirement is not met, the injected mass of CO_2 leading to the bubble point pressure exceeding its limits shall be treated as a reversal, and attributed to E_{reversal} (see rule 4.7.2).

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[74] Note that while there is no all-in-one equation of state that will give the best prediction of all thermodynamic properties of different types of reservoir fluids, the Peng-Robinson equation [48] has shown excellent performance for phase transitions, and it is commonly utilized in reservoir engineering [49].

7.4 Capture site and transport monitoring

7.4.1 The CO_2 Removal Supplier shall continuously monitor the amount of CO_2 captured (in tonnes) at the capture site through direct measurement of the flow in accordance with rule 4.4.7.

7.4.2 The CO_2 Removal Supplier shall at least semi-annually monitor the fraction of eligible CO_2 in the captured CO_2 Stream (F_{eligible}) through radiocarbon analysis and/or based on operational data records in accordance with rule 4.4.5.

This rule does not apply to cases where the CO_2 Stream is captured directly from the atmosphere, or from purely biogenic sources, provided that both of the below requirements are satisfied:

- The CO_2 Removal Supplier provides operational data records that rule out ineligible sources of CO_2 in the captured stream (i.e. $F_{\text{eligible source}} = 100\%$, see subrule 4.4.5 (c)).
- Where applicable, the CO_2 Removal Supplier provides operational data records to show that all processed biomass feedstocks are eligible (i.e. $F_{\text{eligible biomass}} = 100\%$, see subrule 4.4.5 (d))

7.4.3 The CO_2 Removal Supplier shall monitor the consumption (in kg) and consumption rate (in kg per tonne of CO_2 captured) of any sorbents or solvents used for the CO_2 capture process, including initial consumption at the start operations as well as all subsequent re-fills. The monitoring shall be based on actual operation data.

7.4.4 The CO_2 Removal Supplier shall monitor the quantity of all CO_2 transported from the capture site to the storage site (unless the capture site coincides with the storage site).

(a) In the case where CO_2 is transported via pipeline, the CO_2 Removal Supplier shall provide data and documentation on the amount of CO_2 (in tonnes) fed into the pipeline system.

(b) In the case where CO_2 is transported in containers (e.g. via cargo ship, rail, or trucks), the CO_2 Removal Operator shall provide documentation from the logistics operator on the amount of CO_2 (in tonnes) delivered to the storage site.

7.5 Storage site monitoring

7.5.1 The CO_2 Removal Supplier shall provide a permit, authorization, license, or equivalent regulatory control document showing that the storage site is duly approved for permanent geological storage of carbon dioxide to the extent required by local regulation.

7.5.2 The CO_2 Removal Supplier shall provide documentation of the characterization of the storage site and its suitability for permanent geological storage of CO_2. The documentation shall show that the storage site fulfills the minimum criteria of suitability for geological storage to the extent defined in the applicable local regulations.[75] Furthermore, the documentation shall detail the manner in which the suitability was assessed. For example, such documentation might include:

- Description of local requirements for storage site characterization.

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[75] Note that as per rule 3.2.11, geological storage of CO_2 is only allowed in jurisdictions where such minimum criteria exist.

- Descriptions and/or results of the experimental and computational methods utilized to assess the storage site (e.g. storage capacity; areal and vertical extent of the storage reservoir and pore space; and geomechanical, geochemical and flow properties of the reservoir), such as results from seismic and geologic surveys, or data from offset wells, geological earth models, or other numerical simulations.
- A discussion of the site characterization results and their implications for long-term behavior of the storage site (such as changes in injectivity, or the nature of CO_2 trapping), and how this information relates to storage permanence and monitoring needs.

7.5.3 The CO_2 Removal Supplier shall periodically monitor the accessible[76] well construction materials (e.g. cement and casings) for signs of corrosion (such as loss of mass or thickness, cracking, or pitting) to ensure that any injected CO_2 remains properly contained, and that the utilized materials have sufficient structural strength to meet the requirements of the applicable local regulations. The monitoring shall be conducted with a method in accordance with applicable local regulations or, if no such regulations exist, in accordance with industry standard practices (e.g. corrosion coupons, electrical resistance probe, or other corrosion probes or sensors).

7.6 Monitoring CO_2 release and reversal

7.6.1 The CO_2 Removal Supplier shall periodically monitor the geological storage reservoir and its surroundings (to the extent defined in subrule a) for any release of greenhouse gases or other reversal events (see rule 4.7.1).

(a) The monitoring region shall cover the geological storage reservoir and the surrounding region which may be endangered or otherwise negatively affected by the injection activity. The CO_2 Removal Supplier shall determine the extent of this region based on locally applicable regulations. For example, this area corresponds to the *area of review* as defined in the United States Code of Federal Regulations,[77] or the *storage complex and surrounding area* in the sense of Directive 2009/31/EC of the European Parliament and of the Council,[78] or other similarly defined areas based on locally applicable regulations.

(b) The choice of monitoring technology shall be based on industry best practices, and detailed in the monitoring plan. The following options shall be considered and used as appropriate:

  - Technologies that can detect the presence, location, and migration paths of CO_2 in the subsurface and at surface.
  - Technologies that provide information about the pressure-volume behavior, and areal/vertical distribution of the CO_2 plume or CO_2 charged water to refine numerical 3D simulations for geological models of the storage formation.
  - Technologies that can provide a wide areal spread in order to capture information on any previously undetected potential leakage pathways

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[76] Note that certain well barriers (e.g. cement on the outside of the production casing) might only be accessible for testing during the initial well construction process.

[77] 40 CFR 146.81(d) "Area of review"

[78] 2009/31/EC Article 4(3)

across the areal dimensions of the monitoring region in the event of significant irregularities or migration of CO_2 out of the storage reservoir.

Potential monitoring techniques include but are not limited to various subsurface, near surface, or remote monitoring techniques, such as wireline-deployed well logging tools, e.g. acoustic and resistivity; wellbore-deployed pressure and temperature gauges or fluid monitoring tools; electrical resistance tomography and similar electromagnetic surveys; seismic geophysical monitoring; sampling of the soil, vadose zone or groundwater; isotopic or chemical tracers; surface gas flux monitoring; and satellite or other remote imaging.[79]

(c) The CO_2 Removal Supplier shall quantify and account for the amount (in tCO_2e) of GHGs released in each reversal event according to the requirements of section 4.7.

(d) In case a reversal event is detected, the CO_2 Removal Supplier shall without delay take action to:

- Prevent further reversal from occurring.
- Determine the cause of the reversal event and apply appropriate corrective measures.
- Notify the Issuing Body.

Note that subrule d does not apply to cases where minimal CO_2 release or other reversal occurs due to monitoring or maintenance operations, provided that such events are planned, controlled and unavoidable (e.g. when small amounts of fluids are pumped from the storage reservoir for monitoring purposes without re-injection).

(e) The CO_2 Removal Supplier shall keep a detailed, time-stamped record of all release events from the storage reservoir.

7.6.2 The CO_2 Removal Supplier shall set normal, alert and threshold values for monitored parameters, and design and implement operating procedures in case the alert or threshold value is reached. The values shall be derived from applicable local regulations or, if no such regulations exist, from other relevant sources, such as peer-reviewed scientific literature or industry best practice. The values shall be periodically reviewed to ensure the safety of the operations.

7.6.3 The CO_2 Removal Supplier shall at least monthly monitor the injection facility for any injection leaks from the wellheads and other relevant infrastructure at the storage site (e.g. pipes, valves, etc.) through visual inspection by an operator equipped with a CO_2 detector or other appropriate sensing equipment. Any detected injection leaks shall be attributed to E_{released}, and quantified and accounted for according to the requirements in section 4.4 (see especially rule 4.4.4).

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[79] For a review of potential monitoring techniques, see e.g. [50–52]

7.7 Site closure and post-injection monitoring

7.7.1 The CO_2 Removal Supplier shall ensure that access to the storage site is retained for monitoring purposes throughout the post-closure period.

7.7.2 The CO_2 Removal Supplier shall continue to monitor the storage site and its surroundings for release of CO_2 or other reversal events (see rules 4.7.1 and 7.6.1) to verify the storage permanence during and after site closure (post-injection period) as stated in the applicable legal framework (see rule 3.2.11). The monitoring shall continue until the transfer of responsibility or, if no regulations on the transfer of responsibility exist in the applicable legal framework, as long as required by the local requirements for storage site closure and post-closure site management.[80] The monitoring frequency may be reduced during the post-injection period and site closure, as long as the level of monitoring allows for detection of reversals or irregularities. Similarly, if a reversal is detected, the monitoring frequency shall be intensified.

7.7.3 The CO_2 Removal Supplier shall periodically monitor that the pressure decay in the reservoir, and the location of the CO_2 plume or CO_2 charged water conform to the predictions derived from the reservoir model and relevant monitoring data collected during the pre-injection and injection periods. The predicted behavior of the subsurface CO_2 shall be periodically updated based on the ongoing site monitoring. The post-injection period monitoring frequency shall be based on the predicted timeframe of the pressure decay and migration of the CO_2 plume or CO_2 charged water.

7.7.4 The CO_2 Removal Supplier shall identify criteria to ensure that the injected CO_2 will be retained within the geological storage during post-injection period and site closure. The criteria shall be based on the requirements of this methodology and the applicable local legislation and regulations. The CO_2 Removal Supplier shall demonstrate compliance with the criteria during the closure period. The criteria shall at least include the following:

(a) The site shall meet the established project objectives, including absence of CO_2 leakage and impacts to social and environmental resources.

(b) The storage reservoir shall be sufficiently understood to assess the extent of CO_2 trapping, and future evolution of the CO_2 plume or CO_2 charged water distribution, dispersion and migration.

(c) The likelihood of future leakage shall be demonstrated to be negligible, and the accuracy of predictive models shall be proven.

(d) All wells shall be plugged or sealed according to the local regulations, taking into account the post-injection period monitoring requirements. When the injection has ceased, the CO_2 Removal Supplier may for example:

  - Seal the injection well immediately upon cessation of injection.
  - Convert an injection well to a monitoring well. Monitoring wells not used for sampling during the post-injection period should be plugged to eliminate the potential to become conduits for fluid movement.

(e) Surface facilities and equipment associated with the geological storage activities shall be removed, except to the extent required for monitoring purposes.

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[80] The precise length of the time period required for post-injection monitoring can vary based on e.g. local regulations and site performance records (see rule 7.2.2).

Facilities and equipment integral to other operations or intended for different uses need not be removed.

7.7.5 The CO_2 Removal Supplier shall periodically assess the internal and external integrity of the monitoring wells at regular intervals until the wells have been plugged or sealed.

7.7.6 After site closure, the CO_2 Removal Supplier shall create a site closure report including relevant information for the future landowners and planners. Such information may for example include:

- Information on the entities and authorities relevant to any possible future drilling activities.
- Documentation on the injection and monitoring well sealing.
- Maps and cross-sections indicating the location of the injection and monitoring wells and the CO_2 plume or CO_2 charged water.
- Documentation of the timeline of the operations (e.g. injection-phase, post-injection phase, site closure).
- Information on the storage site characteristics.

8

Risk and uncertainty management

8.1 Overview

The primary objective of identifying risks and uncertainties is to detect early and ongoing events and ambiguities that could affect the predetermined objectives of the storage project. While it is important to manage and mitigate both risks and uncertainties, it is useful to separate the concepts. Here, *risk* refers to events and situations, whose outcomes and occurrence probabilities are (reasonably well) known in advance, while *uncertainty* refers to aspects of decision-making which are not easily quantified [53].[81]

There are many different ways to further categorize both risks and uncertainties into different types [54, 55], such as the simple classification presented in table 8.

Table 8: Classification of risks and uncertainties.

Risks	Uncertainties
Pure	Irreducible (aleatoric)
Speculative	Epistemic
	Knightian

Risks can be classified based on the type of potential outcome. With *pure risk*, there is no possibility of gain and the outcome is either ‘loss’ or ‘no loss’ (e.g. machinery breakdown), whereas with *speculative risk*, there is also a chance of a positive outcome (e.g. project financing decisions) [55, 56].

Uncertainties can be classified in terms of their relation to additional data and knowledge. *Irreducible uncertainty* refers to the inherent randomness and unpredicted variability of certain processes (e.g. unexpected fluctuations in reservoir geology or CO_2 behavior, or damage due to natural disasters). Such uncertainties cannot be reasonably mitigated with additional data, and are thus a constant source of ‘background uncertainty’ [56]. On the other hand, *epistemic uncertainty* results from missing or incomplete information (e.g. missing measurement data, undocumented legacy wells in the project area), and can be diminished by gathering more data [56, 57]. Additionally, there is often a third categorization referred to as *Knightian uncertainty*, or the ‘*unknown unknowns*’, i.e. situations where there is a deep level of ambiguity about the process itself and the means to evaluate its effects (e.g. predicting technical development) [56, 58].

Several risks and uncertainties concerning the technical and non-technical (e.g. financial or political) aspects of geological storage of CO_2 have been identified across the entire activity boundary, including risks to human health, climate, and key environmental factors such as ecosystems and groundwater [56, 59, 60]. This methodology, together with applicable local

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[81] Note that the word ‘uncertainty’ is often used in other contexts as well, such as in reference to quantification uncertainty, i.e. measurement error.

legislation and regulations, sets guidelines and rules to mitigate the possible risks and ensure that the CO_2 is safely retained in the selected geological storage reservoir. Appropriate and transparent collection of data as well as regularly updated monitoring plans are key factors in managing and mitigating risks, but effective risk mitigation also requires efficient and transparent communication and collaboration between the CO_2 Removal Supplier and the local authorities and stakeholders.

8.2 Storage permanence and risk of reversal

Carbon capture and geological storage is generally considered a secure and effective option for climate change mitigation [60]. The IPCC Special Report on Carbon Dioxide Capture and Storage [20] concluded that:

> “For large-scale operational [geological] CO_2 storage projects, assuming that sites are well selected, designed, operated and appropriately monitored, the balance of available evidence suggests the following:
>
> - It is very likely the fraction of stored CO_2 retained is more than 99% over the first 100 years
> - It is likely the fraction of stored CO_2 retained is more than 99% over the first 1000 years.”

While the general understanding on the assessment and management of risks related to CO_2 release from geological storage has improved since the publication of the IPCC Special Report [56, 59–69], similar estimations of the overall storage permanence have been published more recently as well [70, 71]. The IPCC has also recently reiterated that “if the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere.” [72, p. 21]. Furthermore, the storage capacity, permanence and effectiveness of the stored CO_2 may also increase over time due to geochemical interactions of CO_2 with the surrounding rock and formation water [20].

Even in scenarios that assume pessimistic input parameters and poor management of the storage site, leakage of CO_2 to the atmosphere has been estimated small or moderate, and the associated economic costs minor [60, 63, 70, 73]. In a worst case scenario of a CO_2 storage project carried out in a poorly regulated environment (characterized e.g. by unknown or unidentified abandoned wells in the project area and limited wellbore integrity), the fraction of stored CO_2 retained was estimated to be be around 80% over the first 1000 years and around 70% over the first 10,000 years [70].[82] In another study, it was noted that “even at unrealistically high well permeability, leaked CO_2 is very unlikely to be released to the atmosphere because of the interception by overlying geologic strata” [63]. The associated economic costs of leakage (the monetized leakage risk) have been estimated to be likely orders of magnitude below storage costs [73], and their impact to CCS deployment negligible under a realistic leakage scenario, or at most minor in the worst case [63].

It is important to note that a low overall permanence risk does not imply the absence of risk entirely, nor the lack of need to assess and manage risks in geological storage projects. Indeed, the low risk estimates cited above rely on the concept of a *well selected and managed* storage site, of which proper risk management is an integral part. To ensure the long-term safety of a geological storage project, it is essential that the CO_2 Removal Supplier carries out comprehensive risk and uncertainty assessment and mitigation.

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[82] The median retention estimate in a poorly regulated environment was significantly lower, amounting to approximately 92% of stored CO_2 retained over the first 1000 years and 78% over the first 10,000 years.

Due to the above considerations on storage permanence and risk of reversal, and given that this methodology imposes requirements to ensure that the storage site is well selected and the geological storage project well managed as a whole, it is considered that in this methodology, there is no such material risk of reversal (in the sense defined in the Puro Standard General Rules) that would necessitate a default percentage deduction from the Output volume for all projects.

8.3 Key risks and uncertainties

All stages of the geological storage value chain possess associated risks and uncertainties. These are, however, mostly well understood and have been comprehensively reviewed in the scientific literature—see e.g. [56, 60] and references therein. Table 9 summarizes and categorizes some of the risks and uncertainties that might materialize in the various stages of a geological storage project.

Table 9: Potential risks and uncertainties associated with geological storage of CO_2

Project stage	Technical risks and uncertainties		Non-technical risks and uncertainties		
	Site characterization	Operational	Financial	Political	Social
Capture	Device installations and operational defects Measurement errors	Exhaust gases Liquid and solid waste Waste by-products CO_2 stream impurities Equipment failures	Plant design and operation Economic and financial factors	**National:** Government funding crises Government preferences for investments Restrictions of CCS projects due to pollution and/or geological characterisation Lack of government support or incentives Licensing requirements, absence of a clear regulatory framework Absence of frameworks for e.g. reversal liability Policy changes Corruption	**Public opinion:** Lack of public awareness and support Misinformation **Education:** Insufficient knowledge and understanding Limited awareness of the potential benefits and limitations **Safety and Health:** Risks associated with storage and transportation of CO_2 Health concerns related to CO_2 leaks (reversal)
Transport	Pipeline accidents Pipeline corrosion Equipment breakdown	Technical or mechanical breakdowns of equipment Seal and valve failures Formation of stable precipitates Collisions Pipeline explosions	Technological feasibility and cost-effectiveness (e.g. transport distance, terrain, route)		

Continued on next page

Table 9: Potential risks and uncertainties associated with geological storage of CO_2 (Continued)

Project stage	Technical risks and uncertainties		Non-technical risks and uncertainties		
	Site characterization	**Operational**	**Financial**	**Political**	**Social**
Storage	Chemical reactions Model oversimplifications	Groundwater contamination CO_2 migration Wellbore and seal integrity Induced seismicity Fracture and fault development and propagation Unwanted chemical reactions affecting reservoir properties	Geological reservoir characteristics Reservoir scale Managing pressure build-up	**International:** Lack of advanced technologies Political controversies between countries Inefficiency and non-binding nature of international agreements	

While the risks presented in table 9 vary in terms of likelihood and severity, several key risks can be identified throughout the activity boundary [56, 59, 60]. Such identified key risks in the various stages of the activity boundary are elaborated and discussed below. Note that some risks affect one another, and might have important compounding effects. For example, induced seismicity might damage surface equipment or compromise storage reservoir integrity and thus increase risk of CO_2 leakage.

Capture

Waste products

Description

Depending on the capture technology and feedstock utilized, various potentially harmful solid and liquid wastes and exhaust gases might be generated during the capture phase, necessitating proper waste management procedures to avoid environmental and health-related risks [56]. Some waste products, such as air pollution control residues from municipal solid waste incineration, are considered hazardous in many jurisdictions, and can be highly alkaline, corrosive, and contain elevated concentrations of soluble salts (e.g. chlorides and calcium compounds), heavy metals (e.g. lead, nickel, and cadmium), and other toxic compounds and pollutants [74].

Example

Waste products might include various types of combustion residuals (e.g. fly ash, bottom ash, and air pollution control residues); waste water; and degraded flue gas filtering or CO_2 absorbent materials (e.g. amine reclaimer wastes).

Mitigation

Waste management practices and regulations surrounding e.g. flue gas management have significantly improved over the last few decades [75], and it is important to integrate proper waste treatment and management practices into the capture operation. Recycling is generally agreed to be the best management strategy for waste that has already been created, and landfills should be avoided as much as possible, although applications for hazardous wastes are often limited [74]. For air pollution control residues and similar alkaline wastes, treatment options such as accelerated carbonation might be utilized to lower their toxicity [76, 77].

CO_2 stream impurities

Description

Depending on capture technology and feedstock utilized, the captured CO_2 stream may contain several chemical impurities, which can have significant practical, health, safety, and environmental implications for the CO_2 transport and storage systems unless properly managed. Even a small number of impurities can cause the CO_2 stream properties to change [47]. Some impurities such as H_2S or SO_2 are toxic and may result in acute damage to the environment or human health if leaked [47, 56, 78]. Impurities may also affect the phase behavior and properties of the CO_2 stream/plume (e.g. density, buoyancy, saturation pressure, and critical temperature); impact key operational parameters (e.g. storage capacity and injectivity of the reservoir); cause damage to equipment; lead to undesired chemical reactions inside the reservoir (e.g. pore blockage or fluid-caprock interactions); promote corrosion of e.g. pipeline or injection well materials; or result in degradation of absorbent materials [47, 56, 78].

Example

Impurities might include water (H_2O), hydrogen (H_2), hydrogen sulfide (H_2S), carbon monoxide (CO), nitrogen (N_2) and its oxides (e.g. N_2O), sulfur oxides (SO_x), oxygen (O_2), methane (CH_4), and argon (Ar) [47, 78].

Mitigation

From a technical standpoint, the composition of the CO_2 stream and the impurities therein can be efficiently detected and monitored with modern analytical techniques, such as gas chromatography, mass spectrometry, or various types of spectroscopy [78]. Financially, the cost to capture and separate the CO_2 stream is often high, and can affect the feasibility of the project [47]. Nevertheless, due to the potentially severe consequences that might be caused by impurities, it is important to conduct proper purity analysis and monitoring of the captured stream at regular intervals. There is an industry need for guidance on performing purity analysis before carbon dioxide is transported and stored [47, 78]. Various national regulatory authorities and global standard-setting organizations have established regulations, guidelines and best practices regarding CO_2 stream composition and impurities[83] [47].

Transportation

CO_2 leakage

Description

Depending on the mode of transportation utilized, CO_2 leaks during transportation might cause severe acute damage to human beings and ecosystems [2, 56, 79, 80]. The captured CO_2 will be transported to the storage site via pipeline or road, rail, or marine tankers, all of which might leak, ranging from slow insidious seepage from joints and seams to a catastrophic leak from a pipeline failure. Although CO_2 is non-toxic *per se*, it is an asphyxiant, and exposure

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[83] For example, ISO/TR 27921:2020 Carbon dioxide capture, transportation, and geological storage — Cross Cutting Issues — CO_2 stream composition.

to elevated concentrations might lead to drowsiness, hypoxia, or even death.[84] Being denser than air, leaked CO_2 might furthermore accumulate in low-lying areas in stable atmospheric conditions with low wind speeds, exacerbating the hazard [2, 81]. High levels of CO_2 leaked e.g. from buried pipelines can also be harmful to plants, microbes, the soil environment and ecosystems in general [79, 81].

Example

CO_2 leakage might occur through seal or valve malfunctions, or leaks and ruptures caused by e.g. vibrations, stress, corrosion, pressure fluctuations, extreme weather events or natural disasters [56, 81]. In the worst case scenario of a catastrophic pipeline rupture, the hazard zone might extend several hundred meters from the source of the leak [80], which could severely impact the environment and communities nearby.

Mitigation

As CO_2 is usually transported in large quantities at elevated pressures, ensuring the robustness of the transportation infrastructure is paramount to avoid risk of large-scale leakage events. Particularly in the case of transport via pipelines, although the accident rate is low [2, 81], the consequences of leakage can be severe, and safety aspects need to be properly taken into account during the design, construction, operation, maintenance, and monitoring of the pipelines [2, 56]. For example, the United States (where a significant majority of the world's CO_2 pipelines are located) has implemented strict CO_2 pipeline management requirements [2].

Storage

CO_2 leakage

Description

Depending on the nature and characteristics of the storage site and its surroundings, the release of CO_2 into the atmosphere, groundwater aquifers, shallow soil zones, or natural resource reservoirs can lead to environmental or health risks and economic losses [50, 56]. The CO_2 will spread out underground during and after injection, and might travel distances of several kilometers and reach e.g. abandoned wells in the storage formation, which can then leak if degraded or inadequately sealed [50, 82]. Furthermore, CO_2 might escape the storage reservoir through transmissive faults or fractures, which might be pre-existing or generated by pressure and temperature changes in the reservoir during injection [50, 83].

Example

CO_2 leakage might result from compromised integrity of either active or abandoned injection wells (e.g. due to mechanical and chemical stress, corrosion, material degradation or human errors in design or sealing), or through natural pathways such as faults or fractures [50, 70]. It's worth noting that in certain regions, such as North America, the long legacy of oil and gas exploration has left behind huge numbers of exploration and production wells, and in some locations a plume of injected CO_2 might realistically encounter several such existing wells [84].

Mitigation

The risks of leakage from the storage reservoir can be efficiently mitigated through proper site selection and characterization, as well as careful well design and monitoring (see also section 8.2).

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[84] Concentrations of around 1% CO_2 might cause drowsiness, followed by hypoxia and dizziness (4% CO_2), asphyxia and loss of consciousness (10% CO_2), and finally death at around 20% CO_2 [2, 56, 80].

Groundwater contamination

Description

Leakage of CO_2 or brine from the storage reservoir (see above) might also impact shallow groundwater resources and compromise the quality of drinking water resources [56, 59, 85–87]. Introduction of CO_2 into groundwater aquifers through underground leaks from the storage reservoir may result in formation of carbonic acid and subsequent decrease in water pH. Changes in pH enhance the solubility of hazardous trace elements and other contaminants naturally found within the aquifer rocks, and may ultimately lead to contamination of water resources [56, 87–89]. Trace metals might also be transported into the freshwater aquifer through leaking fluids, which might even be a more significant source of trace metals than the *in situ* mobilization due to pH change [86].

In the case of storage in saline aquifers, the injected fluids may cause large-scale pressure changes and displacement of native brines, impacting subsurface volumes much larger than the CO_2 plume itself [85]. In the case the storage formation is hydraulically communicating with freshwater resources (e.g. through high-permeability conduits such as transmissive faults or abandoned boreholes), the brine displacement and subsequent mixing into the freshwater might jeopardize the quality of drinking water resources even if the CO_2 itself is securely trapped [85, 90].

Example

Contaminants might include trace metals such as lead (Pb), arsenic (As) or mercury (Hg); organic compounds; or brine [85, 87, 89]. Changes in pH might also result in other water quality problems such as increased water hardness due to calcium dissolution [88].

Mitigation

The risks of leakage from the storage reservoir can be efficiently mitigated through proper site selection and characterization, as well as careful well design and monitoring (see also section 8.2).

Induced seismicity

Description

Injection of large amounts of high-pressure CO_2 into the subsurface can affect the original mechanical equilibrium state of the reservoir and trigger seismic events [91]. In general, the connection between fluid injection and the risk of increased seismic events is well established, and such induced seismic events have been observed in CO_2 injection projects as well [56, 59, 83, 91–93]. However, in the context of geologically stored carbon dioxide, induced seismicity has not been a major operational issue in the past [83, 92], and the vast majority of recorded events have been limited to microseismicity,[85] i.e. events so minor that they are not perceptible at the surface [91, 92, 94]. Nevertheless, the risk exists and needs to be addressed, as some induced seismic events can well be large enough to be a nuisance, and at worst, capable of property damage and human harm [92, 94]. Large magnitude events could damage injection wells or surface infrastructure, but even a small to moderate earthquake (e.g. of magnitude M ~4) might jeopardize the reservoir integrity by introducing fractures (and/or increasing the permeability of thereof) within the caprock, thus increasing risk of CO_2 leakage to the surrounding strata [91,

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[85] Microseismicity usually implies an earthquake with a moment magnitude M less than about 2 or 3 [59, 91]. For reference, in parts of the world with good construction practices, earthquakes smaller than approximately M 6 do not usually result in significant human harm or property damage [93]. Note that while seismic events within the caprock might compromise its integrity and should be avoided, microseismicity within the confines of the storage reservoir might also have positive aspects due to enhanced permeability [56].

93]. Furthermore, perceptible seismic events can disturb the local population even when not large enough to cause human harm or damage, and significantly affect the public perception of the project [59].

Example

In general, induced seismic events result from changes in pore pressure following injection, which can alter the effective stresses in the reservoir formation and lead to deformation or seismic events by reopening or creating faults or fractures, particularly in regions with pre-existing tectonic activity [56, 91, 93]. It is in fact not uncommon for microseismic events to be observed during CO_2 injection operations, and very small events numbering in the thousands have been measured in several projects [91, 92].

Mitigation

The risk of induced seismicity can be at least somewhat mitigated through careful geological characterization during site selection, by e.g. avoiding sites with extensive faults (the magnitude of an earthquake produced by a fault slip correlates with the size of the fault), or favoring highly porous and permeable laterally extensive reservoirs where the resulting pore pressure increase as a result of CO_2 injection is smaller [93].

There are various statistical, numerical and other methods geared towards forecasting induced seismic events, although significant knowledge gaps in that respect—owing to the fact that fault systems in general are difficult to detect and have complex activation mechanisms—render prediction and control of CO_2 injection induced seismicity extremely difficult [91]. As to the assessment of damage and nuisance risks, there is a significant body of experience dealing with *natural* seismic hazards, which can provide a rational basis for deciding whether risks are acceptably low and safely manageable in a given project. In particular, the probabilistic seismic hazard assessment (PSHA) and probabilistic seismic risk assessment (PSRA) methods are mature and widely used in the natural hazard and structural engineering communities, although some adaptation from natural to induced hazards is necessary[86] [59, 91].

8.4 Risk and uncertainty assessment

The overall risk of an event or situation is often defined as the combination of two parameters: the *probability* (likelihood) for the event to be realized, and the *severity* of the event, if realized. In broad terms, risk management is composed of three main steps: analysis, evaluation, and treatment of risk [69] and references therein. In the case of geological storage of CO_2, effective risk management is based on systematic risk identification, ranking, quantitative assessment, and a treatment or mitigation plan [64].

There are multiple methods to quantify risks and uncertainties, each with their advantages and limitations (for a comprehensive review, see [56]). Regardless of the approach, it is important to identify and assess the potential risk scenarios *before they occur*, in order to develop effective mitigation plans, address potential issues, and improve the overall success of the project [60]. A risk matrix, such as exemplified in table 10, is often utilized to identify and assess the severity and likelihood of risks, and has also been applied in the context of geological storage [60, 65, 66, 68]. It is designed to aid in risk management by setting threshold values and recommended actions for different levels of risk: negligible risks may be ignored, but if a risk is deemed as e.g. undesirable or intolerable, mitigation measures need to be applied.

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[86] For instance, the natural earthquake frequency is often stable in time whereas the injection induced seismicity depends on the temporal and spatial variations related to injection behaviors [91].

While a risk matrix is a useful general tool, it is important to realize that the severity and likelihood of risks depend on the context, and must be separately and carefully considered for each individual risk. For example, the acceptable likelihood of occurrence for safety-related risks is significantly lower than for risks related to project financing or timelines. The severity of a particular type of event is highly specific as well. For instance, the impact of a CO_2 leakage event significantly depends on the pathways and spatial distribution of the flux [67]: a high, localized flow rate (e.g. pipeline explosion) poses an acute risk to human health and safety, but a similar total amount of CO_2 leaked with a low, dispersed flow rate (e.g. well leakage) would not have as severe acute consequences to human health, although climate or environmental impacts would still persist.

Table 10: An example of a risk matrix utilized in the context of geological storage of carbon. Modified from [60, 68].[a]

20–25	Inoperable	⬛	Categories/Groups • Air/Atmosphere • Surface – Near Surface • Subsurface • CO_2 Transportation • Ownership and Environment • Community
10–16	Intolerable	🟥	
4–9	Undesirable	🟨	
2–3	Acceptable	🟩	
1	Negligible	🟦	

Control measures			Very low 1	Low 2	Medium 3	High 4	Very high 5
			LIKELIHOOD ⟶				
Light	1	SEVERITY ⟶	**1**	**2**	**3**	**4**	**5**
Serious	2		**2**	**4**	**6**	**8**	**10**
Major	3		**3**	**6**	**9**	**12**	**15**
Severe	4		**4**	**8**	**12**	**16**	**20**
Extreme	5		**5**	**10**	**15**	**20**	**25**

[a] Originally based on the Schlumberger Hazard Analysis and Risk Control Standard SLB-QHSE-S020 [65].

8.5 Requirements for risk and uncertainty management

Note that the Puro Standard General Rules contain requirements on risk assessment and management, particularly in the context of permanence and risk of reversal. Note further that requirements relating to an important aspect of risk management, i.e. the assessment and mitigation of environmental and social impacts, are also included in section 3.8.

8.5.1 The CO_2 Removal Supplier shall establish and maintain a comprehensive and project-specific risk assessment and mitigation process complying with the requirements of this methodology, the Puro Standard General Rules and other Standard Requirements, as well as any applicable local laws, regulations, and other binding obligations.

8.5.2 The CO_2 Removal Supplier shall create, maintain, and periodically update a comprehensive risk assessment of the geological storage activity. The risk assessment shall encompass all stages of the activity boundary, and include a qualitative and/or quantitative analysis and evaluation of risks and their significance as described in subrules a-c.

(a) The methods utilized for the analysis and evaluation of risks must be scientifically justifiable and detailed in the risk assessment. For example, the CO_2 Removal Supplier may utilize risk assessment frameworks stemming from applicable local statutory requirements, relevant international standards (such as ISO 31000),[87] scientific literature, or industry best practices.

(b) The risk assessment shall consider the risks and potential negative impacts to at least the following:

- The environment (including but not limited to soil quality, water contamination, ecosystems, habitats, and biodiversity).
- The atmosphere.
- Human health and safety.
- Local communities and their socio-economic situation.

(c) The risk assessment shall contain at least the following components, encompassing the entire activity boundary:

- Risk identification, including characterization of each identified risk related to the geological storage activity; the conditions and context in which the individual risks might be realized; and the potential impacts of each identified risk.
- Risk analysis and estimation, including characterisation of the risk likelihood and severity, assessing the significance of the risk to the CO_2 Removal project.
- Risk evaluation, determining whether the risk likelihood and its severity are at an acceptable or tolerable level.
- Risk management measures, including a plan to mitigate and prevent the identified risks. Preventive and corrective measures shall be identified or planned as contingency measures to reduce risks and uncertainties.

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[87] ISO 31000:2018 Risk management — Guidelines.

8.5.3 As a part of the risk assessment, the CO_2 Removal Supplier shall assess whether there exist any such project-specific risk factors (such as those related to the specific infrastructure or storage reservoir utilized) that might lead to an elevated overall risk of reversal (in the sense described in section 8.2).

(a) In cases where the temperature and pressure of the geological storage reservoir are not sufficient to maintain all injected CO_2 in a liquid or supercritical phase (i.e. the *dense phase*), the assessment shall explicitly consider the risks related to storing CO_2 in the gaseous phase, taking into account any potential adverse effects to storage capacity, integrity, or injectivity resulting from the increased buoyancy, decreased density, or other changes in physical properties of the CO_2 Stream compared to the dense phase.

(b) In the case where, based on the assessment, the fraction of stored CO_2 retained is likely less than 99% over the first 1000 years, the CO_2 Removal Supplier shall undertake appropriate mitigation measures to reduce the overall risk of reversal to an acceptable level[88] or, if no such measures are feasible, apply a commensurate deduction to the reported Output volume.

8.5.4 The risk assessment shall, to the extent possible, be based on actual project data acquired during all stages of the geological storage activity. The risk assessment shall be periodically updated together with the monitoring plan. The CO_2 Removal Supplier shall set and periodically review appropriate preventive and corrective safeguards based on the risk assessment.

8.5.5 The CO_2 Removal Supplier shall record and disclose to the Issuing Body any risk realization events (including corrective measures taken and potential new safeguards or preventive measures set), as well as any resulting negative impacts or claims thereof, including but not limited to any legal actions and/or other written complaints filed by affected parties. The records shall be made available to the Auditor.

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[88] An acceptable level of overall risk of reversal is defined as being likely that the fraction of stored CO_2 retained is more than 99% over the first 1000 years.

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