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Carbon dioxide capture, transportation and geological storage — Quantification and verification

Capture du dioxyde de carbone, transport et stockage géologique — Quantification et vérification

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Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 265, *Carbon dioxide capture, transportation, and geological storage*.

Introduction

This document is intended to serve as a reference document for future development of any technical standards that could be approved by TC 265 for the quantification and verification (Q&V) of greenhouse gas (GHG) emissions and emission reductions from CCS projects. This document is a review of current practices and requirements, for the Q&V of carbon dioxide captured, transported and geologically stored; as well as for direct and indirect GHGs that can arise from integrated CCS project activities associated with injection of carbon dioxide into geological formations for the purposes of isolation from the atmosphere (and ocean) over the long term. While carbon dioxide (CO_2) is the primary target of the capture process, other GHGs (such as methane, CH_4) may be entrained in the capture stream, and emissions can include GHG's other than CO_2. This document includes limited discussion of other environmental impacts.

This document integrates the various aspects of Q&V adopted by other ISO/TC 265 Working Groups (WGs) into a comprehensive project framework.

The UNFCCC Paris Agreement (adopted on 12 December 2015) lays the foundation for countries to work cooperatively to limit the increase in global average temperature to between 1,5 °C and 2 °C above pre-industrial levels, by reducing emissions of greenhouse gases (GHGs) into the atmosphere and by increasing removals of GHGs from the atmosphere. Many of the climate models considered by the IPCC in their most recent assessment report (IPCC, 2014) suggest that keeping average global temperature rises to less than 2 °C will require large scale deployment of carbon dioxide capture, transportation and geological storage technologies (CCS) in order to reduce anthropogenic emissions from the electrical sector and from industries where there are no viable alternatives. The IPCC (2014) also suggest that CCS with bio-energy (BECCS) will be required to remove carbon dioxide from the atmosphere to meet medium term emission objectives. In the longer term (i.e. 70 to 100 years), it may be necessary, and viable, to further reduce harmful concentrations of CO_2 in the atmosphere by capturing CO_2 directly from the atmosphere for injection into geological formations (DACCS).

While many countries have existing domestic GHG emission reporting requirements, the Paris Agreement emphasizes "robust accounting" for all countries (UNFCCC, 2015, Article 6, paragraph 2), covering both anthropogenic emissions of greenhouse gases by sources and removals of greenhouse gases by sinks (Article 4, paragraph 2). The key principles for accounting and reporting identified in the Paris Agreement are transparency (to ensure that actions are shared and equitable, and that outcomes are real), accuracy, completeness, comparability and consistency, and the avoidance of double accounting (UNFCCC, 2015, Article 4, paragraph 13). Environmental integrity (i.e. no harm to ecosystems or biodiversity) is a fundamental principle for all activities, as are issues relating to the socioeconomic impacts of a project.

ISO/TC 265 was established to develop technical standards for the design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of CCS. Six working groups (WGs) have been established. They all report through to the Technical Committee (TC) and are charged with focusing on particular aspects of the CCS technology chain.

WG1 – Capture

WG2 – Transport

WG3 – Storage

WG4 – Quantification and Verification

WG5 – Cross-cutting Issues

WG6 – CO_2 storage through Enhanced Oil Recovery (EOR)

This document established under WG4 is intended to provide a credible foundation for future standard approaches for the quantification and verification (Q&V) of GHGs associated with CCS projects (for geological storage or for EOR). Future standards developed in this area will improve understanding and confidence in CCS related GHG mitigation by regulatory authorities, investors and civil society, as well as enhance validation processes underpinning project compliance obligations.

The development of this document complements the development of other CCS and non-CCS, but relevant, ISO standards and TRs, including in particular the whole ISO/TC 265 catalogue. Documents are referenced from the EU, UNFCCC, IPCC, and various government bodies. As CCS Q&V is an ever-evolving area of examination, this document has been based on the best available information at the time of its release.

The principal GHG considered within this document is carbon dioxide (CO_2), other GHG's (as listed in Chapter 5), are included in the Q&V of CCS projects, but are not usually significant. To some extent, GHG and CO_2 are used somewhat interchangeably and the reader is invited to consider the context of the terms. Most of the GHG captured through the CCS system will be a relatively pure stream of CO_2, perhaps mixed with other gases such as N_2, but in an Enhanced Oil Recovery (EOR) system the recycled CO_2 could also include methane (CH_4). Emissions from fossil-fired industrial activity could also contain some N_2O.

This document aims to provide a transparent and non-prescriptive body of information relating to Q&V processes for CCS projects.

Carbon dioxide capture, transportation and geological storage — Quantification and verification

1 Scope

1.1 General

This document presents a review of publicly available literature identifying materially relevant issues and options relating to "good practices" for quantifying and verifying GHG emissions and reductions at the project level. Its scope covers all components of the CCS chain (e.g. capture, transport, storage) and includes a lifecycle assessment approach to estimating project level emissions and emission reductions from project assessment, construction and operations, through to completion and post-closure activities. This document considers the following at the project level:

— a variety of Q&V related boundaries applicable to all components of a CCS project;

— the composition of the CO_2 stream, including its purity, and requirements for measuring and verifying the physical and chemical state of the CO_2 stream in CCS projects;

— identification and quantification of GHG emissions and reductions across integrated CCS components;

— monitoring objectives, methodologies, and sampling strategies, including locations, periods, and frequencies;

— GHG data collection and reporting;

— verifying GHG expectations with agreed verification criteria;

— life cycle assessment (LCA) of CCS projects.

1.2 Limitations

Q&V approaches to measuring and verifying GHG emissions, reductions and removals for CCS projects continue to evolve. This document identifies the gaps and limitations in current levels of knowledge, of empirical methodologies and application of good practices for CCS Q&V.

This is a Technical Report and so does not seek to recommend technical standards for any specific Q&V method. This document cites existing ISO standards and other good-practice protocols that have been developed to quantify and verify GHGs from integrated CCS projects.

1.3 Stakeholders' requirements

This document aims to inform all stakeholders who influence, or are directly or indirectly involved in the reporting of emissions and emission reductions, or removals, for CCS projects. Stakeholders may include, for example, CCS project developers and operators, policy makers, regulators and other government oversight bodies, verifying entities, the financial community, equipment manufacturers, owners of other resources (e.g. water, coal, oil and gas), and members of the general public.

1.4 Review of the references

This document makes reference to a variety of sub-national, national and international laws applicable to CCS projects; current Q&V practices to measure GHG emissions and reductions, or removals, by CCS projects; existing ISO standards that are directly and/or indirectly relevant to CCS projects; identified stakeholder requirements; and the anticipated outcomes of other ISO/TC 265 WGs.

The discussion of Q&V is applicable to both onshore and offshore environments. At this stage, the offshore experience is from two Norwegian projects, Sleipner and Snohvit, while the onshore experience draws on an expanding range of storage, and CO_2 EOR projects, in North America and China; and from a cumulative body of research, pilot and demonstration projects, in Algeria, Australia, Canada, Europe, Japan and the USA.

References are cited throughout this document, including relevant standards and protocols. These references are listed in alphabetic order in the Bibliography.

1.5 Nomenclature

BECCS	Bio-energy with CCS
CCS	Carbon Capture and Storage (or Carbon dioxide Capture, transportation and geological Storage)
CDM	Clean Development Mechanism
CEMS	Continuous Emission Monitoring System
CMS	Continuous Measurement System
CO_2-e	Carbon dioxide equivalent
DACCS	Direct air carbon dioxide capture and (geological) storage
EIA	Environmental Impact Assessment
EOR	Enhanced Oil Recovery
EU ETS	European Union Emissions Trading Scheme
GHG	Greenhouse Gas
IEA GHG	International Energy Agency Greenhouse Gas R&D Programme
IPCC	Intergovernmental Panel on Climate Change
IPCC SR	IPCC Special Report on CCS (2005)
LCA	Life Cycle Assessment
MRR	Monitoring, Reporting Regulation (ref. EU)
Mt	1 million (metric) tonnes
Q&V	Quantification and Verification
tonne	1,000 kg
tCO_2-e	tonne CO_2 equivalent
TR	Technical Report
UNFCCC	United Nations Framework Convention on Climate Change

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 27917-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
baseline
reference basis for comparison against which project status or performance is monitored or measured

Note 1 to entry: The IPCC (2014, Annex 1, Glossary, p.1253) defines baseline as "the state against which change is measured". In natural systems, a baseline represents the range of pre-existing natural variation of that system, which may include a complex range of diurnal, tidal, seasonal, annual, and climatically-driven natural fluctuations.

[SOURCE: ISO 21500:2012, 2.3, modified]

3.2
carbon capture and storage
CCS
process consisting of the separation of CO_2 from industrial and energy related sources, transportation and injection into a geological formation, resulting in its long-term isolation from the atmosphere

Note 1 to entry: CCS projects should also provide for the long-term isolation of CO_2 from oceans, potable water supplies and other resources.

[SOURCE: IPCC special report on CCS, 2005]

3.3
client
organization or person requesting validation or verification

Note 1 to entry: The client could be the responsible party or the GHG program administrator or other stakeholder.

[SOURCE: ISO 14064-1:2006, 2.25]

3.4
CO_2 (GHG) leakage
leakage
unintended release of CO_2 (or other GHGs) out of pre-defined containment

Note 1 to entry: Examples of containment are compressors, pipelines, trucks, ships, wells and geological formations. In the context of this document , leakage does not refer to the concept through which efforts to reduce emissions in one place shift emissions to another location or sector where they remain uncontrolled or not counted. Specific regulations at the national or sub-national level may further define leakage within specific contexts.

3.5
CO_2 stream
stream consisting overwhelmingly of carbon dioxide

Note 1 to entry: A CO_2 stream is likely to contain impurities such as other GHGs, and may also include substances added to the stream to improve the performance of the CCS stream or to enable detection of the CO_2. The minimum concentration of CO_2 in the CO_2 stream is usually subject to regulatory discretion and approval, but should be overwhelmingly CO_2.

[SOURCE: ISO 27917-1]

3.6
CO_2 stream composition
percentage by volume of each component of the *CO_2 stream* (3.5)

Note 1 to entry: The CO_2 stream composition is usually subject to regulatory discretion and approval. It is less common to report stream composition as a mass fraction.

3.7
CO_2 stream purity
percentage by volume of CO_2 as a component of the *CO_2 stream* (3.5)

3.8
detection limit
detection threshold
smallest value of a property of a substance that can be reliably detected by a specified measuring method in a specified context

3.9
emission factor
normalized measure of GHG emissions in terms of activity

Note 1 to entry: For example, tonnes of GHG emitted per tonne of fuel consumed. Valves and other such equipment might have typical leakage rates based on measurement from similar equipment. Emission factors can be applied based on experience for such equipment.

[SOURCE: Annex II of the IPCC special report on CCS, 2005]

3.10
GHG/CO_2 emission
emission
total mass of GHG (i.e. CO_2 or CO_2-e) released to the atmosphere, or surface water bodies, over a specified period of time

Note 1 to entry: Emissions from a geological storage complex occur at the interface between the ground and the atmosphere or at the interface between the seabed and ocean or lake. "GHG/CO_2 emission" is equivalent to the UNFCCC term "seepage" referred to in the CDM modalities and procedures for CCS project activities (see Reference [75]).

[SOURCE: ISO 14064-2:2006, 2.5, modified]

3.11
GHG/CO_2 emission reduction
calculated net decrease of GHG emissions between a *baseline* (3.1) scenario and the CCS project output

Note 1 to entry: A GHG emission reduction may also be referred to as "CO_2 avoided", although CO_2 avoided may also refer to CO_2 removals from the atmosphere.

[SOURCE: ISO 14064-2:2006, 2.7, modified]

3.12
GHG removal
total mass of GHG removed from the atmosphere over a specified period of time

Note 1 to entry: CCS projects could achieve GHG removals through BECCS (Bio-energy with CCS) or by DACCS (Direct air CO_2 capture and geological storage).

[SOURCE: ISO 14064-2:2006, 2.6]

3.13
fugitive emission
release of GHG from anthropogenic activities such as the processing or transportation of gas, petroleum or CO_2

Note 1 to entry: Fugitive emissions include unintentional releases such as leaks and spills, and intentional releases such as vents and flares for the purposes of safety, maintenance or to operate specific pieces of equipment (see Reference [91]).

[SOURCE: Annex II of the IPCC special report on CCS, 2005]

3.14
geological reservoir
subsurface body of rock with sufficient porosity and permeability to contain and transmit fluids (including super-critical phase GHGs) with an overlying impermeable seal (or caprock) which prevents escape of the fluids

[SOURCE: Annex II of the IPCC special report on CCS, 2005]

3.15
geological storage complex
subsurface geological system extending vertically to comprise storage units, and primary and secondary seals, extending laterally to the defined limits of the CO_2 storage project

Note 1 to entry: Limits can be defined by natural geological boundaries, regulation or legal rights.

3.16
greenhouse gas
GHG
gaseous constituent of the atmosphere, both natural and/or anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds

Note 1 to entry: The most common greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), nitrogen triflouride (NF_3) perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Emissions from these gases are reported under the Kyoto Protocol, and aggregated into carbon dioxide equivalents (CO_2-e) using factors called global warming potentials (GWPs).

[SOURCE: ISO 14064-2:2006, 2.1]

3.17
greenhouse gas activity data
quantitative measure of activity that results in a GHG emission or removal

Note 1 to entry: Examples of GHG activity data include the amount of energy, fuels or electricity consumed, material produced, service provided or area of land affected.

3.18
greenhouse gas emission or removal factor
conversion factor relating activity data to GHG emissions or removals

3.19
greenhouse gas information system
policies, processes and procedures to establish, manage and maintain GHG information

3.20
greenhouse gas report
stand-alone document intended to communicate an organization's or project's GHG-related information to its *intended users* (3.23)

[SOURCE: ISO 14064-2:2006, 2.15]

3.21
greenhouse gas source
process, activity or mechanism that releases a GHG into the atmosphere

[SOURCE: ISO 14064-2:2006, 2.2, modified; Annex II, IPCC CCS report 2005, modified]

3.22
integrated CCS project
project that involves capturing CO_2 from large point sources, transporting it to a storage site, injecting it into deep geologic formations (storage complex), and *monitoring* (3.28) to verify that it remains isolated from the atmosphere

3.23
intended user
individual or organization identified by those reporting GHG related information as being the one who relies on that information to make decisions

Note 1 to entry: The intended user could be the client, the responsible party, GHG program administrators, regulators, the financial community or other affected stakeholders, such as local communities, government departments or non-governmental organizations

[SOURCE: ISO 14064-2:2006, 2.22]

3.24
level of assurance
degree of assurance that the *intended user* (3.23) requires for verification

Note 1 to entry: The level of assurance is used to determine the depth of detail that a verifier designs into their verification plan to determine if there are any material errors, omissions or misrepresentations.

Note 2 to entry: There are two levels of assurance, reasonable or limited, which result in differently worded verification statements.

[SOURCE: ISO 14064-2:2006, 2.24, modified]

3.25
materiality
concept that individual, or the aggregation of, errors, omissions and misrepresentations could affect the GHG assertion and could influence the intended users' decisions

Note 1 to entry: The concept of materiality is used when designing the validation or verification and sampling plans to determine the type of substantive processes used to minimize the risk that the validator or verifier will not detect a material discrepancy (detection risk).

Note 2 to entry: The concept of materiality is used to identify information that, if omitted or misstated, would significantly misrepresent a GHG assertion to intended users, thereby influencing their conclusions. Acceptable materiality is determined by the validator, verifier or GHG program based on the agreed level of assurance.

[SOURCE: ISO 14064-2:2006, 2.28]

3.26
measurement
determination of quantities through physical devices

Note 1 to entry: Examples of measurements are temperature, flow, concentrations, length, distance, etc. Measurement may be direct (e.g. length with a meter) or indirect. Indirect measurements may require two steps, firstly sampling and then analysis. Indirect measures may also use a model to convert the measurement of a given quantity into the measurement of another one, for example, from velocity to flow rate, taking into account the pipe and fluid characteristics.

3.27
uncertainty (of measurement)
parameter associated with the result of a measurement that characterizes the dispersion of values that could reasonably be attributed to the measurement property

3.28
monitoring
continuous or repeated checking, supervising, critically observing, measuring, or determining the status of a system to identify variance from an expected performance level or *baseline* (3.1)

3.29
GHG quantification
act of measuring and/or estimating and/or predicting the amount of GHG emissions, reductions and removals associated with a CCS project

3.30
reporting scope
physical and temporal boundaries of information reported

3.31
responsible party
person or persons responsible for the provision of the *GHG quantification* (3.29) assertion and the supporting GHG information

[SOURCE: ISO 14064-1:2006, 2.23, modified]

3.32
sampling
selection of a subset from a population to estimate characteristics of the whole population

3.33
sampling strategy
set of technical principles or steps that aim to establish, depending on the objectives and the site considered, the sampling density, distribution, locations, and frequency for each sampling area

3.34
venting
intended release of GHG from pre-defined containment

3.35
verification of GHG assertion
systematic, independent and documented process for the evaluation of a GHG assertion against agreed verification criteria

Note 1 to entry: A GHG assertion is a factual and objective statement of performance related to GHGs made by an organization or project.

[SOURCE: ISO 14064-2:2006, 2.26, modified]

3.36
verifier
competent and independent person, or persons, with responsibility for performing and reporting on the verification process

Note 1 to entry: This term can be used to refer to a verification body.

[SOURCE: ISO 14064-1:2006, 2.36]

4 Principles

4.1 General

Principles are fundamental norms, rules, or values that guide a system or program. In reviewing other emission quantification programs, a range of potentially relevant principles can be loosely grouped by their underlying purpose despite the possibility of considerable overlap.

One group of principles relates to the accuracy of measurements. These support the validation of the amount of stored CO_2 for compliance purposes. Another group of principles relates to fungibility of measurements. These support the facilitation of emission oriented transactions, for example, the generation of a tradable credit for a unit of emissions reduction. The final group of principles relates to the equity and accessibility of measurements. These support cost effective measurement approaches that avoid imposing cost-prohibitive Q&V regimes and so encourage broad deployment of CCS projects as a reduction strategy. The distinctions between the three groups are useful because they help to point out the various objectives that could be considered in developing Q&V programs. Each group is discussed in more detail in the remainder of this clause.

4.2 Principles relating to the accuracy of measurement

4.2.1 Overview

The application of principles is considered fundamental in ensuring GHG-related information is an accurate representation of the actual measurement of emission reductions as is desirable on a fit-for-purpose basis. Principles are the basis for, and guide the application of measurement requirements. These principles are based on ISO 14064-1.

4.2.2 Relevance

Identification of the intended user and purpose of the GHG emissions quantification in order to guide decisions regarding which GHG data and measurement methodologies are appropriate.

4.2.3 Completeness

The inclusion of all relevant GHG emission reductions and removals.

4.2.4 Consistency and comparability

The use of consistent and internationally acceptable methods and approaches for measuring GHG emissions across all projects to enable meaningful comparisons of GHG-related information.

4.2.5 Accuracy

Establishing minimum levels of accuracy or precision in measurement methods and approaches will help to reduce bias and uncertainty.

4.2.6 Transparency

Disclose sufficient and appropriate GHG-related information to allow intended users to make decisions with reasonable confidence.

4.2.7 Conservativeness

Use conservative assumptions, values and procedures to ensure that GHG emission reductions or removal enhancements are not over-estimated.

4.3 Principles relating to the fungibility of emission reductions

4.3.1 Real

The demonstration that actual and sustainable emission reductions occurred over the long-term and that emission reductions would not have otherwise occurred or been required by law. This principle has been applied, for example, by setting baselines for reduction by averaging emissions over a period of years to avoid a potential adverse and perverse incentive of CCS projects ramping emissions up to inflate emission baselines in an effort to be awarded with more tradable credits. This issue is closely related to the concept of permanence. Baselines should be determined in a conservative way and should be justified transparently (see guiding principles above).

4.3.2 Additionality

The demonstration that the project results in GHG emission reductions that are additional to what might have occurred under business as usual (reference CDM).

4.3.3 Quantifiable

The GHG outcome of a CCS project is normally quantified according to transparent and scientifically sound methodology/ies.

4.3.4 Permanence

The concept of permanence is applied to CO_2 storage to indicate the expectation that in well designed and operated CO_2 storage projects, injected CO_2 will not leak out of the storage complex over the long term and, that if such leakage occurs, there will be no unaccounted CO_2 emissions to the atmosphere or ocean and no contamination of regulated resources. Typically, the concept is operationalized through regulatory requirements to use monitoring, risk assessment and modelling results to demonstrate that leakage has not been detected for a defined period after injection operations have ended and that there is no significant risk of leakage occurring in the future. See IPCC Guidelines, US EPA UIC Class VI regulations, EU-ETS as examples.

4.3.5 Environmental effectiveness

The ability of a project to result in overall net emission reductions as verified through monitoring, evaluation, and verification processes.

4.3.6 Enforceable

The ability to legally ensure that the emission reductions remain secure through the life of the program in which they are created/used, i.e. by compatibility with a robust accounting system.

4.3.7 Economic efficiency

The extent to which the program rules minimize transaction costs thereby facilitating reductions.

4.4 Principles relating to equity and relationship with stakeholders

4.4.1 Equity

The extent to which any program rules do not impose an unfair advantage or disadvantage to a nation or economic actors.

4.4.2 Transparency

Disclosure of sufficient and appropriate GHG-related information provides intended users, and all stakeholders, with reasonable confidence in the outcomes.

4.4.3 Political acceptability

The extent to which the program impacts are acceptable to participants and other stakeholders.

4.4.4 Consistency with IPCC Guidelines

The extent to which project quantification approaches are consistent with IPCC guidelines including Chapter 5 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories that gives a complete accounting methodology for CCS.

5 Defining the CCS system and boundaries

5.1 General

It is necessary to establish the boundaries of the system and all its sub-systems in order to carry out a complete and accurate quantification of project-level GHG emissions and emissions reductions (see the principles explained in Clause 4). All GHG flows that are to be quantified are defined in reference to these boundaries, namely, transfers between sub-systems (within the whole system), outputs (or leakages) beyond the boundaries of the system, and external inputs. A clear disclosure of boundary decisions/conditions is necessary to avoid any omission or double counting of GHG emissions and removals and to carry out quantification in a transparent and replicable way.

The objective of this clause is to review the spatial and temporal boundaries that are typically applied to a CCS project for Quantification and Verification purposes, being consistent with other ISO/TC 265 requirements, and also recognizing that operators may undertake GHG Quantification and verification for a variety of purposes (e.g. regulatory approvals, voluntary program or economic reasons). As concerns the spatial boundaries, it is consistent with UNFCCC (2012)[1)] which describes the CCS system as follows:

> *"(a) the installation where the carbon dioxide is captured;*
>
> *(b) any treatment facilities;*
>
> *(c) transportation equipment, including pipelines and booster stations along a pipeline, or off-loading facilities in the case of transportation by ship, rail or road tanker;*
>
> *(d) any reception facilities or holding tanks at the injection site;*
>
> *(e) the injection facility; and*
>
> *(f) subsurface components, including the geological storage site and all potential sources of seepage, as determined during the characterization and selection of the geological storage site.*
>
> *The CCS project boundary also encompasses the vertical and lateral limits of the CO_2 geological storage site that are expected when the carbon dioxide plume stabilizes over the long term during the closure phase and the post-closure phase."*

Due to the technical specificities of a project or a regulatory framework, an operator might be able to justify other boundaries. An operator may choose to focus on only individual component units, for example, if different owners operate the various component units. It may also be the case that an integrated CCS project involves only one boiler within a multi-boiler power station. A pipeline may carry CO_2 from multiple sources, or that storage may take place in only one part of a field or may accept combined CO_2 from multiple sources (and third parties).

1) Kyoto Protocol's CDM : CCS Modalities and Procedures

A power plant, for example, that has mandated CO_2 emission constraints may account for the emissions associated with CO_2 capture through a specific regulatory program and might seek to avoid double counting by excluding them from the capture system boundary. Finally, when carrying out a life cycle assessment (LCA), other adjustments may be required to the boundaries.

5.2 Spatial boundaries

5.2.1 Overview

The term "spatial boundaries" describes the physical plant, equipment, and geologic formations associated with a CCS project, and in the case of LCA, certain additional CCS project inputs and outputs. A typical CCS project boundary is conceptually depicted in Figure 1. It illustrates an integrated CCS Project and its main components, or systems that will be detailed in further subclauses.

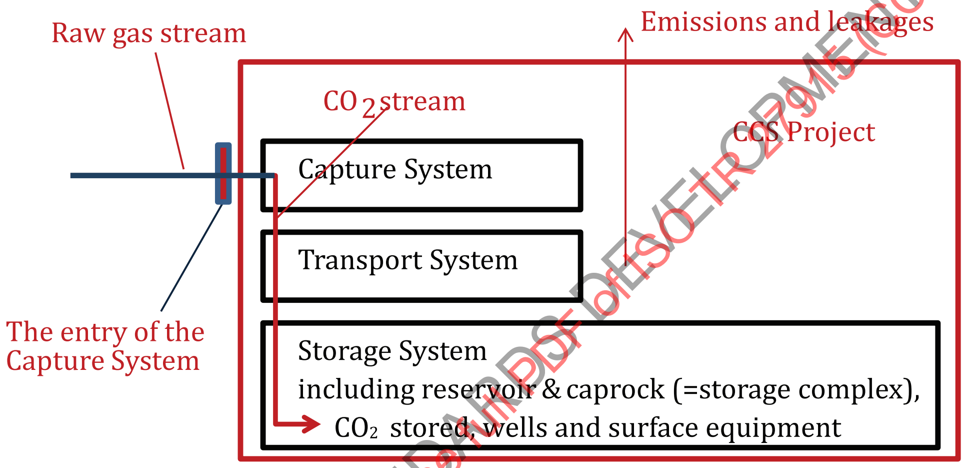

Figure 1 — Full range of CCS boundaries

5.2.2 CCS Project

The main boundary is the integrated CCS project. The boundary begins at the point of capture at which GHG emissions are prevented from entering the atmosphere. It is completed at the point where GHGs are injected and stored into the sub-surface where they are expected to remain permanently. When a CCS operation is added to an existing emission source, emissions and emission reductions are quantified as described in this clause.

All GHG releases outside the CCS system, be they intentional (venting, flaring) or unintentional (leakage), at any point in an integrated CCS project are typically quantified as emissions and accounted for as such, as illustrated on Figure 1.

In the case of other production inputs (e.g. fossil fuel and/or fossil resource consumption), they may enter the system at intermediate points, such as pumps or compressors. Specific requirements may be imposed on operators such as quantification of CO_2 only and/or non-CO_2 GHGs may need to be considered either in the context of a carbon reporting scheme or LCA.

In the case of CO_2 injection for EOR purposes or other recycling operation, the CO_2 that is recycled within a closed system (i.e. recirculation loop) is not considered leakage as the CO_2 is re-injected, however, GHG emissions could occur in the processing and transportation of CO_2.

5.2.3 Capture system boundaries

The capture system contains processes and activities used to separate the CO_2 from (typically) industrial processes, subsequently prevent it from reaching the atmosphere, and prepare it for transportation to the storage site. It is usually not feasible to transport and store dilute streams of CO_2

(see Reference [33]) and so the capture system concentrates the CO_2 to a high purity stream. These processes and activities may include a temporary storage component.

The capture system boundary begins at the point where fluid separation begins. It is easy to conceptually identify this point, however, in practice, it is highly dependent on the type of source of CO_2 and the capture process utilized to separate it from other gas components. There might be a variety of processes in a capture system. Cleaning and compression of the CO_2 stream following capture in many cases will be also considered part of the capture system, upstream of transportation.

Different capture processes are applied to power plants or other industrial CO_2 sources (such as refineries, cement or steel production, etc.). Among this variety of situations, a few examples will be discussed here, keeping in mind that a coal-fired electrical generation plant is often quoted for illustration of CCS projects. In the basic case where a post-combustion capture process is applied to such a coal-fired power plant, the capture system boundary may begin at the location at which the flue gas is diverted from the stack or at the location at which contaminants are removed from the flue gas. It would be useful to consider whether pre-treatment of the flue gases is required by regulation or whether it is simply necessary for the capture technology. If removal of critical air contaminants is mandated, then the boundary might begin at the point at which the flue gas enters the CO_2 capture system following this treatment.

For non-power CO_2 sources, such as refineries and upgraders, the capture system boundary might begin where the duct work joins the capture facilities to processes such as for coking or hydrogen production. For cement plants, the capture system boundary might begin where the gas stream from the calcination unit flows to the capture unit. Steel plants would be similar, with capture system boundary beginning where the gas stream CO_2 from the blast furnaces or coking facilities enters the capture facilities.

Oxy-fuel combustion (see Reference [56]) and gasification (or pre-combustion) (see Reference [65]) systems raise more complex issues. In the case of oxy-fuel combustion, the capture process is integrated with the combustion process and there is a partial stream of CO_2 because of the internal looping for dilution of the oxygen. In such cases, the boundary

— might begin after the boiler, e.g. at the point at which the CO_2 rich stream is polished and enters the compression system, or

— might include the entire system since an air separation unit (ASU) is considered integral to the integrated electrical generation and CO_2 capture processes.

In both cases, it is good practice to account for CO_2 emissions from recirculation.

In the case of gasification, the CO_2 may be captured at several different points depending on the nature of the process. If the syn-gas is burned in a turbine, the capture may be after the turbine (conventional post-combustion capture). If hydrogen (H_2) is the combustion fluid, then the entry point will be the point at which the CO_2 and H_2 are separated following the shift conversion process.

The downstream boundary of the capture system is located at the point where CO_2 is delivered to the transportation system. Typically, this would be the entry valve (upstream isolation valve) into the transportation mechanism, either by pipeline or by another means, such as ship, truck or rail.

There may be a variety of processes between the entry point and the entry valve for the transportation system, including O_2 distillation, stripping, purification, post-combustion compression, and buffer storage. More detail is provided in ISO 27912.

5.2.4 Transportation system boundaries

The transportation system contains all those processes, activities and physical equipment that move the CO_2 from its capture location to its storage location. The most common mode for transporting CO_2 is by pipeline. In this case, the transportation system boundary would begin where the capture system boundary ends, typically the pipeline entry valve (see ISO 27913). The transportation system boundary extends through the pipeline system and ends at the isolating joint with a valve used for delivery to the storage system boundary. Typically, this will take place at a wellhead or wellhead distribution system for onshore storage or at the injection platform for offshore storage. In the case where delivered CO_2 will be further divided, the boundary might be located at the isolating valve upstream of the storage field (see ISO 27913). Any booster stations along the pipeline route are considered part of the transportation system and any emissions from these stations need to be factored in.

Besides using pipelines, CO_2 transport can take place by ship, train, or truck. The main differences between these and pipeline transport are that vessels are likely to be present at loading and unloading facilities in order to ensure a buffering capacity and that emissions are likely to be associated with loading and unloading operations. For the purpose of the ISO/TC 265, it was decided that any buffer storage that may exist would be allocated to the capture system or to the storage system and not the transportation system (ship, train or truck). The same would apply for loading and unloading facilities, although this may be inconsistent with IPCC guidelines (see Reference [42]). Since the CO_2 is likely to be liquefied cryogenically for such transport, the loss of CO_2 from the tanks used in this transport could be accounted for within the transportation system.

5.2.5 Storage system boundaries

The storage system boundary begins at the isolating joint with a valve prior to the wellhead or wellhead distribution system (onshore) or the injection platform (offshore), which is the limit of the transportation system boundary. The storage system is composed of facilities and activities used to prepare and inject the CO_2 and to ensure its long-term storage. It includes, but may not be limited to, surface facilities, injection wells, and the geological storage complex as defined in Clause 3 and in ISO 27914. This is also valid in the case of EOR, however, the "storage complex" can be named "EOR complex". The storage system may also include monitoring wells and production wells, if present. This subclause gives further details.

5.2.6 Geological storage complex

The storage system primarily includes the storage complex, composed of two main underground geological elements: a) the reservoirs or geological systems where CO_2 is injected and b) the caprock (or seals) that is (are) necessary to maintain the safety and integrity of the storage. Overlying geological and underlying geological layers are typically outside the storage complex (see Reference [42], [55] and [26]), however, they may be considered for monitoring activities or for the purpose of measurement of leakages/emissions, as stated in 5.4.

The full extent of the storage system boundary is defined by the physical presence of the CO_2 injected, after its migration and advection into the rock as an independent phase (gas, liquid or supercritical state), or over a longer period, after its ultimate migration (probably including dissolution in water, chemical transformations, and finally, mineralization). This volume is often called the CO_2 plume. It contains lateral and vertical bounds.

The "volume of influence" of the storage operations (often simplified to "area of influence") may be observed over a much greater volume than the physical presence of the CO_2, due mainly to the displacement of brines and pressure increase. It is, therefore, outside the limits of the storage system. This volume of influence may be referred to as "Area of Review" (US and Canada) or "surrounding domains" (EU; CDM in UNFCCC, 2011). Regulatory bodies may or may not consider this volume of influence in CCS permitting and/or accounting programs. Similarly, the area of monitoring may be wider than the limits of the CO_2 plume.

5.2.7 Wells

The storage system includes the injection wells. This includes the full set of potential emission pathways related to these wells such as tubing, casing, exterior cement and, after closure, cement plugs and other activities to abandon the wells.

If monitoring wells are present, they would typically be considered part of the storage system boundary, as well as monitoring activities. Even if they are not connected to the CO_2 plume, in principle these wells would be considered for GHG quantification purposes.

If recirculation or fluid production operations are underway, either directly connected to the storage complex or along the stratigraphic column, the wells producing subsurface fluids would typically be considered as within the storage system boundary as would pressure relief wells or plume steering wells.

5.2.8 Surface equipment

The storage system boundary will also include the physical equipment and surface facilities used for injection into storage. This includes the wellhead(s) for injection wells, pipes that are above ground, unloading facilities, buffer storage if any, CO_2 compression and preparation units if any (e.g. in the case of an EOR facility, in case of heating or cryogenically delivered CO_2, in case of a necessary boosting/recompression stage, in case of removal of condensable gases or impurities, etc.). In the case of offshore storage or if offshore EOR is performed, the surface equipment generally includes the relevant facilities between the injection platform and the wellhead on the seabed, since they are outside the transportation system.

In addition, the recirculation facilities and their interaction with other operational units (e.g. introduction of "new" CO_2, fluid separation, etc.) are considered as part of the EOR facility in an oilfield. It may well be determined that it would be better to define a separate Recirculation Unit (gas/liquid separation, recompression) and consider the interactions between these components of an EOR system for reporting purposes.

NOTE In the context of EOR, the CO_2 being injected is composed of two inputs: new CO_2 and recycled CO_2 (including in situ reservoir CO_2). Within the recirculation unit, further work is needed within ISO/TC 265 to specify how these inputs are quantified as well as possible leakages, and what difficulties/uncertainties are to be addressed in this respect. Note that the storage complex might also be considered an oil reservoir or might be directly connected to an oil reservoir, it might also be named "EOR complex".

Figure 2 illustrates the elements that are usually considered in the storage system boundary and identifies common elements that remain outside, according to the description above. Due to the technical specificities of a project or a regulatory framework, an operator might be able to justify other boundaries. For example, in case a recycling loop is present, in Figure 2 it is identified within the system but site-specific consideration may provide a different interpretation and separate it out.

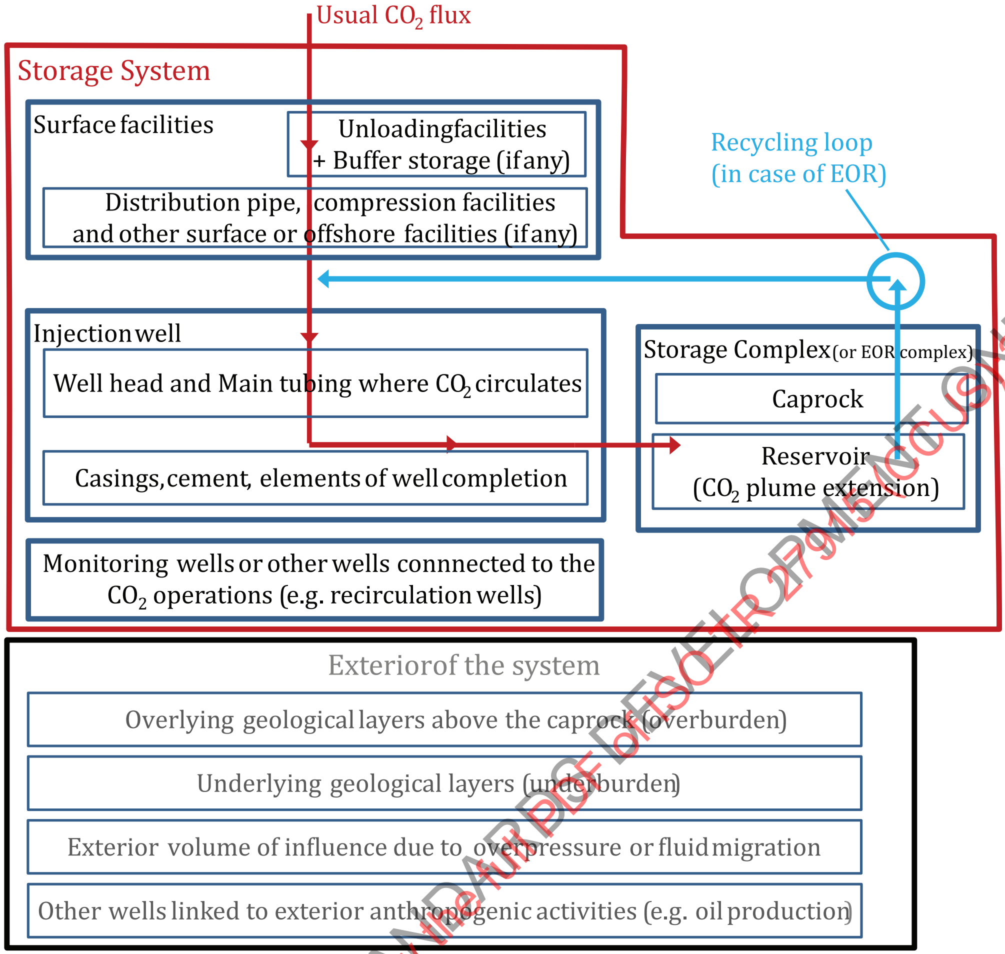

Figure 2 — Storage system boundaries

5.2.9 Life cycle assessment (LCA) boundaries

LCA considers both the increased inputs and the second order effects of the outputs generally without regard for political or jurisdictional boundaries. For CCS projects, LCA would often consider the embedded emissions in defined inputs (e.g. electricity, water, fossil energy, raw materials) and outputs [e.g. increasing production of hydrocarbons, subsequent combustion of the oil and gas produced (Reference [74])]. Hence, in this case, the reporting boundaries may be different from the spatial and time boundaries. Clause 8 discusses these issues in detail and describes relevant inputs and outputs of the CCS system.

5.2.10 Reference to baseline scenario

The primary environmental benefit of CCS is preventing an amount of CO_2 from entering the atmosphere. Typically the amount of CO_2 emission reductions will be less than the amount of CO_2 stored as there are ancillary or additional emissions associated with the processes of operating CCS projects and there may be release/leakage events during those processes.

A fundamental difference between CO_2 stored and CO_2 emission reduction is that the latter refers to a baseline scenario, from which the quantified emissions of the project scenario are deducted to calculate the emission reduction.

Some programs or regulations governing CCS quantification will establish the specific method that suits the program objectives, in order to define a baseline scenario (e.g. CDM or ISO 14064-2:2006).

Another approach might be to use emission factors or "historical emissions" from the emission source that could be derived from an average over time or from a single year's emissions.

Projects are commonly required to report annual emissions, but usually not against a quantified baseline scenario (e.g. EU-ETS, Emissions Trading System). There is only a requirement to report on the amount of CO_2 sent to an approved CCS storage facility and to report on all emissions of CO_2 throughout the CCS project.

5.3 Temporal boundaries

Temporal boundaries refer to the timeframes for quantification. CCS projects tend to have a long life; from start-up through operation to closure. They include several phases that can be schematically gathered into three main periods (Figure 3).

— Preparation period that includes site screening and characterization, then project design, construction and commissioning. This period is of interest for LCA considerations.

— Operational period, which includes the capture, transport and injection phases. The length of this period varies, but for industrial scale projects is likely to be in the order of decades (generally 20 to 30 years or more). In the case of EOR, recycling activities will be within the operational stage.

— Post-injection period: During this period, the capture and transport systems are inactive (or dismantled), while within the storage complex, CO_2 plume migration, geo-mechanical and chemical reactions are likely to continue for many years. This period can be divided into Closure and Post-closure periods: The closure period begins after the cessation of injection, that generally induces the decommissioning (dismantlement) of capture and transport facilities (unless re-used in other projects). The post-closure begins after regulated abandonment (plugging) of the wells (and transfer of responsibility to the designated authority, if applicable).

Many decades (after injection) are likely to be used as the analytical basis for conducting an LCA, taking into account the long-term mechanisms that are identified and simulated in existing sites such as Weyburn or Sleipner. For example, the simulation work on the Weyburn field suggests that pressure equilibration could take as long as 100 years following cessation of injection (see Reference [88]).

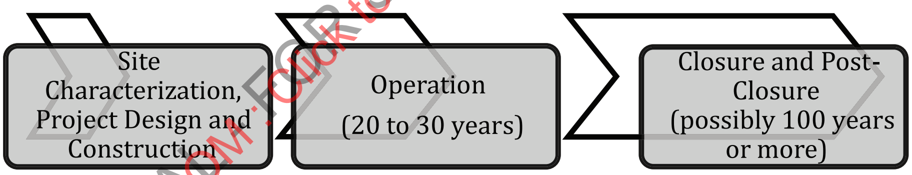

Figure 3 — Simplified CCS project evolution

CCS programs focused on GHG emissions are typically organized around annual quantification requirements (EPA, EU ETS, Alberta Protocols) during the operational stage.

Annual or periodic reporting can be required for a longer period, to demonstrate storage security over time. The regulatory programs or protocols that permit CCS projects typically focus on the life of the project which will usually go beyond the final injection of the CO_2 and into the post-injection period (for example, Alberta Protocols).

During post-injection, the integrity of the storage complex will be the key focus. Of primary interest will be CO_2 migration, the geochemical changes (e.g. CO_2 dissolution and mineralization) and any indication of leakage or emission. Therefore, monitoring activities are likely to be maintained, to check that CO_2 approaches its predicted long-term distribution (see Reference [42]).

The closure period may take a number of years as the reliability of the storage is assessed in anticipation of the transfer of responsibility to public authorities (if applicable for the jurisdiction).

Roles and responsibilities for Quantification reporting and Verification may change over temporal boundaries, as well as responsibilities for implementing monitoring activities (e.g. for the post-closure period, because of the possibility of transfer of responsibility).

5.4 Use of boundaries for Quantification

5.4.1 Importance of Quantification and verification

The Quantification and verification process is essential for inventory accounting and for cap and trade accounting, but it is also an important part of the legitimization of CCS as a legitimate and permanent emission reduction technology. In principle, all GHGs inputs or outputs should be quantified, including all activities defined within the physical boundaries. This is the objective of Clause 6 that describes the quantification methodology, Clause 7 that describes the measurement strategy and Clause 9 that describes the verification process.

All inputs and outputs need to be quantified at the boundaries of the CCS system. As stated in Clause 6, two approaches may be considered in this respect: use of emission factors or direct measurement associated with a mass balance approach between two end points of a system (or sub-system). Some of the CO_2 emitted to the atmosphere may be detected and quantified directly; but much of it will need to be quantified through emission factors or through a difference in a mass balance between the two end points. All these data will also go through the verification process.

Further work is needed within TC 265 to specify the boundaries and principles for quantification of an EOR system. It might be assumed that the quantities will be carefully measured within the EOR field by all its surface and subsurface monitoring facilities. The only commercial EOR project to be considered from a storage perspective is the Weyburn project in Saskatchewan, Canada. Its entry point for new CO_2 is the pipeline (transportation system) entry to the field facilities. The new CO_2 is then blended with the existing CO_2 prior to injection/reinjection (see Reference [88]). CO_2 produced back with the oil is separated, recompressed in electric drive compressors and put back into the production cycle. Other EOR projects are expected to account for GHG storage. For example, US EPA accepted a MRV (monitoring, reporting and verification) plan for Denver Unit in Wasson field, Texas, that is operated for the primary purpose of EOR.

5.4.2 Leakage and risk consideration

The primary objective of a CCS project and its regulatory follow-up is to ensure that the CO_2 remains confined within the geological storage unit, or storage complex. According to the definition of leakage, any CO_2 that migrates outside the entire CCS system boundary is considered as a leakage event. This is also valid for any migration outside the storage complex, even though:

— it may take a long time for this CO_2 to reach the atmosphere or ocean or regulated resource. It may even remain trapped in the overburden to the storage complex;

— some regulatory programs do not explicitly prohibit leakage to the atmosphere [e.g. permits in the US, so long as “Underground Sources of Drinking Water (USDW)” are not contaminated].

According to the principle of permanence in Clause 4, in well designated and operated projects, the injected CO_2 will be considered as “stored” as long as it remains within the defined bounds of the storage complex. However, there might exist potential emission pathways (or leakages) from the storage system, possibly activated by slow or long-term processes. If leakage out of the storage complex occurs, the objective is to account for these CO_2 emissions.

Note that while this TR is focused on GHG accounting, the non-endangerment of resources and the prevention of adverse impacts (on the environment or on human health) are addressed in many cases through additional and possibly independent regulatory or other requirements.

Wells that penetrate the seals but are independent of the CO_2 storage operation (e.g. already-existing oil production wells) are often not considered to be part of the storage system boundary but they are very likely to pose a leakage risk and therefore are typically considered in risk assessments and monitoring programs (see Reference [42], Reference [26] and its Guidance documents # 1 and 2, 2011).

6 Quantification methodologies

6.1 General

This clause includes four parts. 6.2 reviews key elements of GHG accounting approaches for CCS. 6.3 reviews emission sources associated with CCS projects. 6.4 provides a series of case studies illustrating the application of GHG quantification approaches. 6.5 provides a discussion of commonalities, differences, and important issues that arise from a comparison of the case studies. The objective of this clause is to provide the background for future standards for quantification. This clause includes descriptions of programs and rules that are in place and is not intended to propose standards for quantification.

6.2 Key elements of GHG accounting approaches for CCS

6.2.1 Overview

This subclause reviews several elements of quantification methodologies including purpose and type of program, scope and emission quantification methods.

6.2.2 Program purpose and type

One purpose for implementing a quantification program is to account for the GHG emissions and GHG transfers associated with CCS systems. An additional purpose is to quantify GHG emission reductions associated with a CCS project. These approaches share common methods for quantification and differ primarily in the details of boundary and baseline. Four designed-for-purpose types of GHG accounting approaches have been identified and briefly described below.

a) Inventory account is used to develop an inventory of emissions, as is the case with national GHG inventories under the UNFCC, the USEPA GHG Reporting program, and programs in Australia (2014) and Canada. These kinds of programs aim to collect data on emissions and removals to provide an accounting of mass emissions. At the project level, this approach may be used to inform about the entities' GHG emissions in absolute terms and to determine the amount of CO_2 stored using mass balance equations.

b) Cap and trade account is used to quantify and report emissions in compliance with scheme rules. A cap and trade system sets an overall cap for all participants involved in the scheme, with allowances to emit being allocated or sold to individual participants. After quantifying and reporting emissions for a set period, participants should surrender allowances equal to their emissions. This type of system allows for trading by participants where they have a surplus or shortfall in allowances. In the EUETS, each CCS system (capture, transport and storage) is treated as a separate installation and should quantify and report emissions annually, surrendering allowances equal to those emissions.

c) Baseline-emission reduction account is used to develop emission reductions from a baseline, as is the case with the CDM and the ISO standard for GHG management (see ISO 14064-2), these kinds of programs calculate the difference between a baseline scenario and actual project emissions to determine emission reductions.

d) LCA is used to address the environmental aspects and potential environmental impacts of a product system throughout its life cycle. The scope of a LCA as defined in ISO 14040:2006, depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ depending on the goal and purpose of a particular LCA. For CCS, it can be used for different purposes such as the comparison of a service or product with or without CCS, or to quantify net emissions from the suite of direct and indirect emissions. As a GHG quantification technique, life cycle inventory study (LCI study), which does not include the impact assessment phase, is the most comparable although

LCA can go beyond and include also the evaluation of other potential environmental impacts. The methodology of LCA is discussed in detail in Clause 8.

6.2.3 Scope

6.2.3.1 Overview

The GHG accounting protocols reviewed for this document outlined specific requirements for the period of reporting, the types of GHG included and their sources within the CCS systems. The range of requirements is described below.

6.2.3.2 Period of reporting

The period of reporting varies among programs. Some focus on annual emissions, others on annual and cumulative emissions, and others focus on project life or specified monitoring periods.

6.2.3.3 GHG types

The full set of GHGs covered by the UNFCCC and its Kyoto Protocol include:

— carbon dioxide (CO_2);

— methane (CH_4);

— nitrous oxide (N_2O);

— hydrofluorocarbons (HFCs);

— perfluorocarbons (PFCs);

— sulfur hexafluoride (SF_6);

— nitrogen trifluoride (NF_3).

For purposes of reporting national inventories under the UNFCC, the above GHGs are converted into a common carbon dioxide equivalent (CO_2-e). CO_2-e is calculated using the mass of a given GHG multiplied by its global warming potential (GWP), which describes the radiative forcing impact of one mass-based unit of a given GHG relative to an equivalent unit of carbon dioxide over a given period of time. The total GHG emission is expressed as a carbon dioxide equivalent mass in tCO_2-e (see ISO 14064-1:2006, 2.18 and 2.19).

The most common emissions associated with CCS accounting is CO_2 (in tonnes); some programs include other GHGs in inventory accounting programs that address specific CCS systems (i.e. capture, transport, storage) but there is no uniform requirement for CCS projects.

6.2.3.4 Emission sources

Generally, direct emissions are considered to be emissions from sources under the control of the reporting entity and indirect emissions are emissions from sources that are not under the direct control of the reporting entity. Some examples of these definitions taken from existing standards include the following.

— Direct emission:

Direct greenhouse gas emissions are GHG emissions from greenhouse gas sources owned or controlled by the organization. See ISO 14064-1:2006, 2.8.

— Indirect emission:

ISO 14064-1 provides the broadest concept of indirect emissions and classifies them into four categories shown below. The third is equivalent to the concept of upstream or downstream emission within an LCA. The fourth concept includes idea of "leakage" associated with a CDM project, but it is not a physical leakage and therefore it is not used in reference to CCS accounting.

— Energy indirect greenhouse gas emissions are GHG emissions from the generation of imported electricity, heat or steam consumed by the organization/operator/project (see ISO 14064-1:2006, 2.9).

— Other indirect emissions are GHG emissions, other than energy indirect GHG emissions, which are a consequence of an organization's activities, but arise from greenhouse gas sources that are owned or controlled by other organizations/entities. See ISO 14064-1:2006, 2.10. An example of this might be methane emissions from the mining of coal that supplies the electrical generation and compensation for parasitic load for capture.

— A related GHG source, sink or reservoir is a GHG source, sink or reservoir that has material or energy flows into, out of, or within the project. A related GHG source, sink or reservoir is generally upstream or downstream from the project and can be either on or off the project site. A related GHG source, sink or reservoir also may include activities related to design, construction and decommissioning of a project (see ISO 14064-1:2006, 2.17).

— An affected GHG source, sink or reservoir is a GHG source, sink or reservoir that is influenced by a project activity, through changes in market demand or supply for associated products or services, or through physical displacement. While related GHG sources or sinks or reservoirs are physically linked to a GHG project, affected sources, sinks or reservoirs are only linked to a GHG project by changes due to market demand and supply. An affected GHG source, sink or reservoir is generally off the project site. GHG emission reductions or removal enhancements offset by affected GHG sources, sinks or reservoirs are often referred to as "leakage" (e.g. as in CDM terminology, but not in the context of this document because it is not a physical leakage) (see ISO 14064-1:2006, 2.16). An example might be transportation related activities that move products to or from a CCS project that are influenced by demand for the products which are encased by the CCS project.

Figure 4 illustrates the potential array of direct and indirect emissions associated with CCS projects. Most of the reviewed CCS accounting programs focus on direct emissions associated with CCS. Building on the IPCC 1996 GHG Inventory Guideline, WRI (see Reference [90]) provides a concise categorization of direct emissions for CCS systems:

— stationary combustion;

— mobile combustion;

— fugitive emissions including leaks, spills, vents and other intentional releases for purposes of safety, maintenance or to operate specific pieces of equipment;

— process emissions.

In addition to this list of sources, it is worth noting that this document treats emission flaring as a fugitive emission associated with the disposal of waste gas; this approach is frequently but not always used in other inventory guidelines. Further, this document considers emissions associated with CO_2 transport and recycling.

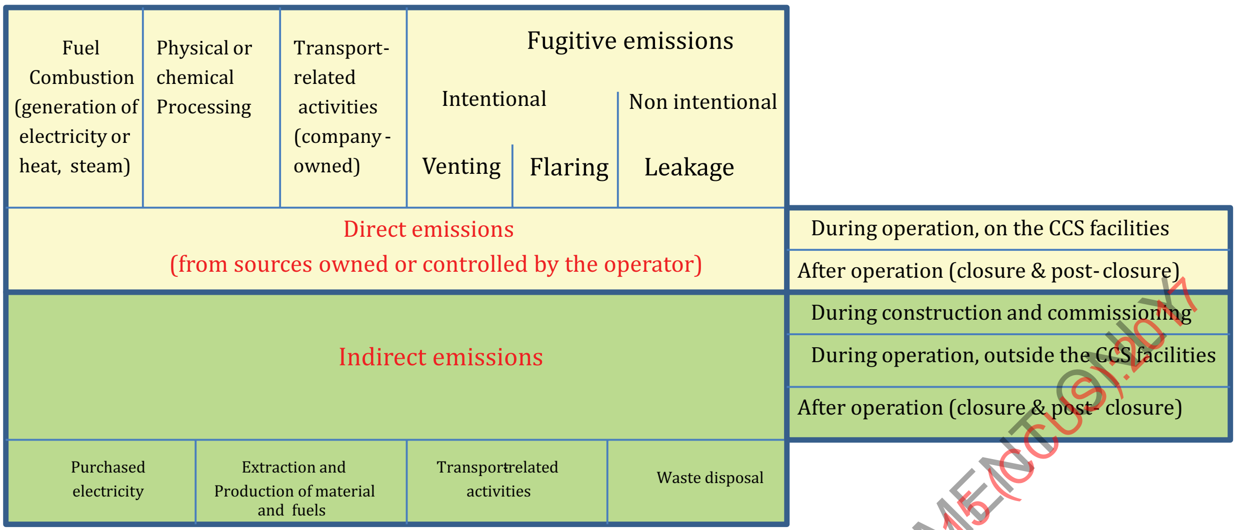

Figure 4 — Typical emission sources associated with CCS

NOTE The high order indirect emissions are not specified here[90].

6.2.4 Emission quantification methods

The methods to quantify emissions may be considered as one of two approaches: use of the emission factor (activity factor) approach or direct measurement and mass balance approach. The choice of the approach can be made depending on the type of emission and the availability of measurement.

The use of emission factors is a common practice in creating emissions inventories for fossil fuel combustion and electricity consumption. To calculate GHG emissions, the amount of fuel consumed, material used, or other activity data is multiplied by an emission factor. To estimate GHG emissions from fuel combustion without CO_2 capture, use of emission factors is accurate. However, applying emission factors to estimate fugitive emissions is less accurate. The emission factors should be developed transparently, based on appropriate data, and updated in a timely fashion. In addition, the use of equipment specific emissions factors (engineering calculations) may be made based on the anticipated or average leakage from specific pieces of equipment (valves, flanges, meters, etc.). To date, there are well-developed factors for the capture and transport systems but not for storage systems. Additional experience and data will be necessary to develop factors for storage systems.

The direct measurement and mass balance approach is also used to measure fugitive emissions and leakages. There could be potential emission pathways (or leakages) from the storage system, possibly activated by slow or long-term processes. Generally, the quantification approaches for a storage system utilize monitoring, direct measurement, risk assessment, and modelling results to determine emissions. A common method for measurement is the use of flow data and mass balance calculation to quantify CO_2 emissions associated with surface facilities in the transport and the storage system. The approaches for quantification of the emissions associated with the storage complex or EOR complex use modelling as well as some approaches for direct measurements as inputs to modelling.

6.3 Sources and emissions identified in CCS systems

6.3.1 Overview

This subclause reviews the typical sources and emissions associated with CCS projects.

6.3.2 Capture system

The quantification of GHGs from the capture system may consider the additional energy used for CO_2 separation and CO_2 treatment for transport. The emissions for the capture system typically include:

— fuel consumption used for flue gas treatment, separation and compression of CO_2 for transport;

— emissions from the incomplete capture of CO_2 from the exhaust;

— fugitive emissions including: leaks and vents from the onsite piping system and flares or vents required due to process upsets.

6.3.3 Transportation system

The quantification of GHGs from the transportation system may consider the energy required for CO_2 transport, leakage from pressurized or cryogenic equipment, emissions from loading and offloading (currently under discussion within TC 265), and venting that may occur during emergency releases or at intermediate storage facilities. Indirect emissions may occur in compression, liquefaction and pumping. Important direct emissions in the transportation system typically include:

— fuel consumption for treatment of CO_2 such as refrigeration;

— fuel consumption for the movement of CO_2 such as compression, pumping, shipping or vehicle use;

— leakage.

6.3.4 Storage system

6.3.4.1 General

The quantification of GHGs from the storage system may consider the energy required to pump or compress and inject or re-inject the CO_2 into the geological formation; any releases or leakage if they occur; or any CO_2 emitted from production wells. Important direct emissions in the storage unit typically include the following.

6.3.4.2 Underground formation and wells

— leaks from the geological formation or a well bore (injection or monitoring);

— CO_2 and other GHGs emitted from production wells (fluid for pressure reduction or production fluids);

— the amount of CO_2 injected into the subsurface complex for purposes of mass balance (not an emission).

6.3.4.3 Surface equipment

— fuel consumed in the operation of surface injection or re-injection (and possibly production) equipment;

— fugitive emissions including: leaks and venting in the injection or re-injection system such as at the distribution manifold at the end of pipeline; distribution pipelines to wells and compression or pumping apparatus; leakage at the production well head;

— fuel consumed/energy used for monitoring and measurement devices.

6.3.4.4 Leakage and risk consideration

— leaks from the geological formation through existing or new fractures or faults;

- leaks through the cap rock or that migrate beyond the cap rock and then to the surface;
- leaks through existing and or unknown boreholes that penetrate the cap rock but that are not part of the project.

6.3.5 Other emissions

As discussed above, sources of indirect emissions may be extensive and the requirement to report them will vary across GHG programs. Indirect energy emissions from purchased energy (principally electricity) are commonly reported (although not in many cap and trade schemes, as these sources may report their emissions separately). Other indirect emissions sources that may be considered in the context of CCS include:

- fuel consumption for construction and decommissioning of facilities;
- upstream and downstream processes for production of the material used for facilities;
- upstream and downstream processes for production of the electricity and fuel consumed;
- additional activities attributable to CCS outside the project boundary.

6.4 Case studies

6.4.1 General

In developing this document, seven quantification programs are reviewed that provide methods for accounting for all, or a large part of, the GHG emissions from CCS projects. The programs include: IPCC[42], CDM[75], EU ETS[27], Alberta CCS Protocol[30], Alberta EOR Protocol[29], US EPA GHG Reporting Program[80], and LCA (see ISO 14040:2006/ISO 14044:2006). LCA as a GHG accounting method is discussed in Clause 8.

Each case study includes background information, the scope of reporting, and accounting methodologies that exist in each program. It is important to note that the case study descriptions present what is in the existing programs. Efforts have been made to avoid describing the program features as recommendations for future standards, and any remaining instances of this are unintended. For ease of comparison, Table 1 summarizes key features of the programs, including the LCA approach that is described in detail in Clause 8.

Table 1 — Case study summary

Program's name feature	IPCC	CDM	EU-ETS	Alberta CCS and EOR protocols	US EPA GHG reporting rules	LCA (ISO 14040/ ISO 14044)
Aggregation level	Nation	Project	Installation (note capture, transport and storage treated as separate installations)	Project	Project, both suppliers of CO_2 (capture) and geologic sequestration of CO_2 (storage) – project based	Dependent on assessment
Purpose	Emissions	Emission reduction	Emissions	Emission reduction	Emissions (subpart PP – amount captured for use offsite; subpart RR - mass balance to determine amount of stored CO_2, includes reporting of component CO_2 calculations)	Dependent on assessment
Period	Annual	Self-defined monitoring periods (intervals of a given crediting period/ (e.g. 7 y/10 y)	Annual	Annual, based on accumulation of shorter term data collection	Annual and cumulative	Annual and/or cumulative (dependent on assessment)
Project Boundary	Country/ nation/ sector	CCS system	CCS system by component	CCS system	Capture and storage systems	Dependent on assessment
GHG Types	All Kyoto GHGs	All Kyoto GHGs	CO_2	CO_2	CO_2	All GHGs
Emission sources	All direct emissions	All direct emissions; significant indirect emissions (may include grid electricity and market effects)	All direct emissions	All direct emissions; includes grid electricity, some up/down stream emissions	All direct emissions	Dependent on assessment

6.4.2 Case study 1: UNFCCC National inventories — Inventory accounting

6.4.2.1 Case study 1: Background

Under the UNFCCC, all Parties are required to submit periodic emission reports known as national inventories. Further, the Paris Agreement, in Article 13.7, also requires all Parties to provide a national inventory report of anthropogenic emissions by sources and removals by sinks prepared by using methodologies accepted by the IPCC. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (hereafter referred to as the 2006 IPCC Guidelines in Case study 1)[42] provide methodologies for estimating national inventories of anthropogenic emissions by sources and removals by sinks of greenhouse gases. In particular, the methodology for CO_2 transport is contained in Chapter 5 Carbon Dioxide Transport, Injection and Geological Storage and the methodology for CO_2 storage is contained in 2.3.4 Carbon Dioxide Capture of Volume 2 Energy. Other portions of the guideline address emissions associated with capture based on the category and sector in which capture takes place.

6.4.2.2 Case study 1: Scope of reporting

National inventories are designed to report all annual anthropogenic emissions and removals in a country; therefore, they theoretically include all GHGs associated with CCS. However, it is not easy to identify all emissions associated with a particular CCS project, particularly regarding indirect emissions. GHG removal is a concept meaning removal of GHGs from the atmosphere to a sink. It is applicable to an increase of stock change of carbon pools (above ground biomass, below ground biomass, dead wood, litter, and soil). Technically, the term “removal” does not apply to the capture and storage of CO_2 derived from fossil fuel combustion because such storage does not result in a stock change of carbon pools. If CO_2 is captured and stored from biomass, the amount of stored CO_2 is regarded as a removal, assuming that activity does cause a decrease of stock change of carbon pools. The term “removal” may also be applicable to direct capture and geological storage of CO_2 from the atmosphere if the technology becomes feasible in the future.

The methodology for CCS does not include indirect emissions, however, most indirect emissions are captured in other sections of the national inventory. For instance, indirect CO_2 emissions resulting from the use of grid electricity in a CCS project is included in CO_2 emissions from energy industries but not specified as a CCS emission. If the indirect emissions take place in a different country, they are accounted for in that country’s national inventory.

6.4.2.3 Case Study 1: Quantification methodology

6.4.2.3.1 General

The 2006 IPCC Guidelines outlines three tiers for estimating GHG emissions from energy systems in 3.3 Methodological Issues of Volume 2 Energy. The Tier 1 method and the Tier 2 method are fuel-based or activity-based. All emissions from fossil fuel combustion activities can be calculated based on the amount of fuel consumed multiplied by an averaged emission factor by fuel type. All fugitive emissions can be calculated based on the amount of activity conducted multiplied by an averaged emission factor by gas and activity. The relationship between the activity level and the GHG emission is determined by a model based on experiences in energy systems. While the Tier 1 method uses default emission factors, the Tier 2 method uses country specific emission factors. In contrast, the Tier 3 method uses site specific or plant specific data, such as monitoring results, direct measurements, and site specific modelling. Typically, Tier 3 is employed because of a lack of empirical data to support the selection of specific emission factors.

The general formula for GHG emissions from fuel combustion in stationary and mobile sources based on country specific emission factors is given in Formula (1):

$$Emissions_{\mathrm{GHG,fuel}} = FC_{\mathrm{fuel}} \times EF_{\mathrm{GHG,fuel}} \tag{1}$$

where

FC_{fuel} is the amount of fuel consumption;

$EF_{\mathrm{GHG,fuel}}$ is the emission factor by GHG and fuel.

The general formula for GHG emissions from energy systems is calculate using Formula (2):

$$Emissions_{\text{GHG,industry segment}} = AL_{\text{industry segment}} \times EF_{\text{GHG, industry segment}} \quad (2)$$

where

$AL_{\text{industry segmen}}$	is the activity level;
$EF_{\text{GHG, industry segment}}$	is the emission factor by GHG and industry (or facility) segment.

6.4.2.3.2 Capture system

The methodology to quantify uncaptured CO_2 in a capture system using a Tier 3 method is contained in the 2006 IPCC Guidelines 2.3 Methodological Issues. The formula to quantify uncaptured CO_2 in a capture unit is shown in Formula (3):

$$Emissions_S = Production_S - Capture_S \quad (3)$$

where

s	is the source category or subcategory where capture takes place;
$Capture_S$	is the amount captured;
$Production_S$	is the measured or estimated emissions, using these guidelines assuming no capture;
$Emissions_S$	is the reported emissions for the source category or sub-category.

The methodology to estimate fugitive emission associated with original activities with or without capture facilities is included in the 2006 IPCC Guidelines Chapter 4: Fugitive or Industrial Process volume.

6.4.2.3.3 Transportation system

The methodology to quantify fugitive emissions in the transportation system is contained in the 2006 IPCC Guidelines Volume 2: Energy and Chapter 5. For pipeline transportation, Tier 1 emission factors are presented based on data from natural gas pipeline transportation because there is not sufficient CO_2 pipeline data available. In addition, the 2006 IPCC Guidelines Volume 2 Chapter 5 stipulates that leakage quantification could be obtained using a Tier 3 approach based on equipment-specific emission factors. For ship transportation, a Tier 3 methodology to meter the amount of gas during loading and discharge using flow metering is introduced. Chapter 5 also refers to possible fugitive emissions from buffer storage, but it simply recommends those fugitive emissions be measured and treated in the transportation system.

6.4.2.3.4 Storage system

The IPCC describes an approach for estimating leakage from a geological reservoir using a site-specific Tier 3 methodology that takes the long timescale of CO_2 storage into account in the 2006 IPCC Guidelines Volume 2: Energy and Chapter 5. In order to understand the long-term fate of CO_2 injected into geological reservoirs, assess its potential to be emitted back to the atmosphere or seabed via leakage pathways, and measure any fugitive emissions. The methodology requires the following:

a) a thorough characterization of the geology of the storage site and surrounding strata including numerical modelling to show how a geologic setting and proper operation will ensure storage is secure;

b) modelling of the injection of CO_2 into the storage reservoir and the future behaviour of the storage system;

c) monitoring of the storage system;

d) use of the results of the monitoring to validate and/or update the models of the storage system.

It should be noted that the IPCC guidelines address the annual reporting duties of national governments and are not limited in time. Therefore, the government should report on all emissions occurring on its territory, even many years after the CCS operation ceased and the site has been closed.

The procedures to estimate fugitive emission from CO_2 storage sites are summarized in Figure 5.

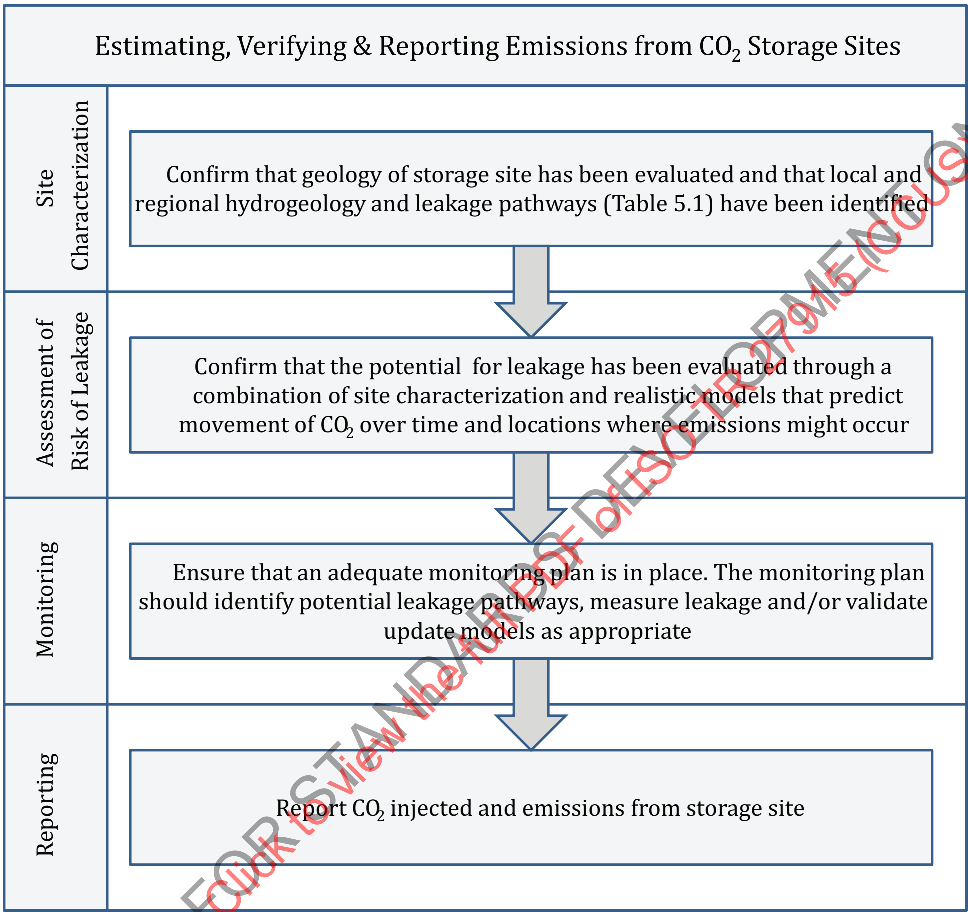

Figure 5 — Procedures for estimating emissions from CO_2 storage sites

The 2006 IPCC Guidelines methodologies for estimating emissions from CCS systems, including indirect emission due to consumption of grid electricity and fuel, are summarized in Table 2.

Table 2 — Examples of emission quantification approaches based on the 2006 IPCC guidelines

System	Type of emissions	IPCC Tier Level	Factors
Capture	Stationary combustion (uncaptured)	Tier 3	Amount of fuel consumed or activity level in primary source CO_2 capture efficiency (%)
	Associated stationary combustion	Tier 2	Amount of fuel consumed
	Mobile combustion	Tier 2	Amount of fuel consumed
	Fugitive emissions	Tier 3	Amount of CO_2 captured Amount of CO_2 transferred to transportation system (amount of CO_2 input in pipeline or ship)
	Purchased electricity or steam	Tier 2	Amount of electricity used Amount of steam used (fuel consumed)
Transportation	Associated stationary combustion	Tier 2	Amount of fuel consumed
	Mobile combustion	Tier 2	Amount of fuel consumed
	Fugitive emissions	Tier 1 or 3 (for pipeline) Tier 3 (for ship)	Amount of CO_2 transferred to transportation unit. Amount of CO_2 transferred to injection site.
	Purchased electricity	Tier 2	Amount of electricity used
Storage	Associated stationary combustion	Tier 2	Amount of fuel consumed
	Mobile combustion	Tier 2	Amount of fuel consumed
	Fugitive emissions	Tier 3	Amount of CO_2 transferred to injection site. Amount of CO_2 injected into underground reservoir
	Geological leakage	Tier 3	Monitoring data of geological CO_2 containment system
	Purchased electricity	Tier 2	Amount of electricity used

6.4.3 Case study 2: ISO 14064-2 and CDM — Baseline emission reduction credit accounting

6.4.3.1 Case study 2: Background

An important implementation of the “Baseline and Credit” approach is the CDM defined by article 12 of the Kyoto Protocol, a legal instrument under the UNFCCC. This global mechanism allows for the generation of certified emission reductions (CER) in countries without a quantified emission limit under the Kyoto Protocol (Non-Annex I countries) to offset emissions produced by the industrialized countries listed in Annex I of the UNFCCC. The mechanism is supervised by an Executive Board with different expert panels as support and infrastructure is provided by the secretariat of the UNFCCC. The basic rules for the CDM are fixed in the “Modalities and Procedures” which were approved by the “Conference of Parties” in 2001, and include overarching criteria for baseline setting, monitoring and independent validation and verification.

Every project should be registered in advance on the basis of a project design document. The project design document should include the determination of a baseline and a monitoring plan, both according to a pre-approved methodology specific for the type of project under consideration. After registration, the project may be implemented according to the project design document. On the basis of independently verified monitoring reports for a specific period of time, the resulting emission reduction is calculated and certified emission reduction credits (CER) are issued by the Executive Board.

In a practical sense, the quantification of GHG emissions is needed for the implementation of "Baseline and Credit" schemes (such as CDM).

NOTE Other baseline emission credit programs include the Alberta Offset Scheme and the US Climate Action Registry. Neither of these two programs was reviewed for this document.

Specifications with guidance at the project level for quantification, monitoring and reporting of GHG emission reductions or removal enhancements are standardized in ISO 14064-2. This International Standard is currently under revision by ISO/TC 207. It contains no specific information or requirements related to CCS projects, but nevertheless, the guidance may also fit well for CCS projects.

6.4.3.2 Case Study 2: Scope of reporting

For CCS projects under the CDM, a dedicated set of "Modalities and Procedures" were developed in 2011, which supplements the comprehensive set of rules for the CDM. A CCS Working Group was established for the assessment of proposals for methodologies and CCS projects. As of the time of this document, there are no reported experiences with regard to the technical solutions for quantifying emissions in CCS projects. Project design documents and monitoring reports are generally open to the public.

Under the CDM, generally all GHG emissions associated with a CCS project, regardless whether they are direct/indirect emissions, are quantified. In the CDM, even emissions occurring outside the project boundary via economic relationships to the project activities need to be considered. In the CDM context, these emissions outside a project boundary are called "leakage" and the term has a different meaning than is otherwise used in this document to refer to the emission of GHGs to the atmosphere (physical leakage).

For CCS projects, like for all other (non-forestry) CDM activities, the permanence of the emission reduction is essential. Therefore, long term monitoring for at least 20 years after the end of the crediting period is required before the liability can be handed over from the project participants to the host country.

CCS-Projects linked with EOR activities are not addressed specifically in the CDM.

6.4.3.3 Case Study 2: Quantification methodology

An emission reduction is defined as the difference between the emissions in a hypothetical baseline scenario (BE) and the emissions of the real project scenario (PE) over a defined interval of time as shown in Formula (4). The crediting period of a project (e.g. 7 years) may be split up in several monitoring periods (e.g. 1 year), but gaps in the time line should not occur to secure completeness of emission reporting.

$$ER_y = (Be_y) - (PE_y) \quad (4)$$

where

ER_y is the emission Reduction in time period y;

BE_y is the baseline Emissions in time period y;

PE_y is the project Emissions in time period y.

See ISO 14064-2:2006, 5.8.

Two different quantification outcomes need to be developed by the project proponent: the quantification of baseline emissions according to a defined baseline scenario (what would happen in the absence of the CCS project) and the quantification of project emissions.

ISO 14064-2 lays out a process for determining the baseline and how the emissions reductions are quantified. The responsibility lies with the project proponent to establish the appropriate criteria and procedures for determining the baseline, which includes the following:

a) the project description, including identified GHG sources, sinks and reservoirs;

b) existing and alternative project types, activities and technologies providing equivalent type and level of activity of products or services to the project;

c) data availability, reliability and limitations;

d) other relevant information concerning present or future conditions, such as legislative, technical, economic, socio-cultural, environmental, geographic, site-specific and temporal assumptions or projections.

All assumptions, values and procedures being utilized for the baseline are conservative, such that, when emissions reductions are applied, the values will not be over-estimated. This allows for the estimation of those reductions from the implementation of the CCS project in a form that can be validated (before implementation) and verified (ex-post) (see ISO 14064-2:2006, 5.4).

NOTE The determination of baseline scenarios for CCS projects is not in the scope and is used here for illustrative purposes.

Under the CDM, the proponent will have created a baseline scenario and be responsible for the identification of GHG sources, sinks, and reservoirs controlled, related to, or affected by the project and also to identify GHG sources, sinks, and reservoirs relevant to the baseline scenario. This will also require that such relevant GHG sources, sinks or reservoirs be amenable to regular monitoring or estimation. Any relevant GHG source, sink or reservoir not selected will need to be explained (see ISO 14064-2:2006, 5.7).

6.4.4 Case study 3: EU ETS — Cap and trade accounting

6.4.4.1 Case study 3: Background

Cap and trade schemes have been established as climate policy instruments at national, sub-national and regional levels. The EU Emissions Trading System (EU ETS) is the largest scheme in operation, noting, however, that China has announced its intention to establish a national scheme beginning in 2017 and that a number of sub-national bodies have developed schemes (for example, Quebec, California, RGGI, etc.). The EU ETS has defined requirements relating to quantification for CCS projects, and is therefore the focus of this clause. At the time of writing this document, no CCS project had been active in the EU so the requirements discussed had not been tested in practice.

The EU ETS is a “cap and trade” accounting approach. A “cap”, or limit, is set on the total amount of certain GHGs that can be emitted by the mandatorily participating installations in the European Union. The emissions cap reduces over time so that aggregate emissions fall. Every installation should report its emissions annually and is obliged to surrender a corresponding amount of Emission Allowances to the authority. Within the cap, companies are allocated or required to buy emission allowances, which they can then trade with one another as needed in case of surplus or shortfall. They can also buy limited amounts of international credits from emission reduction projects around the world (CDM and JI) (see Reference [27]). This trading is allowed because the quantification programs have been deemed comparable, so emission allowances are fungible.

Phase 3 of the EU ETS running from 2013 to 2020 involved several changes from previous phases, with new sectors being brought in under the scheme, including CCS. A key difference in terms of quantification requirements for CCS in the EU ETS compared to Carbon Credit emissions reductions schemes is that operators are not required to set and account a baseline. The incentive for CCS arises from allowances not being required to be surrendered in respect of stored CO_2 that would otherwise be emitted by an installation. While this benefit is open to operators implementing CCS, certain emissions sources associated with capture, transport and storage should be reported, and the equivalent number of allowances surrendered.

For most sectors and activities in EU ETS, only emissions of CO_2 are reported. Only in certain industry sectors are non-CO_2 process emissions required to be reported (e.g. PFCs in aluminium production). For CCS related activities, only CO_2 emissions are required to be reported.

In the case of EU ETS, each installation reports separately on emissions from their activities, and in this scheme capture, transport and storage are considered as separate "installations". The requirements for quantification of CO_2 in CCS activities are specified in the EU-ETS Regulation (see Reference [27]).

6.4.4.2 Case study 3: Scope of reporting

6.4.4.2.1 Capture system

The MRR identifies two scenarios for types of installations where CO_2 capture occurs, either as a dedicated installation receiving CO_2 by transfer from one or more other installations, or by the same installation carrying out the activities producing the captured CO_2 under the same permit. This has important implications in terms of permitting since one industrial site may have more than one "installation" as defined in EU ETS, where activities are undertaken by different operators, e.g. a power plant and CO_2 capture plant may be co-located on the same site, but operated by separate entities in which case, they would be classified as separate installations.

The MRR states that the operator of a CO_2 capture activity shall at least include the following potential sources of CO_2 emission:

a) CO_2 transferred to the capture installation (i.e. any transferred CO_2 that is not eventually transferred on to the transport network because of leaks, etc.);

b) combustion and other associated activities at the installation that are related to the capture activity, including fuel and input material use.

6.4.4.2.2 Transport system

The EU ETS requires the monitoring and reporting of GHGs from CO_2 transport by pipeline to include all ancillary plant functionally connected to the transport network, including booster stations and heaters.

Each operator needs to consider at least the following potential emission sources for CO_2 emissions: combustion and other processes at installations functionally connected to the transport network including booster stations; fugitive emissions from the transport network; vented emissions from the transport network; and emissions from leakage incidents in the transport network.

6.4.4.2.3 Storage system

Where leakages from the storage complex are identified and lead to emissions or release of CO_2 into the water column, then, under the MRR, several tasks need to be undertaken:

a) notify the competent authority;

b) include the leakage as an emission source for the respective installation;

c) monitor and report the emissions.

Until corrective measures, in accordance with Article 16 of Directive 2009/31/EC have been taken, and the results monitored, the emissions will continue to be considered as leaks and should be quantified and reported.

EU ETS requires that at least the following potential emission sources for CO_2 are investigated: fuel use by associated booster stations and other combustion activities including on-site power plants, venting from injection or enhanced hydrocarbon recovery operations, fugitive emissions from injection, CO_2 produced from enhanced hydrocarbon recovery operations, and leakages.

6.4.4.3 Case study 3: Quantification methodology

6.4.4.3.1 Capture system

Installations should quantify both the amount of CO_2 emitted, and the CO_2 captured and transferred to the transport network using standardized approaches of CO_2 emitted, captured and transferred.

6.4.4.3.2 Determination of transferred CO_2

The MRR states that "Each operator shall determine the amount of CO_2 transferred from and to the capture installation using continuous measurement systems (CMS)". CMS is a term adapted from continuous environmental monitoring systems (CEMS) because in the case of CCS it is captured CO_2 being measured rather than emissions.

In the EU ETS, different tiers should be applied for measurement of activity data and calculation factors. In the context of determining activity data, this relates to the required accuracy of measurement with higher tiers requiring lower uncertainty in measurements.

"For determining the quantity of CO_2 transferred from one installation to another, the operator shall apply tier 4 (the highest tier), which applies a maximum permissible uncertainty of ±2,5 %.

6.4.4.3.3 Transport system

The operator of transport networks can determine emissions using one of the following methods annually to ensure reliable results and the lower level of uncertainty:

a) method A (overall mass balance of all input and output streams);

b) method B (monitoring of emission sources individually).

Uncertainty is limited to 7,5 % under the EU ETS.

6.4.4.3.4 Fugitive emissions from the transport network

In a manner similar to US EPA processes, discussed below, fugitive emissions can be based on specific equipment-based emissions factors.

6.4.4.3.5 Emissions from leakage events

Leakage events in the transportation system may be calculated based on input and output temperature and pressure data from the pipeline.

6.4.4.3.6 Vented emissions

The monitoring plan developed under EU ETS regulations covers monitoring for any venting events that may occur within the transportation boundaries.

6.4.4.3.7 Storage system

6.4.4.3.7.1 Vented and fugitive emissions from injection

Emissions from venting and fugitive emissions should be determined.

Monitoring or an accepted alternative methodology can be used to measure or calculate vented CO_2. Measurement of fugitive emissions can be based on an understanding of possible occurrences and an appropriate methodology for measurement or calculation.

6.4.4.3.7.2 Vented and fugitive emissions from enhanced hydrocarbon recovery operations

Within an EOR operation, the EU Directive recognizes the increased complexity brought on by recycling the CO_2 and other operations so increased diligence is required to monitor:

a) the oil-gas separation units and gas recycling plant, where fugitive emissions of CO_2 could occur;

b) the flare stack, where emissions might occur due to the application of continuous positive purge systems and during depressurization of the hydrocarbon production installation;

c) plant specific elements where emissions might occur such as the CO_2 purge system, to avoid high concentrations of CO_2 extinguishing the flare.

6.4.4.3.7.3 Leakage from the storage complex (or EOR complex)

Leakage from the storage complex, either to the atmosphere or to water bodies, has been discussed briefly above. Under the Directive, the release needs to be measured or calculated and reported as an emission. As with transportation, the level of uncertainty is given a maximum value of 7,5 %.

6.4.5 Case study 4: Alberta CCS protocol — Baseline emission reduction credit accounting

6.4.5.1 Case study 4: Background

Government of Alberta (2015)[30] provides another example of the quantification of CO_2 emissions and reductions using baseline, which is quite unique on the point of not requiring functional equivalence to a CCS project. The methodology records the changes in emissions to the baseline case of the CCS project. This methodology is dominantly for CO_2, but other GHGs are included in the tracking and reporting of emissions. In the calculation of emissions from the extraction, processing and transportation of fuels, the ancillary emissions of N_2O and CH_4 are included as CO_2-e, with emissions factors based on Alberta regulation (from Environment Canada reports). The protocol is automatically updated every five years by regulation.

The quantification of the reductions, removals and reversals of relevant sources and sinks for each of the greenhouse gases are completed using the general methodology outlined below. This calculation methodology serves to complete Formula (5) for calculating the emission reductions from the comparison of the baseline and project conditions:

$$Emission\ Reduction = Emission_{\text{Baseline}} - Emissions_{\text{Project}} \tag{5}$$

where

$Emission_{\text{Baseline}}$ is the emission projected from the measured quantity of CO_2 injected in the project condition, but does not include CH_4 and N_2O;

$Emissions_{\text{Project}}$ is the sum of the emissions under the project condition considering construction and well drilling, production and delivery of material inputs, fuel extraction and processing, off-site electricity generation, off-site heat generation, on-site heat and electricity generation, carbon capture and storage facility operation, venting CO_2 at injection well sites, fugitives from injection well sites, subsurface to atmosphere, loss, disposal or recycling of material inputs.

All data should be available for third party verification (ISO 14065 levels) and should be retained, with raw data, for seven years following the crediting period. CO_2 volumes are based on continuous monitoring to the highest level possible and with daily sampling of CO_2 composition averaged on a monthly basis. Reporting is annual. All emissions factors are based on annual Environment Canada reporting. Units of measurement are prescribed within the protocol.

As a final note, the protocol is designed for an integrated project, but can be broken up into component parts in the same way as other methodologies noted in this document.

6.4.5.2 Case study 4: Scope of reporting

6.4.5.2.1 Capture system

The capture activities that are included within the baseline and project condition includes all materials (production and delivery) used in the CO_2 capture process since the Alberta protocol includes indirect emissions that are not considered negligible. It also includes extraction, processing and transportation of fuels used on-site for the capture of CO_2. The Alberta protocol, in addition, accounts for the extraction, processing and transportation of fuels used off-site for the production of heat or electricity used on-site for the production of CO_2. It does not include any flaring, venting or fugitive emissions at the capture site, which are considered as part of the baseline. The Project Condition (i.e. the baseline condition of the project) includes the flaring, venting and any other fugitive emissions that occur upstream of the injected wellhead meter and so these do not influence either the baseline emission or the project emission since the baseline emission is the injected amount of CO_2.

6.4.5.2.2 Transport system

In effect, the reporting during the transportation is restricted to only the actual CO_2 transported. All fugitive emissions are considered to be part of the baseline condition and, as such, are excluded from calculation in the project emissions within the CCS transportation component since they occur upstream of the injected wellhead meter. Reporting will be annual based on monthly averaged records.

6.4.5.2.3 Storage system

The scope of reporting includes the CO_2 injected at the wellhead less any emissions from equipment (flanges, seals, etc.), venting from the well or formation (including methane and nitrous oxide) and any emissions from the subsurface (well or formation) to the atmosphere based on the approved measurement, monitoring and verification plan. Reporting is annual based on continuous metering and monthly averaging.

6.4.5.3 Case study 4: Quantification methodology

6.4.5.3.1 General

Under this scheme, the Government of Alberta (2015)[30] measures the baseline emissions, which are projected back, using the direct measurement of the quantity of gas that has been measured upstream of the injection wellheads in the project condition. Simply stated, the baseline emissions are the measured amount of CO_2 injected at the wellhead. Then the project emissions are calculated accounting for vent and fugitive emissions at the injection well sites and leakage from subsurface to the atmosphere and all significant indirect emissions in a full chain of CCS. The emissions reductions are calculated by subtracting the project emission from the baseline emissions.

6.4.5.3.2 Capture System

In the CO_2 capture component of the CCS system, project emissions include emissions from electricity, heat and transportation fuels produced and used on-site as well as the heat or electricity produced off-site for use by the production process. As well, the emissions from the process itself in the upstream are accounted for and can be calculated from the materials used in the project output (electricity, cement, refined products, etc.).

6.4.5.3.3 Transport system

Quantification is based on measurement of the CO_2 transported in the pipeline system from capture system to Well Head injection. Fugitive emissions and any emissions resulting from the use of pumping/compression are tracked only. These are based on emissions factors for fuel or emissions factor estimates.

6.4.5.3.4 Storage system

Quantification is based on the estimates of emissions from fittings (as used in the EPA measurement, for example) and measurement based on monitoring from the subsurface, with monitoring based on an approved plan. Specifics are not provided in the protocol, but rather moved to approved plans confirmed by a competent authority. The fluid injected can be metered continuously.

6.4.6 Case Study 5: Alberta EOR protocol — Baseline emission reduction credit accounting

6.4.6.1 Case study 5: Background

The Alberta EOR Protocol (see Reference [29]) is based on the capture of CO_2 from waste gases from oil and gas production processes or other industrial processes and the transport and utilization of this CO_2 and related GHGs (N_2O and CH_4) for enhanced oil recovery.

As with the storage protocol, the Alberta EOR protocol requires a monitoring plan to be approved. It also outlines the data handling and verification process. Finally, it includes the units of measurement to be applied in the data collection and reporting.

The listing of emissions to be tracked is extensive, as with other measurement systems in this document, but not all of the tracked emissions may be quantified as seen in Tables 3 and 4.

6.4.6.2 Case study 5: Scope of reporting

6.4.6.2.1 General

The source of the capture of CO_2 are classified into two types, oil and gas production processes or other industrial processes. For the former, it is assumed that fuel consumption for capture, flaring and venting in source gas capture, source gas transport and processing are included within the baseline condition and are, therefore, not counted with the exception of CO_2 from the latter. Fuel consumption of injection gas transportation and injection and flaring and venting at injection sites are counted in the baseline and the project condition regardless the type of sources. Fugitive emissions and electricity use are not counted consistently in all processes for this protocol. For gas from industrial sites, the protocol includes the recirculation of the CO_2 and its reinjection into the reservoir for incremental oil recovery.

6.4.6.2.2 Capture system

Electricity used in the process is not included in the quantification process because it is accounted for in other greenhouse gas regulations. The fuels used for extraction and processing, are however, included within the baseline and project emissions. The delivery of this fuel is not included. Reporting is on an annual basis, although metering is continuous and the composition of the CO_2 is averaged monthly. Fugitive emissions are considered as likely negligible in comparison to other emissions and will not be reported.

6.4.6.2.3 Transport system

While the volumes of CO_2 moved by pipe can be metered, other emissions should be tracked by means of emissions factors for components such as compressors. Fuel used if the CO_2 is moved by means other than pipe will be calculated based on fuel type and emissions factors (CO_2, CH_4 and N_20). Fugitive emissions are considered as negligible in comparison to other emissions and will not be reported.

6.4.6.2.4 CO_2 EOR storage system

Included in the reporting are emissions resulting from the use of pumps or compressors and other onsite equipment. These are based on emissions factors. Also included is the flaring and venting from the site, recognizing that these emissions may include CH_4. Fugitive emissions are, however, considered as likely to be negligible in comparison to other emissions and are not required to be reported (i.e. most emissions will be routed through flare stacks and can be metered). Reporting of emissions resulting from the failure to reinject the produced gas will need to be undertaken.

6.4.6.3 Case study 5: Quantification methodology

6.4.6.3.1 Capture system

The CO_2 is metered into the pipeline system. Flaring and venting, as a result of CO_2 capture from industrial sources, is measured based on metering or emissions factors (these are not considered as within the baseline in this protocol). Similarly, fugitive emissions will need to be tracked from industrial capture (using engineering estimates), although they may not be accounted if deemed insignificant to the overall emissions reductions.

6.4.6.3.2 Transport system

The CO_2 moved can be metered and determined as a volume at standard temperatures and pressures. Other fuel used is measured, recorded and emissions factors applied.

6.4.6.3.3 CO_2 EOR storage system

As noted, the methodology of quantification is accomplished by metering and the use of emissions factors and engineering estimates.

6.4.7 Case study 6: US GHG reporting — Inventory accounting

6.4.7.1 Case study 6: Background

US EPA Greenhouse Gas Reporting Program (GHGRP) found at 40 CFR Part 98 (see Reference [85]) requires the reporting of GHG data and other relevant information from large sources and suppliers in the United States (25 000 tonnes or more per year). The GHGRP was established to “collect accurate and timely GHG data to inform future policy decisions.” (see Reference [85]).

The general approach is similar to inventory accounting as described in the Case study 1 on the IPCC. Guidance is provided for estimating or measuring direct emissions to be aggregated at different levels. The GHGRP currently covers 41 source categories and comprises 47 subparts. Each subpart provides general rule or specific guidance for emissions quantification and reporting for a source type. There is not a subpart associated with CCS at the project level, however, there are subparts that cover aspects of CO_2 capture, injection and storage, but not transportation.

In general, the GHGRP covers a range of GHGs and requires sources to report direct emissions. Inadvertently, the array of source categories covers most of the indirect emissions associated with CCS but they are not attributed to CCS projects. Further, the subparts that relate to CCS cover only CO_2.

6.4.7.2 Case study 6: Scope of reporting

6.4.7.2.1 Capture system

The main subpart addressing CO_2 capture is found in Subpart PP of the GHGRP, which covers “Suppliers of Carbon Dioxide.” It focuses on the upstream supply of CO_2. The source category includes, among others, facilities that capture CO_2 for the purpose of supplying the captured CO_2 for commercial purposes or for sequestering it. The upstream focus means that this subpart does not include the use, storage, or sequestration of supplied CO_2, these are addressed in other subparts or regulatory programs. Subpart

W of the GHGRP includes provisions for reporting fugitive emissions from hydrocarbon facilities and other subparts of the GHGRP also address other fugitives from different industry sectors.

6.4.7.2.2 Transport system

The GHGRP does not include a subpart related to the transport unit of a CCS project. It is not included in the inventory through this approach. In the US, other regulatory programs govern the construction, operation, safety and environmental performance of pipelines.

6.4.7.2.3 Storage system

The main subparts addressing CO_2 injection and storage are found in Subpart RR, "Geologic Sequestration of Carbon Dioxide," and Subpart UU "Injection of Carbon Dioxide". The Subpart RR provisions provide guidance for estimating the amount of CO_2 that is stored as a result of CO_2 injection. The Subpart UU provisions provide guidance for sources that want to only report the amount of CO_2 received for injection. Sources operating CO_2 EOR facilities under the UIC Class II permit program can opt to report under Subpart UU or Subpart RR. Sources operating geologic sequestration projects under the UIC Class VI permit program are required to report under Subpart RR. Both Subparts focus on the mass of CO_2 only. Subpart W of the GHGRP includes provisions for reporting fugitive emissions from hydrocarbon facilities and other subparts of the GHGRP also address other fugitives from different industry sectors.

6.4.7.3 Quantification methodology

6.4.7.3.1 Capture system

Subpart PP is broader than just capture; it calls for the reporting of the following data:

a) mass of CO_2 captured from production process units;

b) mass of CO_2 extracted from CO_2 production wells;

c) mass of CO_2 imported;

d) mass of CO_2 exported.

Only the first item on the list is pertinent for this document. Subpart PP uses formulae based on data from either mass or volumetric flow meters to derive quarterly (every 3 months) and annual mass of CO_2 captured at individual locations and then summed for a facility.

6.4.7.3.2 Using mass flow meters

Using a mass flow meter, the annual mass of CO_2 is calculated as the sum of the quarterly CO_2 concentration (weight % CO_2) multiplied by the quarterly mass flow of CO_2 for each of the four quarters.

6.4.7.3.3 Using volumetric flow meters

Using a volumetric flow meter, the annual mass of CO_2 is calculated as the sum of the quarterly CO_2 concentration (either volume % CO_2 or weight % CO_2) multiplied by the density of CO_2 (either metric tons CO_2 per standard cubic meter for volume or for the whole CO_2 stream if using mass) multiplied by the quarterly volumetric flow of CO_2 (standard cubic meters) for each of the four quarters.

6.4.7.3.4 Aggregation at production process units or wells that measure CO_2 after segregation or do not segregate flow

The total annual mass of CO_2 is calculated as the sum of all the individual annual mass CO_2 calculations for all of the meters.

6.4.7.3.5 Aggregation at production process units or wells measure CO_2 ahead of segregation

The total annual mass of CO_2 is calculated as the sum of all the annual mass CO_2 through the main flow meter less the sum of annual mass CO_2 through subsequent flow meters for use on site.

Subpart W of the GHGRP includes provisions for reporting fugitive emissions from hydrocarbon facilities and other subparts of the GHGRP also address other fugitives from different industry sectors. Subpart W utilizes factors for equipment and fuel.

6.4.7.3.6 Storage system

Subpart UU covers CO_2 injection for purposes such as CO_2 EOR and requires reporters to estimate the mass of CO_2 received for injection each year.

Subpart RR focuses on the receipt, injection, and storage of CO_2. It requires reporting of the following data:

— mass of CO_2 received;

— mass of CO_2 injected into the subsurface;

— mass of CO_2 produced;

— mass of CO_2 emitted by surface leakage;

— mass of CO_2 emissions from equipment leaks and vented emissions of CO_2 from surface equipment located between the injection flow meter and the injection wellhead;

— mass of CO_2 emissions from equipment leaks and vented emissions of CO_2 from surface equipment located between the production flow meter and the production wellhead;

— mass of CO_2 sequestered in subsurface geologic formations;

— cumulative mass of CO_2 reported as sequestered in subsurface geologic formations.

The US EPA methodology covers the use of either mass or volumetric measurements (see above and Clause 7) and converts these back into mass units for the CO_2. The methodology also uses annual calculations based on intermediate monitoring and recording of mass flow and the aggregate of all the sources of CO_2 injected and stored. Where EOR is undertaken, the flows within the recycle loop are similarly measured and incorporated in the aggregate calculations avoiding any double counting of CO_2 streams.

Also, included in Subpart RR is the determination of the annual mass of CO_2 that is emitted through surface leakage. Subpart RR does not prescribe methods for this quantification, but requires the facility to include the basic approach in the MRV Plan and to document actual methods used in the event of a leakage event.

Other subparts, especially Subpart W, provide detailed guidance for measuring or estimating the amount of fugitive CO_2 emissions leaked during the injection process from injection equipment.

The annual mass of CO_2 that is sequestered in the underground subsurface formation is calculated by taking the total annual mass CO_2 injected and subtracting the total mass CO_2 emitted through surface leakage, and the total mass CO_2 emitted from both categories of equipment leaks.

6.4.7.3.7 Monitoring, reporting, and verification (MRV) plan

Like the IPCC National Inventory approach, Subpart RR requires reporters to submit and gain approval of a site-specific monitoring, reporting and verification (MRV) plan that describes the following elements:

— delineation of the maximum monitoring area (MMA) and the active monitoring areas (AMA);

— identification of potential surface leakage pathways for CO_2 in the MMA and the likelihood, magnitude, and timing of surface leakage through these pathways. A strategy for detecting and quantifying any surface leakage of CO_2;

— a strategy for establishing the expected baselines for monitoring CO_2 surface leakage;

— a summary of site-specific considerations for the mass balance equations;

— facility data (including well identification);

— timing.

Subpart RR requires a source to continue reporting until the project is closed. In the case of geologic sequestration under UIC Class VI permits, this is anticipated to be a period of time that extends post-injection until the project demonstrates that CO_2 storage is secure. In the case of CO_2 injection under UIC Class II, this could be a shorter timeframe that ends before or when a project closes. In addition, all sources subject to the GHGRP should submit a basic monitoring plan as part of the umbrella requirements in the early subparts.

6.4.8 Case study 7: LCA

This case study is reviewed in Clause 8.

6.5 Discussion — Key commonalities, differences and noteworthy issues

There are notable commonalties among the programs. Across the board, there is a set of essential methods for quantifying emissions. These methods typically used activity levels and emission factors that have a built-in level of conservatism. Typically, the focus is on direct emissions, although a number of programs also include the indirect emissions that are directly affected by CCS operations. Most programs utilize some kind of a monitoring plan that is prepared in advance and describes how the project will monitor, measure, model, and account for GHG emissions. In the case of LCA, the breadth of scope is greater than in the other programs. Table 3 and Table 4 compare the direct and indirect sources of emissions by program. In Table 3 and Table 4, a “Y” indicates that the program has the relevant feature and an “N” indicates that it does not.

Table 3 — Direct emissions by case study

Stage of CCS	Type of emission	IPCC	EU-ETS	CDM	Alberta protocol	Alberta EOR	US EPA GHG reporting rules	LCA (ISO 14040/ ISO 14044)
Capture	Uncaptured	Y	Y	Y	N	N	NA[a] (see source specific subparts)	Y[b]
	Leak/spill	Y[a]	Y	Y	N	N	Y	Y[b]
	Venting	Y[a]	Y	Y	N	Y	Y	Y[b]
	Associated stationary combustion	Y[a]	Y	Y	Y	Y	Y	Y[b]
	Mobile combustion	Y[a]	N	Y	N	N	NA[a]	Y[b]

NOTE Equipment upstream describes activities that occur prior to production of the product being analyzed (upstream), e.g. material acquisition, fuel processing, etc. and downstream describe activities that occur after production (downstream), e.g. product use, disposal in life cycle approaches.

a Included but not linked to CCS Equipment.

b Depending on project boundary a project of LCA assumed.

Table 3 *(continued)*

Stage of CCS	Type of emission	IPCC	EU-ETS	CDM	Alberta protocol	Alberta EOR	US EPA GHG reporting rules	LCA (ISO 14040/ ISO 14044)
Transportation	Leak/spill	Y	Y	Y	N	N	NA[a]	Y[b]
	Venting	Y	Y	Y	N	NA[a]	NA[a]	Y[b]
	Associated mobile combustion	Y[a]	N	Y	N	NA[a]	NA[a]	Y[b]
Storage	Leak/spill	Y	Y	Y	Y	N	Y	Y[b]
	Venting	N	Y	Y	Y	Y	Y	Y[b]
	Mobile combustion	Y[a]	N	Y	N	Y	NA[a]	Y[b]
	Geological leakage	Y	Y	Y	Y	N	Y	Y[b]
Monitoring	Mobile combustion	Y[a]	N	Y	N	N	NA[a]	Y[b]
Decommission	Stationary combustion	Y[a]	N	N	N	N	Y	Y[b]
	Mobile combustion	Y[a]	N	N	N	N	NA[a]	Y[b]

NOTE Equipment upstream describes activities that occur prior to production of the product being analyzed (upstream), e.g. material acquisition, fuel processing, etc. and downstream describe activities that occur after production (downstream), e.g. product use, disposal in life cycle approaches.

[a] Included but not linked to CCS Equipment.

[b] Depending on project boundary a project of LCA assumed.

Table 4 — Indirect emissions by case study

Stage of CCS	Type of emission	IPCC	EU-ETS	CDM	Alberta protocol	Alberta EOR	US EPA GHG reporting rules	LCA (ISO 14040/ ISO 14044)
Geological exploration	Mobile combustion	Y[a]	N	N	N	N	N	Y[c]
	Grid electricity consumption	Y[a]	N	N	N	N	NA[a]	Y[c]
Construction	Stationary combustion	Y[a]	N	N	N	N	N	Y[c]
	Mobile combustion	Y[a]	N	N	N	N	N	Y[c]
	Grid electricity consumption	Y[a]	N	N	N	N	NA[a]	Y[c]

NOTE Equipment upstream describes activities that occur prior to production of the product being analyzed (upstream), e.g. material acquisition, fuel processing, etc. and downstream describe activities that occur after production (downstream), e.g. product use, disposal in life cycle approaches.

[a] Included but not linked to CCS Equipment.

[b] Included but not linked to CCS and emissions abroad are excluded.

[c] Depending on project boundary a project of LCA is assumed.

Table 4 *(continued)*

Stage of CCS	Type of emission	IPCC	EU-ETS	CDM	Alberta protocol	Alberta EOR	US EPA GHG reporting rules	LCA (ISO 14040/ ISO 14044)
Capture	Grid electricity consumption	Y[a]	N	Y	Y	N	NA[a]	Y[c]
	Equipment upstream	Y[b]	N	Y	Y (chemical)	Y	NA[a]	Y[c]
	Equipment down stream	Y[b]	N	N	N	N	NA[a]	Y[c]
Transportation	Grid electricity consumption	Y[a]	N	Y	Y	N	NA[a]	Y[c]
	Equipment upstream	Y[b]	N	N	N	N	NA[a]	Y[c]
	Equipment down stream	Y[b]	N	N	N	N	NA[a]	Y[c]
Storage	Grid electricity consumption	Y[a]	N	Y	Y	N	N	Y[c]
Monitoring	Grid electricity consumption	Y[a]	N	Y	N	N	N	Y[c]
Decommission	Grid electricity consumption	Y[a]	N	N	N	N	N	Y[c]
Fuel consumption	Upstream	Y[b]	N	N	Y	Y	N	Y[c]
	Downstream	Y[b]	N	N	N	N	N	Y[c]
	Market effects	N	N	Y	N	N	N	N
Electricity consumption	Upstream	Y[b]	N	N	Y	N	N	Y[c]
	Downstream	Y[b]	N	N	N	N	N	Y[c]
	Market effects	N	N	Y	N	N	N	N

NOTE Equipment upstream describes activities that occur prior to production of the product being analyzed (upstream), e.g. material acquisition, fuel processing, etc. and downstream describe activities that occur after production (downstream), e.g. product use, disposal in life cycle approaches.

[a] Included but not linked to CCS Equipment.

[b] Included but not linked to CCS and emissions abroad are excluded.

[c] Depending on project boundary a project of LCA is assumed.

6.5.1 Key differences

While there is general agreement on methodologies among the various measurement schemes, there is difference in detail in what is considered and reported. For example, the Alberta protocols call for extensive tracking of various emissions, but limited reporting by excluding apparently insignificant emissions. Other jurisdictions require much more detail in reporting. As a result:

— Purpose:

The purpose of the program governs decisions on boundaries and may conflict with attempts to create a common standard approach. This means it might be necessary to be able to use something like a menu approach in creating a standard.

— Direct/indirect emission:

The inclusion of indirect emissions can have a large impact on delineating the boundary for purposes of aggregation, especially for upstream emissions such fuel production and grid electricity use and market effect.

6.5.2 Issues for further consideration

— Emission quantification:

a) Permanence and long-term leakage from geological reservoir

At this time, there is no common agreement on methodologies and procedures to account for long term leakage, if it were to occur. The two key issues include the selection of a quantification methodology and period for monitoring. Annualized accounting, such as in a national inventory, does not address permanence in a practical sense, although most existing regulatory and reporting frameworks state that the potential for emissions needs to be assessed, essentially by taking into account site characterization, risk assessment, modelling and monitoring.

As concerns monitoring, there is general agreement amongst GHG programs and regulatory regimes to carry out a monitoring after site closure, with a limit in time (see Reference [42], Reference [75] and EU). The IPCC (2006)[42] proposes that it may be appropriate to decrease the frequency of monitoring, or to stop monitoring, when monitoring results, e.g. the observed CO_2 plume, approach the long-term distribution predicted by the simulation model and show evidence of long-term stability. This principle is widely accepted by most regulatory regimes.

b) Determination of what is tracked and what is reported.

Different programs define the scope of reporting differently. In order to avoid double counting it will be important to coordinate these differences.

c) Feasibility and lack of definition of methodologies.

There are certain areas where methodologies are not well understood (e.g. where the EU ETS refers to using industry best practice, but an industry best practice has yet to be developed). This may be the case in relation to methods for quantifying amounts of CO_2 leaked to the atmosphere.

— Emission reduction quantification:

Currently, the Alberta protocols appear to be two of the few programs to quantify emission reductions using baseline methodologies. This approach does not require a functional equivalence to compare project emissions to baseline emissions and therefore may be difficult to include in trading programs.

The concept of CO_2 avoided is theoretically assumed to be the functional equivalence between a reference plant and plant with CCS in the IPCC Special Report (see Reference [41]); however, it is not considered in this document.

7 Measurement and monitoring

7.1 General

Measurement is the determination of the quantity of GHGs emitted through direct measurement or estimation based on modelling results, or estimation based on emissions factors indicating fuel types, activity levels, or utilized equipment. The objective for measurement is to collect precise, accurate, current, and repeatable data for emissions quantification.

Monitoring can provide assurance for measurement data. It can also provide a robust methodology for identification and attribution of leakage and the sources of leaked emissions. For example, baseline information on flux, concentration, or composition might be used to separate biologically-produced CO_2 from leakage in the soil zone. Monitoring is the repeated checking, supervising, critical observation, measuring, or assessing the status of a system. This process will ensure the integrity of measurements over time. The objective of monitoring is to determine flows or to identify change from baselines. It also provides input into models to confirm that expected performance levels are attained. Appropriate monitoring devices, which are likely to improve with time, form a basis for the measurements. The accuracy and efficiency of the data generated for use in quantification approaches are largely dependent on the monitoring technique adopted, including the use of the appropriate point of observation within CCS systems.

For example, the monitoring and measurement of CO_2 flow in a pipeline can be quite accurate (for example, the uncertainty limitation of 2,5 % in the EU Directive for EU ETS), whereas, the use of seismic surveys to measure CO_2 stored in the ground have limitations and a larger acknowledged uncertainty. In addition to the appropriate physical devices, sampling strategies (the timing and location of the measurements to be taken) need to complement the goals of the data to be collected. To understand stream purity and quantify the concentration of impurities (including gases), some form of analysis will usually be required based either on sampling and laboratory analysis or on the use of inline analysers.

7.2 Purpose

The purpose for measurement is to collect accurate, current, and repeatable information for effective Q&V. The accurate measurement of a relevant parameter is required to quantify the emissions prevented from reaching the atmosphere (captured, transported, stored and released by means of energy use and leaks). The accuracy of monitoring equipment is normally expected to continuously improve over time and with experience.

The definitions of quantification (methodologies used to quantify emissions and removals associated with a CCS project) and verification (confirmation by examination and provision of objective evidence that specified criteria have been met) require that measurement is undertaken with the end points of verification in mind (see Clause 6). Good baseline information is essential to estimate the impact of other sources of GHGs that may exist within the integrated CCS project boundary such as biological CO_2 production in the near surface (the soil zone).

7.3 Review of monitoring for ccs

For most surface processes within an integrated CCS project, monitoring can use a variety of physical devices to measure the flow of GHGs. These devices rely largely on flow rates along with pressure and temperature measurements although mass meters are available (see Clause 6, US EPA). The combination of flow rates with chemical analysis (inline or by sampling and laboratory analysis) of the constituents of the CO_2 stream, allows for calculations of the volumes and masses of the various constituents. Leakage events can be determined not only by pressure drops and visual inspections, but also by the use of a number of techniques that can also be deployed in the field to look for any potential leaks from buried pipelines or from storage locations (these are identified below) such as laser systems, infrared systems and others. This allows for a timely and effective management of related issues.

In addition to direct measurements, it is possible to use indirect measurements. These are identified in the US EPA CFR Part 98 Mandatory Reporting of Greenhouse Gases: Petroleum and Natural Gas

Systems; Final Rule, 2010, for example, and discussed in Clause 6. Ancillary emissions associated with fuel combustion can be calculated from conversion factors developed for different fuel types such as within a number of protocols that have been proposed to measure GHG emissions related to the CCS chain (such as mobile sources, recompression in an EOR setting) and can be found in publications like McCormick (2012)[58] or Blue Strategies (2012)[8] using emissions factors by fuel and by country (see Clause 6).

CO_2 has been captured from multiple sources for many decades (natural gas sweetening, industrial and food grade CO_2 sources by way of examples) and has been injected into the ground for purposes of enhanced oil recovery (dominantly from natural sources of CO2, https://edx.netl.doe.gov/group/natcarb). The first major integrated CO_2 geological storage project with integrated monitoring is Norway's Sleipner Project, which has been operational since 1996. An effective monitoring program was an integral component of this project as a means of verifying CO_2 prevented from reaching the atmosphere for tax purposes and is illustrative of the use of measurement technologies.

Many supra-national, national and sub-national bodies have created regulations or protocols for the measurement of CCS activities to ensure effective collection and calculation of emissions and emissions reductions from CCS projects to provide for quantification and verification (for example, the Alberta 2007 protocol Quantification Protocol for Enhanced Oil Recovery, Alberta Environment, October 2007, or the US EPACFR Part 98 Mandatory Reporting of Greenhouse Gases: Petroleum and Natural Gas Systems; Final Rule, 2010, which provides calculations for the calculation of emissions within petroleum and natural gas projects).

Countries which have developed regulations and protocols include the US EPA (*Geologic Sequestration of Carbon Dioxide: Draft Underground Injection Control (UIC) of the USA)* and various US states, Canada (and several provinces), the EU (*EU Directive on Geological Storage of Carbon Dioxide*), and some member nations (the UK's *Storage of Carbon Dioxide (Licensing, etc.) Regulations 2010)*, Australia (Offshore Petroleum and GHG Storage Act of 2006 and associated regulations and guidelines), and some states, Japan (*Marine pollution prevention and control method)* and others.

In addition to national legislation and regulations, some industry, research and consultation organizations have attempted to establish monitoring and measurement guidelines and programs, such as the CO_2 Capture Project and Det Norske Veritas.

The available monitoring technologies for storage and EOR include many methods that target atmosphere, soil, water and geological stratum. Table 5 serves to illustrate monitoring research on the application, cost and nature of some relevant CCS monitoring technologies.

Demonstration projects like In Salah (now ceased operations), Sleipner, Weyburn, Otway (a pilot project as opposed to a commercial demonstration), Gorgon (an example of the careful preparation for a major project), and others have environmental monitoring systems that generate large amounts of data for the purposes of quantifying GHGs. Analysis of seismic surveys (see Reference [10]), gravity survey (see Reference [1]), groundwater chemical composition data (see Reference [59]) which reflect the CO_2 plume migration and storage security has demonstrated the effectiveness of monitoring technology to confirm storage.

Table 5 — Reports and guidelines addressing containment of injected CO_2 in geological storage

Nation/organization/institute	Title	Content
CO2 Capture Project (CCP)	A Technical Basis for Carbon Dioxide Storage	CCS monitoring scheme: working guideline and case research
DNV	Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2	Monitoring, verification, accounting and report (MVAR) working goal, outline and reasonable working flow suggestion
US Carbon Sequestration Council (USCSC)	Global Status of Geologic CO_2 Storage Technology Development	Status of monitoring technology development, cost and in-site application outcome

Table 5 *(continued)*

Nation/organization/institute	Title	Content
UK Department of Trade and Industry (DTI)	Monitoring Technologies for the Geological Storage of CO_2	(1) Geologic storage suggestion and supervise framework; (2) monitoring technology introduction: application, performance, detection limit and limitation; (3) monitoring cost; (4) monitoring practice; (5) summarizing of offshore monitoring practice; (6) onshore monitoring deployment; (7) UK status of research and future research and development.
US National Energy Technology Laboratory (NETL)	Best Practices for: Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations	(1) importance, goal and objective of monitoring, monitoring practice; (2) monitoring technology introduction: description benefit and challenge; (3) DOE support and monitoring technology development; (4) monitoring goal and objective solving; (5) MVA developing of different scenario.
British Geological Survey (BGS)	IEAGHG-Monitoring Selection Tool	

7.4 Measurement and monitoring in CCS systems

7.4.1 General

This subclause reviews the measurement and monitoring approaches for CCS projects and for each system within a CCS project.

7.4.2 CCS projects

Figure 6 is a compilation of measurement points for CO_2 emissions and leakage based on regulations common to CCS projects around the world. The key measurement points designate the boundaries of the project and its component parts. These do not represent the only measurement points, but do demonstrate the key links within the chain.

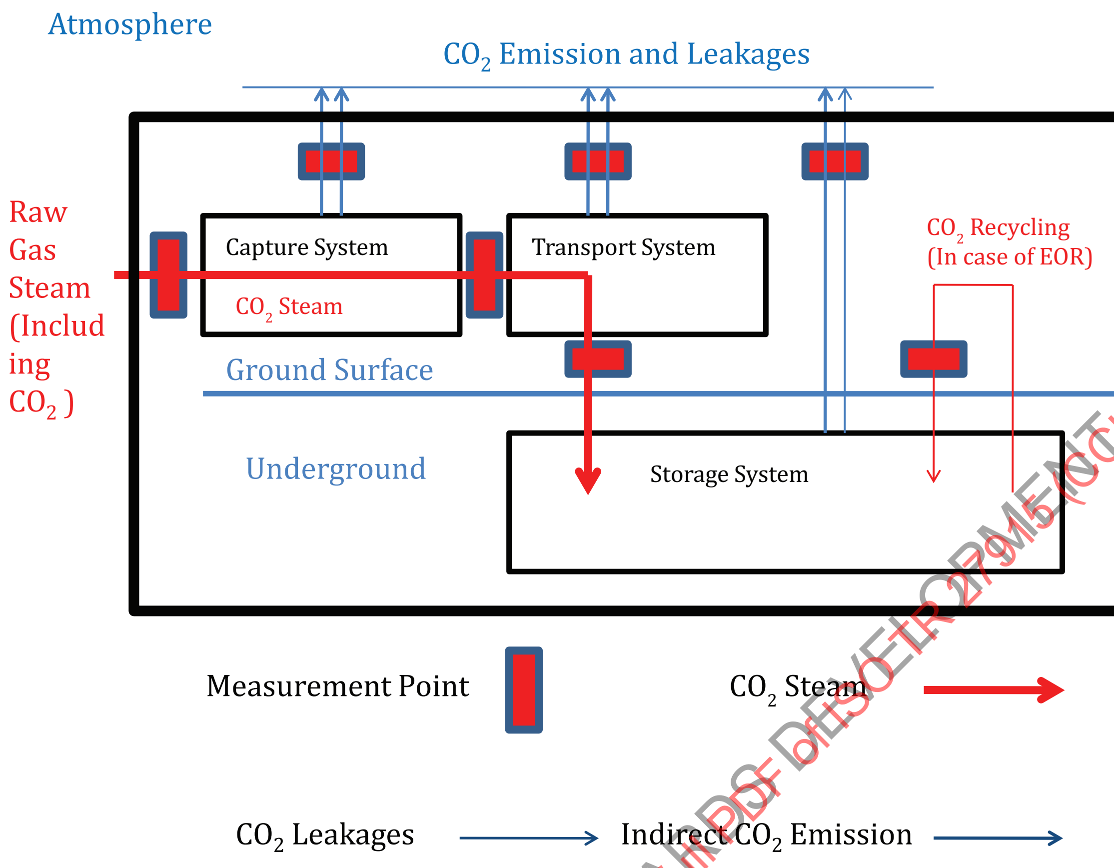

Figure 6 — Overview of requirements for measurement of full chain CCS project

Table 6 shows more detail for CCS measurement and monitoring points for Q&V (other measurements may be necessary for different objectives, such as contractual or regulatory constraints, environmental impacts, improvement of models, etc.).

Table 6 — CCS Measurement and monitoring

CCS Measurement and monitoring	CCS Project					
	Capture system		Transportation system		Storage system	
	Post-combustion, pre-combustion, oxyfuel-combustion others		Pipeline, truck, train, ship		Oil reservoir (EOR), coal bed(ECBM), aquifer	
	Inlet(s)	Outlet(s)	Inlet(s)	Outlet(s)	Inlet(s)	Outlet(s) (EOR, ECBM)
CO_2 emission reduction	Metering: Temperature, pressure, concentration of CO_2, flow rates Mass of CO_2 captured		Metering: Temperature, pressure, fluid composition of CO_2, flow rates Mass of CO_2 transported		Metering: Temperature, pressure, fluid composition of CO_2, injection rates Mass of CO_2 injection and re-injection	
Direct CO_2 leakage from CCS	Monitoring: Leakage from capture systems Metering: CO_2 concentration temperature, pressure		Monitoring: Leakage from pipeline and tank Metering: CO_2 concentration, temperature, pressure		Monitoring: leakage from wellbore, soil, et al. Metering: CO_2 concentration, temperature, pressure on the ground surface Geological systems (see Table 6),	
Indirect CO_2 emission from CCS	Metering: Additional energy consume for capture and compress		1.Metering: Additional energy (consume for pipe pumper (booster), heat preservation, 2. Metering: Additional fuel for truck, train, ship		Metering: Additional energy (electrical power, or fuel) for injection pumpers, et al.	

NOTE 1 There are commercial CO_2 concentration meters (sensors), which can be selected depend on the required accuracy and sensitivity.

NOTE 2 There are commercial temperature and pressure meters (sensors), which can be selected taking into account the state of fluid and range of pressure and temperature.

NOTE 3 There are different methods showed in this table to detect the migration of CO_2 fluid underground, they can be selected for monitoring CO_2 leakage underground.

7.4.3 Capture system

The potential emission sources within the capture system include direct and indirect emissions from the additional energy used for CO_2 separation and CO_2 treatment for transport, incomplete capture, and fugitive releases. Physical devices (e.g. sensors, meters) can be used to determine the concentration of CO_2, flow rates, pressure, and temperature at various points within the system. The IPCC also allows the use of Tier 1 and Tier 2 approaches based on accepted factors for determining these emissions. In commercial transfers of CO_2 a higher grade or commercial transfer meter is commonly used at the point of transfer.

There may also be a need to quantify the emissions associated with a baseline scenario. This might entail measuring the emissions from the use of additional fuel for the capture and compression of CO_2. It may also include the emissions from the construction of the capture facility and even decommissioning. Tier 1 and 2 approaches using emission factors may be sufficient for this calculation.

7.4.4 Transportation system

The potential emissions from the transport system may include direct and indirect emissions from the energy required for CO_2 transport, leakage from pressurized or cryogenic equipment, emissions from loading and offloading (currently under discussion within TC 265), and venting that may occur during emergency releases or at intermediate storage facilities. Indirect emissions may occur in compression, liquefaction and pumping. Most of the measurements may be based on emission factors.

CO_2 emissions from transport systems may be metered by flow metering the liquid together with pressure, temperature and fluid composition with the volumes and masses of the GHGs calculated from these results. The critical measurement points will be the inlet(s) and outlet(s) of the Transportation system or transfer points within the transportation system, particularly where non-pipeline methods are used.

The main source of indirect CO_2 emissions within the transportation system boundary, assuming pipeline transmission, may be the emissions resulting from pressure booster stations along the pipeline route. Emissions can be calculated based on the fuel used directly or indirectly (i.e. the electricity from the local grid based on the fuel mix for that grid system) using standard default values accepted for that region. In the event that other forms of transport are used, the emissions from boats, trains or trucks can be calculated based on the quantity of fuel consumed. Since non-pipeline transport is likely to be CO_2 liquefied by means of cryogenics rather than solely pressure, there will be some venting of the CO_2 (perhaps with traces of other GHGs) as a result of warming of the liquid in spite of the insulation in the buffer storage and/or transportation tanks. This leakage can be measured by physical devices and the volume/mass of each GHG released calculated.

In addition to the operational emissions of GHGs within the transportation unit boundary, there is the potential for upsets requiring the venting of sections of pipelines, tanks, etc. Understanding the volumes and gas composition within each individual piece of equipment will allow a rapid calculation of the GHGs emitted.

7.4.5 Storage system

The IPCC uses Tier 3 approaches for quantifying emission from storage systems in part because there is not an extensive database to support the development of most factors and also as a reflection that site-specific conditions play an important role in emissions measurement and monitoring. This subclause reviews possible methods for determining this data.

Underground formation and wells

— The amount of CO_2 stored is usually determined using mass balance that subtracts the amount of any possible leakage from the amount injected. Monitoring may be used to demonstrate that the injected plume is retained in the storage or EOR complex.

— Losses from storage (e.g. extraction, leakage from geologic system, migration out of storage or EOR complex, losses from wells that fail to isolate) may be determined through direct measurements and modelling.

— If existing well bores are an important potential leakage pathway, monitoring in wellbores or in the subsurface above the storage or EOR complex may be useful in detecting and quantifying leaks.

— The amount of CO_2 emitted at production wells or for other extraction purposes can be measured using meters. If large numbers of wells are involved in a project, data may be aggregated at collection points to avoid the propagation of calibration errors at individual wellhead meters.

Surface equipment

— The amount of CO_2 received at the plant gate and injected can be measured with flow meters at transfer points and wellheads. As with production/extraction, emissions may be aggregated at appropriate collection points to avoid the propagation of calibration errors for individual wellhead meters.

— Indirect emissions from the fuel consumed in the operation of surface injection (and possibly production) equipment can be measured using emission factors and meters to determine quantity of consumed fuel.

— Fugitive emissions: Including leaks and venting in the injection system such as at the distribution manifold at the end of pipeline; distribution pipelines to wells and compression or pumping apparatus, and leakage at the production well head may be determined using direct measurement or a series of emission, activity, and equipment factors coupled with actual data from the project.

— For CO_2 EOR, the operator may also need to determine losses from the production, separation, compression and other fluid handling systems as well as energy expended by the fluid handling system.

— Temporary upsets within an EOR operation are possible. It is likely in such a circumstance that the gas stream will be flared for safety reasons. In this case, the volume of gas redirected to the flare stack can be calculated based on the gas composition and gas volume (mass).

Leakage and risk consideration

— The operator may need to determine the amount leaked from the geological formation through existing or new fractures or faults, the cap rock, migration out of the storage complex, and through existing and/or unknown boreholes that penetrate the cap rock. The review of programs for this document suggests that there are no commonly accepted methods for quantifying amounts leaked. Instead, it appears that a general approach, using modelling, engineering estimates, and direct measurements, may be emerging.

— It may be useful to develop a plan to confirm that the predictions made during site characterization and injection design are correct. It would be desirable for this plan to specify the type of direct measurements required to confirm the predictions, including frequency, schedule, precision, and accuracy of measurements as well as mechanisms to record, transmit and archive the data.

— In addition, it may be necessary to determine emissions from the energy expended during monitoring.

Monitoring technologies are being continuously improved. Rather than present a specific date for state-of-the-art in monitoring technologies, this document acknowledges that advances are being made and cites several papers that reviewed the status of monitoring technologies at various points in time. This include Reference [40], as a general review, and In Salah[59][60], Gorgon[12], Sleipner[27][10], Snohvit[87], CO_2SINK[70], RECOPOL[70] and Weyburn[88].

7.4.6 Impurities

The composition of the CO_2 stream will depend on the source (e.g. steel manufacturing, cement manufacturing) and the process (oxy-combustion, post-combustion) (see Refence [67]). Measuring the exact amount of CO_2 in this stream is necessary for quantification but it is also important to determine the contents of the impurities.

Apart from CO_2 itself, usually the main components of the CO_2 stream are annex gases such as N_2, O_2, H_2 and Argon, possibly CH_4 and CO in lesser quantities, and water. Other components can be present in very low concentrations such as Sulfur oxides (including SO_2), Nitrogen oxides (including NO_2), H_2S, mercury and other metals, possibly trace organics (e.g. benzene). Dedicated units within the conversion/separation processes are generally necessary to remove these impurities prior to the CO_2 capture unit or prior to its transportation.

These impurities are likely to have physical or chemical effects on the behaviour of the CO_2 stream, on surface facilities or on the storage system. The identification of these effects is outside the scope of this document; however, in principle the monitoring plans could take into account all kinds of risks, including those related to the impurities.

7.4.7 LCA approaches

Life cycle assessment based on ISO 14040 to ISO 14044 evaluates the full GHG impacts of an integrated CCS project. This methodology allows for the energy and environmental impacts to be determined over the full project life cycle, from construction, energy usage, operations, to end of life of project. LCA studies would typically use kWh, quantity of raw material or product, or CO_2 avoided (see Clause 8) as the functional unit for the measure of impact to ensure consistency of comparison of different projects and their impacts. For this reason, LCA studies will use all the measurements taken for the full CCS system and for the individual components within the overall system and provide estimates of the life cycle impacts. LCA may also go beyond the GHG calculations of impacts to provide a broader calculation of environmental and health impacts from default values for emissions to the environment (for example, particulates, heavy metals and other emissions from the use of fuel, fuel extraction and equipment utilization).

8 Environmental impacts of CCS other than GHG capture/emission

8.1 Objectives

While the primary issue of the CCS is the GHG captured/emitted, other environmental impacts resulting from the CCS system, may also be considered. The present chapter gives a methodological framework to assess the environmental impacts of CCS processes using two possible methodologies: life cycle assessment (LCA) and environmental impact assessment (EIA). The LCA goes beyond the GHG quantification that was described in previous clauses of this document, but follows the same principles. The environmental impact assessment (EIA) is an alternative approach that is not as complete as LCA. Both EIA and LCA are described in the following subclause.

References: for LCA: ISO 14040 to ISO 14044, for GHG: ISO 14064-1/ISO 14064-2/ISO 14064-3, for EIA: European Directive 2014/52/EU.

8.2 Definition of EIA and LCA

LCA, as defined in ISO 14040, studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle to grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences. If the choice is made to use a life cycle assessment (LCA) approach for a CCS project, the responsible parties are likely to apply the principles of ISO 14040 to ISO 14044 and follow as much as possible the steps identified in these standards.

The LCA treats the "cradle to grave" aspects of a project or provide the necessary information to allow for the comparison of overall impacts, for example, the use of fossil fuels versus the use of renewable energy. To accomplish this latter task, a life cycle assessment (LCA) will need to be conducted leading to a quantitative assessment of factors likely to be significantly affected by the CCS project such as abiotic depletion, acidification, eutrophication, photochemical oxidation, ozone depletion, toxicity indicators, water use, land use, throughout the life of the project from construction to decommissioning within defined boundaries.

The EIA could be required by the intended user or some regulatory authorities. The prime objective of an EIA is to study the evolution of the relevant aspects of the environment impacts before and after the implementation of the CCS project. The EIA informs the intended user and/or the regulator of the direct or immediate environmental impacts, such as population, human health, biodiversity, land, soil, erosion, cultural heritage, including architectural, archaeological and landscape aspects, and provides elements for the issuance of appropriate permits for development. The International Association for Impact Assessment (IAIA) defines an environmental impact assessment as “the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made.”

8.3 LCA methodological framework

The following elements may serve as basis for the calculation of the life cycle assessment of CCS.

- Comparisons are made between the initial situation (or baseline reference) where CO_2 is emitted to the atmosphere and the CCS project where CO_2 is captured, transported and stored (see 5.2.7).

- Spatial Boundaries, LCA considers both the increased inputs and the outputs generally without regard for political or jurisdictional boundaries. For CCS projects, LCA would often consider the embedded impacts in defined inputs (e.g. electricity, water, fossil energy, raw materials) and outputs [e.g. increasing production of hydrocarbons, subsequent combustion of the oil and gas produced (see Reference [74])]. Figure 7 illustrates some of these elements. The spatial boundary for LCA would therefore begin with the inputs and extend through the outputs. As stated in 5.2, the three main sub-systems are represented in Figure 7 and they consist of the following:

  - Capture system: Pre-processing unit, chemicals production, capture units or boilers, post-processing units, compression and purification, etc. In effect, anything upstream of the isolation valve entering the transportation system.

  - Transport system: Either by pipe, or by boat, rail, including the loading and unloading facilities. In the case of transportation by means other than pipeline, loading facilities and unloading facilities will be considered, note that in the ISO/TC 265 framework, it was decided that buffer storage and loading/unloading facilities would be included in the capture unit or the storage unit, and not the transportation unit while the IPCC 2006 guidelines include these components within the transportation unit boundaries.

  - Storage system: All aspects downstream of the isolation valve between the transportation and the storage or EOR site. In the case of storage, this includes the distribution lines to the storage injection wells and the underground storage complex. In the case of EOR, the surface facilities required to recycle the CO_2 produced with the produced oil is considered in the LCA, even if they may formally be considered outside the CO_2 storage system (see 5.2.5).

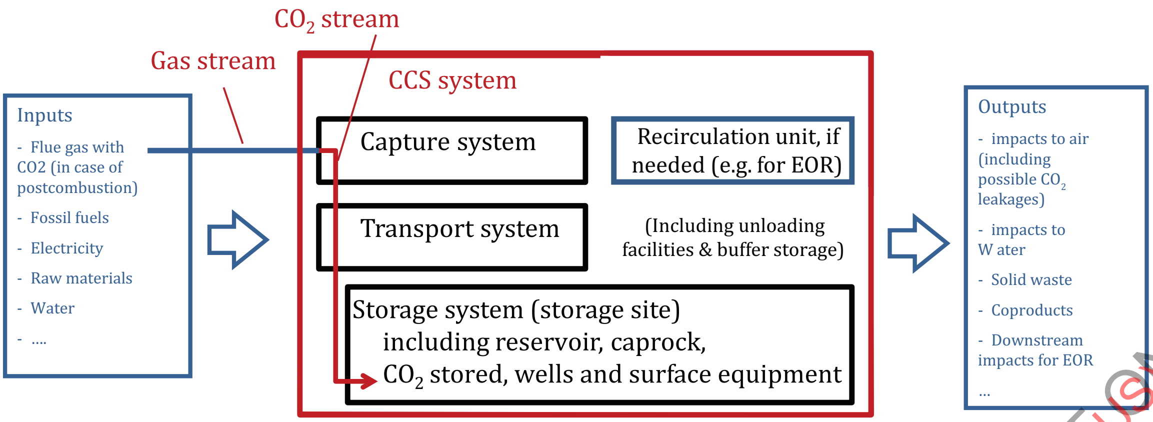

Figure 7 — LCA spatial boundaries

— Functional unit: The functional unit is defined as "a measure of the performance of the functional outputs of the system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related" (see ISO 14040). In the case of CCS, the selection of a functional unit will depend on the required outcome of the analysis. The required outcome may be to compare different CCS technologies with one another, or to concentrate on one specific CCS technology and/or compare CCS routes against alternatives such as renewable energy production (see Reference [37]). Therefore, the functional unit may be expressed as 1 kWh of electricity produced, or 1 tonne of steel or cement or glass, etc. produced, or one tonne of CO_2 avoided. Within an LCA system, the functional unit is considered only within the temporal boundaries decided for the LCA study. This may not take into account the long-term storage or permanence of the CO_2 stored (that storage beyond the end of the project as discussed within this TR).

NOTE This "functional unit" is defined in ISO 14040, a counting unit to present the results. It is to be distinguished from an "operational unit", that is industrial equipment (e.g. compressor, pipe) that has a given function in order to perform the CCS objective.

— Temporal boundaries: The temporal boundaries reflect the periods during which the CCS project impacts on the environment. After plugging of the well (including removal of all surface facilities according to national or sub-national regulation), the impact of CCS on the environment is likely to be non-existent or negligible (see 5.3) and the risk of leakage normally declines. This stage is defined as the post-closure stage (see below). Longer time horizons are possible, if they can be justified.

— List of stages of the project:

  — Building, construction and dismantlement. It includes the building, settlement and eventually dismantlement of plants, pipes, wells, etc. and the related energy and material consumption.

  — Operational stage. It includes the CO_2 production and its injection. During this period, capture, transport and injection are operational. In the case of EOR, the operational stage includes the recycle loop of CO_2 and will continue beyond the upstream supply of fresh CO_2.

  NOTE In the Weyburn study (2004)[8], the estimated time to pressure equilibration is 100 years from the conclusion of injection, this is probably beyond the expected period of time considered within a CCS Project.

  — Closure stage. It takes place after cessation of injection and ends at plugging of the well, when site closure criteria are met, that provide a high degree of confidence that injected CO_2 will be retained and that risk associated with the project are *de minimis*. (See ISO 27914 Geological Storage, Chapter 9_Monitoring and Validation and Chapter 10_Closure).

