Practical guidance for monitoring plans for CCS, under the Monitoring and Reporting Guidelines for CCS of the EU Emission Trading System

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1 Executive Summary (restricted)

On 8 June 2010 the Commission Decision amending Decision 2007/589/EC regarding the inclusion of Monitoring and Reporting Guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide (EU, 2010) entered into force. The Monitoring and Reporting Guidelines have put a large emphasis on the quantification of CO_2-streams. In the Monitoring and Reporting Guidelines for CCS new emission sources from transfer, capture process, bypasses, fugitive, vented and leakage are required to be monitored. This requires the implementation of monitoring techniques which before were rarely or never used in the EU emission trading system.

This report provides an overview of the present technical status of monitoring equipment and best available technologies for monitoring CO_2-streams and CO_2-emissions.

Monitoring of CO_2-streams from combustion or process installations with CEMS is no common practice. Uncertainty of CO_2 CEMS systems for flow and concentration are larger than the required 2.5% in the MRG. These uncertainty requirements in the MRG for CO_2 (< 2.5%) are far more stringent than for e.g. NO_x (< 20%), for which NO_x CEMS systems can meet the uncertainty requirement of 20%. This is a point of further study.

Technical monitoring of compressed CO_2-streams within the MRG uncertainty requirements from capture installations and in transport networks is still in the development stage. Only a few measuring techniques are available for monitoring compressed CO_2-streams. The volumetric flow measurement systems with orifice plates, turbine meters and the Coriolis mass flow measurement systems look the most promising at this moment.

For the orifice plate and turbine measurement systems exact knowledge of the prevailing CO_2 density and viscosity at the point of measurement is needed. Theoretical calculation procedures for density and viscosity at a given pressure and temperature are available, but are rather complicated and not easily available or verifiable. Therefore standardization of these calculation procedures is highly recommended for general application and acceptance by the competent authorities and independent bodies.

For the quantification of fugitive emissions from capture installations, transport networks and at storage sites the EPA method 21 is regarded as the best practice technology. However, no hard data is available about the uncertainties associated with the quantification of fugitive CO_2 emissions. There is very few CO_2 leak detection equipment on the market, which is readily suited for fugitive CO_2 emission measurement. Further development and standardization of measurement methodologies is recommended.

For onshore and offshore storage sites it is difficult to indicate which techniques are most suitable for quantification of CO_2 leakages. There is almost no data about the uncertainty in the quantification of these monitoring techniques. Therefore further research, practical experiences and standardization of methods are needed to establish proven and accepted methodologies for quantifying CO_2 leakages.

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2 Introduction

2.1 Background and objectives

On 8 June 2010 the amended Commission Decision 2007/589/EC with respect to the inclusion of Monitoring and Reporting Guidelines (MRG) for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide (EU, 2010) entered into force. It amends Directive 2003/87/EC, so as to include the capture, transport and geological storage of carbon dioxide within the Community scheme from the year 2013 onwards.

These Monitoring and Reporting Guidelines (MRG) will probably be transposed into Dutch regulation by means of adaptation of the "Leidraad CO_2-monitoring" issued by the Dutch Emission Authority (NEa, 2007). The Monitoring and Reporting Guidelines describe monitoring and quantification of CO_2-streams in CCS. A system with minimum required tiers depending on the size of source streams and installations is given. In the MRG additional emission sources are required to be monitored and quantified (such as from CO_2 transfer, from the capture process, from bypasses, fugitive emissions, emissions from venting and leakages). This requires the implementation of new monitoring techniques and methodologies which before were rarely or never used in the EU emission trading system.

The combination of new techniques and new source streams gives a number of unresolved issues, whether the required uncertainties can be met. The way in which these issues will be resolved have an impact on the implementation of the monitoring methodologies of full scale CCS in the Netherlands and has a large influence on the costs for the monitoring systems. This report provides an overview of the present technical status of monitoring equipment and best available technologies.

This report was prepared within the framework of Sub Programme (SP) 4 of the CATO2 project. The subject of SP 4 is "Regulation and Safety" and addresses regulation, operational practices, environmental impacts, and safety of CO_2 transport and geological storage.

2.2 Research questions

The following specific research questions relating to the implementation of the Monitoring and Reporting Guidelines were identified:

- How to interpret and to meet the monitoring requirements for CCS in the Monitoring and Reporting Guidelines?
- What are the current technologies and best practices for metering the various gas streams containing CO_2 in CCS?
- What are uncertainties associated with the different metering and monitoring technologies at the various metering points in CCS?
- What are the main advantages and disadvantages for choosing a specific metering technology?

This report excludes:

- The calculation of the total uncertainty of each step in the monitoring and reporting chain for the various steps in the CSS process. This will be the subject of $CATO_2$ deliverable for year 1 under the title "Analysis of the uncertainty requirements of the Monitoring and Reporting Guidelines for CCS under the EU Emission Trading System" (CATO-2 Deliverable WP 4.1-D4.1.03).

2.3 Reading guide

The report is structured in the following way:

- Chapter 3 provides a brief overview of what is additional for CCS in the Monitoring and Reporting Guidelines.
- Chapter 4 gives a brief overview of the type of source streams and the type of capture processes.
- Chapter 5 gives the specific and key requirements in the Monitoring and Reporting Guidelines in the transferred, captured, transported and stored CO_2 streams.
- Chapter 6 deals with the main topic of this report for metering technologies and best available technilogies which can be applied in CCS.
- Chapter 7 deals with remaining issues that need further attention to resolve ambiguity and create general acceptance and approval by competent authorities for a chosen methodology by an operator.

3 CCS in the Monitoring and Reporting Guidelines

3.1 Recent developments

In the Monitoring and Reporting Guidelines (MRG) under European Emission Trading System (EU-ETS) an inclusion to the Directive 2007/589/EC (EU, 2010) for the monitoring and reporting of carbon capture and storage (CCS) has been made.

On June 8, 2010 the amendment of the Monitoring and Reporting Guidelines (MRG) has become officially published. In this report the requirements from this amendment (EU, 2010) have been studied and evaluated. The guidelines set out in this report are only meant as guidance to the MRG and have no legal status. One should always refer and comply to the requirements as set out in the official amendment of the MRG (EU, 2010).

For the sake of clarity and ease in reading this report all mentioned references that are made to certain annexes and paragraphs refer to annexes and paragraphs of the *amended Directive 2007/589/EC* (EU, 2010) unless otherwise indicated.

3.2 General requirements

The requirements for monitoring and reporting of CO_2 emissions from carbon capture and storage (CCS) are additional to the already outlined methodology for monitoring and reporting of combsution and process emissions in the original Directive (2007/589/EC).

So all requirements (such as tiers, type A, B or C installation, monitoring and reporting and so on), that apply for any type of process, any type of installation and any type of fuel, remain mandatory. This implies that establishing a monitoring and reporting methodology for an installation with CO_2-capture and storage shall fulfil all the requirements as already given in the MRG. Therefore the requirements for carbon capture and storage (CCS) are additional to the monitoring and reporting methodology as already set out in the MRG.

Also the requirements from the Storage Directive (EU, 2009) regarding monitoring are mandatory and have to be implemented in the monitoring plan.

In this report recommendations are given how these additional requirements for carbon capture and storage as set out in the amendment of the MRG (and where relevant in the Storage Directive) can be interpreted and applied in a practical way. Furthermore metering and best available technologies are described, that can be applied for the various CO_2 containing streams.

4 Source streams and type of capture processes

4.1 General aspects

The methodology for monitoring and reporting of CO_2 emissions is not influenced by the different technologies for capturing CO_2. It does not matter how CO_2 is captured and purified as long as the input, output and discharge streams are identified and monitored properly. In this report guidelines are given how to identify and monitor the various CO_2-streams and how to fulfil the requirements of the MRG.

4.2 Source streams

Two types of source streams with CO_2 can be identified in the MRG:

- Process streams from industrial plants with (almost) pure CO_2
- Gas streams from combustion processes

CO_2 capture from gas streams from combustion processes can be grouped in three basic capture technologies, which have their own characteristics:

a) Post combustion
b) Pre combustion
c) Oxy fuel

Within these basic systems there is a variety of technologies for capture, of which some techniques are in the development stage, whilst others are more or less suitable for applications at full scale. Despite the differences in capture techniques, the methodology for drafting the monitoring plans and execution of these plans during the ongoing monitoring and reporting periods is the same. A very brief and general overview of these three capture technologies is given in the next paragraph. Many literature sources can be found for the description of the different capture technologies. One of the comprehensive descriptions can be found in the IPCC report on "Carbon Dioxide Capture and Storage" (IPPC, 2005).

4.3 Capture technologies

The three basic principles of the capture technology are shown in figure 4.1. Within these basic principles varieties of the specific technology for capture exist and a number are still in a development stage.

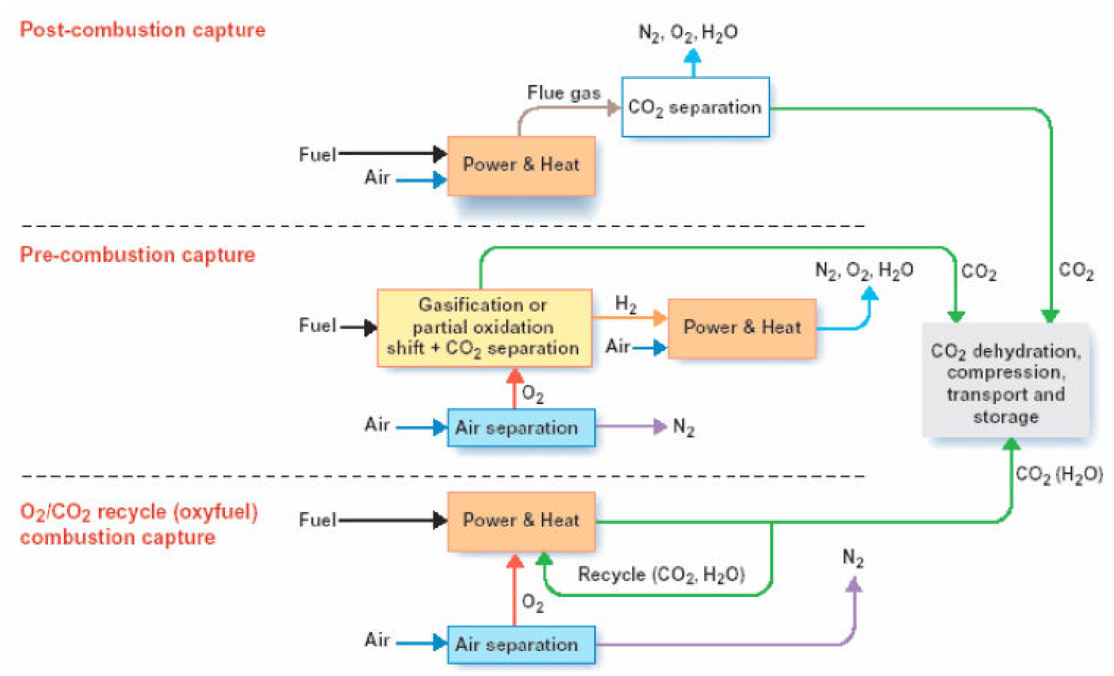

Figure 4.1 The three main principles of CO_2 capture technology for power plants; source (VGB, 2004).

The basic principles for these three systems are only briefly described below, focussing on the main CO_2 streams and non-captured CO_2 stream(s).

In the *post-combustion* system the exhaust flue gas is fed to the capture installation, where in a number of cases the flue gas is precleaned for removal of trace components, SO_2, HCl and so on to prevent malfunctioning of the capture process. Then the CO_2 is captured from the flue gas and compressed for transport. The inert gases in the flue gas (among others N_2, O_2 and Ar) are vented to the atmosphere. In this vented stream also traces of CO_2 will be present as the efficiency of capture processes is less then 100%.

In the *pre-combustion* system the fuel is gasified to CO and converted with steam to CO_2 and H_2. After precleaning (mainly sulphur removal), the CO_2 is captured from this CO_2/H_2 stream, after which a H_2-stream remains for combustion. Also in this H_2-stream traces of CO_2 can be present.

In the *oxy-fuel* system the fuel is combusted with pure oxygen. The exhaust flue gas with CO_2 and H_2O, small amounts of N_2, O_2, Ar and trace components (among others NO_x, SO_2) is fed to the capture installation for further processing and compression. The remaining small amounts of N_2, O_2, Ar are vented off, but also will contain some CO_2.

In all these three processes a main stream of CO_2 is obtained for transport and storage and a small stream of CO_2 is vented to the atmosphere. The present reported capture efficiencies range from 95% to >99%. This means that up to about 5% (by mass) of the CO_2 is vented to the atmosphere at the capture installation in one or more streams. This could be not only direct emissions to the atmosphere, but also through indirect emissions from degassing of the water from the dehydration step at compression. The quantification of these CO_2-streams and uncertainties involved will be quantified in more detail in this report.

5 Requirements for CCS in the MRG

In this chapter the requirements for CCS as stated in the Annexes of the MRG (EU, 2010) are elaborated in more detail and is indicated to what points attention should be paid in the monitoring plan.

5.1 Overview of Annexes in the MRG

In the MRG (EU, 2010) several Annexes describe the monitoring requirements for CCS. An overview of these Annexes are given below with the main topic underlined:

Annex I paragraph 5.7	**Transferred CO_2**
Annex XII	Guidelines for determination of emissions or amount of transfer of greenhouse gases by **continuous measurement systems**
Annex XVI	Activity-specific guidelines for determination of greenhouse gas emissions from **CO_2 capture activities** for the purpose of transport and geological storage in a storage site permitted under Directive 2009/31/EC
Annex XVII	Activity-specific guidelines for determination of greenhouse gas emissions from **transport of CO_2 by pipelines** geological storage in a storage site permitted under Directive 2009/31/EC
Annex XVIII	Activity-specific guidelines for the **geological storage of CO_2** in a storage site permitted under Directive 2009/31/EC

5.2 Transferred CO_2 and uncertainty

In the MRG (EU, 2010) no definition is given for "transferred CO_2". The amount of transferred CO_2 is interpreted as the amount of CO_2 transferred *from* or *to* any installation according to Annex I paragraph 5.7.

In Annex I paragraph 5.7 two types of streams are mentioned:

- Pure CO_2 streams (although no requirement for the minimum purity for "pure" CO_2 is given).
- Streams to other installations holding a greenhouse gas emission permit.

The MRG are not fully clear which uncertainty requirement applies for the annual transferred CO_2:

- From Annex I paragraph 5.7 it is interpreted that CO_2 streams which are mainly more or less pure CO_2, should be monitored with an uncertainty of 1.5% or less.
- The other gas streams containing CO_2 (e.g. in flue gases and compressed CO_2) should be monitored according to the tiers stated in the respective Annexes. From those Annexes it is deduced that Tier 4 with an uncertainty of less than 2.5%, applies for the

transferred CO_2 from the capture installation, in the transport network and to the storage site (unless technically not feasible).

It is thus not fully clear from the MRG at which purity of CO_2, which uncertainty shall be applied (1.5% or 2.5%).

Annex I, paragraph 5.7 gives further requirements for the amount of transferred CO_2 (which should be kept in mind and taken into account):

- The amounts of transferred CO_2 at the transferring and receiving installations shall be the same. When these amounts differ within the margin of uncertainty then the arithmetic average shall be used at the transferring and receiving installations. This Annex I paragraph 5.7 also gives guidelines when the amounts are not the same.
- The amount of CO_2 originating from biomass shall be subtracted from the transferred amount of CO_2.

5.3 CO_2 transferred to the capture installation

Two cases can be identified from Annex XVI in the MRG (EU, 2010) for the amount of CO_2 transferred to the capture installation.

Case 1 is the situation when **all** CO_2 from the combustion or process installation is transferred to the capture installation. This could be the case when the combustion or process installation and the capture installation fall under one and the same emissions permit. In that case it is **not** obligatory to install a continuous CO_2 monitoring system between the combustion or process installation and the capture installation. One can then rely on a calculation method for the total amount of CO_2 that is transferred to the capture installation. The MRG requires that it shall be demonstrated to the competent authority that all CO_2 is transferred to the capture installation. It is strongly recommended to apply the calculation method as it has the lowest uncertainty (see CATO-2 WP 4.1 deliverable 3) as the input streams (flow) and carbon content are known (e.g. from an accountable invoice or measured with a high quality procedure and with low uncertainty).

Case 1 can be applied to:

- Post combustion with CO_2-capture of all generated CO_2 (full scale installation)
- Pre-combustion process
- Oxy-fuel process
- Certain process streams (e.g. CO_2 from the ammonia production from natural gas)

Case 2 is the situation when only a **part** of the CO_2 from the combustion or process installation is transferred to the capture installation. In that case a continuous CO_2 monitoring system (for flow and concentration) is needed between the combustion or process installation and the capture installation.

Examples for case 2 are among others:

- the case of a demonstration capture plant in which only a part of the CO_2 is captured from the combustion

- process installations which have a CO_2 stream as a by-product.

The tiers for the amount of transferred CO_2 to and from a capture installation are stated in Annex XII, which are as follows:

- Tier 1 10 %
- Tier 2 7.5 %
- Tier 3 5 %
- Tier 4 2.5 %

Annex XVI states that as a minimum Tier 4 (with a total uncertainty of less than 2.5%), shall be applied unless technically not feasible. However for the period 2008-2012 as a minimum Tier 2 (7.5%) may be applied (Annex I, paragraph 6.2).

5.4 Transferred CO_2 in transport networks

In Annex XVII the monitoring and reporting of emissions from CO_2 transport networks is described.

The following potential CO_2 emission sources are identified at the transport network:

- Combustion at installations functionally connected to the transport network e.g. booster stations
- Fugitive emissions
- Vented emissions
- Accidental emissions (e.g. from leakages incidents)

The operator can choose one of two methods (method A and method B) for determination of the CO_2 emissions. However there are some constraints which are explained further.

Method A employs a mass balance calculation in which the own emissions (e.g. from fuel use in booster stations) are added to the difference between the received amount of CO_2 and the transferred amount of CO_2. As already stated Tier 4 (with an uncertainty <2.5%) applies for the received and transferred amount of CO_2.

Method B employs an emission calculation of the sum all measured emissions at the installation in the bulleted list above.

The constraint in the MRG for using one or the other method is, that the operator has to demonstrate that his choice for Method A or method B leads to more reliable results with lower uncertainty. If an operator chooses for Method B prove has to be given that the overall uncertainty for greenhouse gas emissions shall not exceed 7.5%.

When an operator uses method B and monitors the CO_2 transferred to and from the transport network for commercial reasons, then the operator shall use method A for validation of the results of method B. In this case an operator has to apply both methods. This could be lead to extra effort and cost. In the CATO-2 WP 4.1 deliverable 3 report this is worked out in more detail.

5.5 CO_2 emissions from storage

Both the MRG (EU, 2010) and the Storage Directive (EU, 2009) set out requirements for monitoring and reporting. The requirements are elaborated below in more detail.

Requirements in the Monitoring and Reporting Guidelines (MRG)

The MRG (EU, 2010) indicate the following potential CO_2 emissions sources at a storage site:

- Fuel use at booster station and other combustion activities
- Vented and fugitive emissions from injection
- Vented and fugitive emissions from enhanced hydrocarbon recovery
- Leakage form the storage complex

According to the MRG all emission sources shall be included in the emissions permit. Furthermore it is not allowed to add or to subtract any emissions or transfer of CO_2 to and from the storage site. The MRG give the methodology how to report the emissions from the four potential CO_2 emissions sources mentioned above.

Requirements in the Storage Directive

In brief the Storage Directive (EU, 2009) describes requirements how and where to select a storage site; how risks and responsibilities shall be covered, and how to monitor and report CO_2 emissions. For those aspects reference is made to the Storage Directive.

The relevant requirements regarding <u>monitoring</u> and <u>reporting</u> of CO_2-emissions (but also of injected CO_2-streams) are restated below:

- Statement 19 & Article 4.4:
    - A storage site is to be selected if there is no significant risk of leakage
- Statement 20:
    - CO_2 emissions from **<u>EHR</u>** (Enhanced Hydrocarbon Recovery) should be treated under the MRG.
- Statement 27, Article 7.4, 9.4, 12.1, 12.3, 14.2:
    - **Monitoring and reporting** of the **<u>composition</u>** of the injected CO_2 . This shall be within certain limits. The operator should only accept and inject CO_2 streams that have been analysed including corrosive substances and for which a risk assessment has been carried out.
- Statement 28 and article 13.1
    - **Monitoring** if the injected CO_2 behaves as expected, whether any **<u>migration</u>** or **<u>leakage</u>** occurs and if any identified leakage is damaging the environment or human health.
- Statement 32 and article 17.2
    - After **<u>closure</u>** of the storage site the operator stays responsible for (among others) **monitoring and reporting**
- Statement 35 and article 18.6:
    - **<u>After transfer of responsibilities</u> monitoring** should be **<u>reduced</u>** to a level, which still allows identification of leakages or significant irregularities.

- Statement 37 and article 20.1:
    - Authorities may have to bear costs (after transfer of responsibilities) for at least a period of **30 years for monitoring**.

The way to monitor and report these requirements in a practical way is elaborated in more detail in chapter 6.5 of this report.

5.6 Drafting the monitoring plan

Depending on the number of owners of installations in the CCS-chain separate monitoring plans might be needed for each installation or group of installations (e.g. the combination of combustion plant with a capture plant). Each owner should draft his own monitoring plan for (e.g.):

- Process or combustion installation
- Carbon capture plant
- Transport network or single pipeline
- Storage site(s)

The monitoring plan should be drafted according to the EU-ETS Directive and the MRG (EU, 2007 & EC, 2010) and shall cover the list of items as stated in Annex I, Chapter 4.3 of the MRG. These items are given in Appendix III of this report.

The monitoring plan also shall cover the monitoring requirements in the Storage Directive 2009/31/EC (EU, 2009). The key elements of these requirements are given in Appendix IV of this report.

The monitoring plan should be drafted in such a way that it is accepted by the competent authorities and that the results of monitoring can be verified by independent bodies.

6 Monitoring & metering

In this chapter the specific monitoring requirements from the MRG for CCS are elaborated in more detail and guidelines are given which metering techniques can be applied.

In figure 6.1 the locations are indicated where continuous monitoring and metering takes place for the principal stream of CO_2 in the CCS chain. The smaller emission sources are not shown in the figure, such as emissions from auxiliary equipment, fugitive, vented and leakage emissions (which of course must be taken into account).

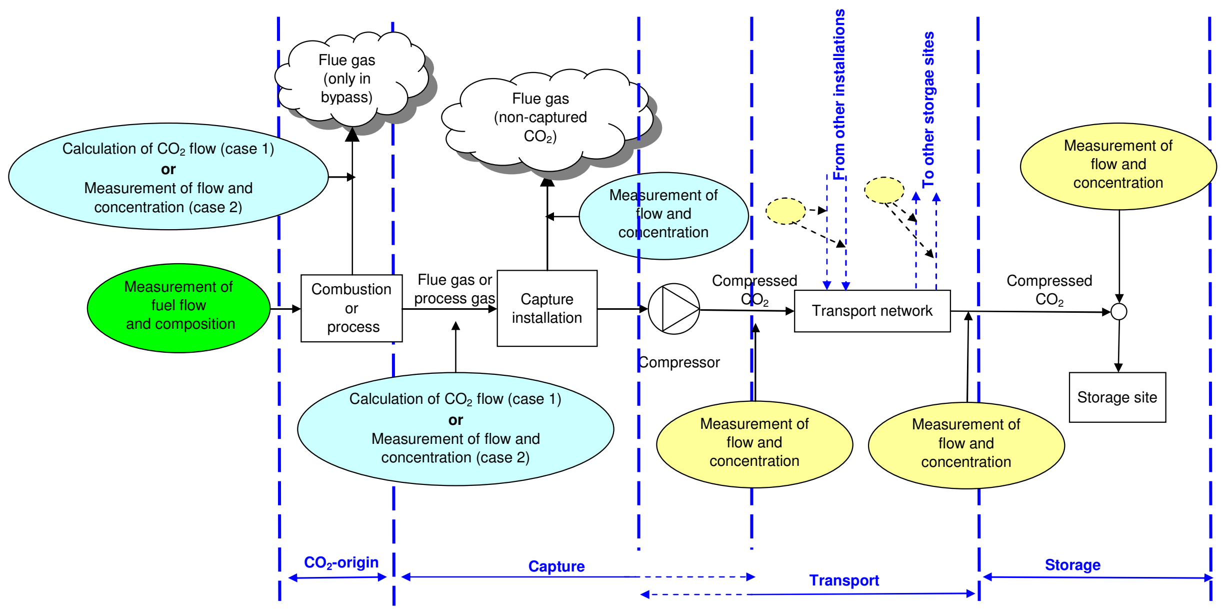

Figure 6.1 Continuous monitoring and metering locations for the principal CO_2 stream in the CCS chain (without showing the other and smaller emission sources (such as emissions from auxiliary equipment and fugitive, vented and leakage emissions).

The system border for the capture installation and transport network can be different for individual permit holders. The compressor could be part of the capture installation, but could also be part of the transport network. The transport network can be a single line to a storage site or could be a pipeline network with multiple entrance and exit points. At each of the entrance and exit points metering systems should be present (indicated in figure 6.1 with a yellow circle).

As can be deduced from figure 6.1 that for continuous monitoring only two types of CO_2 streams are present: CO_2 in flue and process gases and compressed CO_2. For both types of CO_2 streams an overview and guidelines are given for the monitoring and metering techniques in the following paragraphs.

6.1 Monitoring CO_2 emissions from capture

Continuous CO_2 emissions

Continuous CO_2 emissions at the capture installation occur (in general) at two locations:

- At the vent or discharge point(s) of the capture installation, together with the other flue gas components such as nitrogen, oxygen, argon and trace gases (e.g. SO_2, NO_x, CO, HCl), which have to be released continuously. As capture efficiencies range between ~95% to >99%, the amount of discharged CO_2 ranges from <1% up to ~5% (by mass).
- At combustion or process installations which have only part of their CO_2-emissions captured (e.g. at semi full-scale capture installations) and therefore a part of the CO_2 stream has to be bypassed continuously. These CO_2 emissions belong to the combustion or process installation and shall be accounted for in the permit of those installations.
- At any other flue gas stream from fuel fired (e.g. diesel, gas or oil) auxiliary units at the capture installation. Examples of these auxiliary units could be small boilers or pumps. The necessity of auxiliary fuel fired units will be small as in general the capture installation is build close to an existing installation (e.g. power plant) with sufficient electrical power and steam for operating the capture installation. The CO_2-emissions from these auxiliary fuel fired units can easily be calculated from the fuel input flow following the standard procedures as described in the MRG. For these units no flue gas monitoring is required.

Determination of continuous CO_2-emissions

The emissions from the capture installation are determined following a mass balance approach according to the formula in annex XVI:

$$E_{capture\ installation} = T_{input} + E_{without\ capture} - T_{for\ storage}$$

With:

$E_{capture\ installation}$	-	Total greenhouse gas emissions of the capture installation
T_{input}	-	Amount of CO_2 transferred to the capture installation
$E_{without\ capture}$	-	Emissions of installation if CO_2 was not captured. i.e. emissions of all other activities at installation
$T_{for\ storage}$	-	CO_2 transferred to transport network

T_{input}

For case 1 as identified in chapter 5.3 in this report, when ***all*** CO2 is transferred to the capture installation the amount T_{input} can be easily *calculated* with the lowest uncertainty from the fuel input following the requirements and procedures as already laid down under EU-ETS (see also . the CATO-2 WP 4.1 deliverable 3 report). For case 2 when only ***part*** of the CO_2 is transferred to the capture installation (e.g. in the case of bypassing at semi full-scale capture installations), the flow as well as the concentration of CO_2 has to be measured. For the case of combustion installations T_{input} relates to the situation of flue gases. In general the CO_2-concentration in the flue gases originating from the combustion process are in a range of about 10 – 20 vol%. The measurement techniques are described in paragraph 6.2 in this report.

$E_{without\ capture}$
For all the auxiliary units generating CO_2-emissions at the capture installation the requirements and procedures as laid down in the MRG shall be followed. The CO_2 emissions can easily be calculated from the fuel flow and composition. No actual monitoring of flue gas emissions is needed.

As capture processes have a capture efficiency of less than 100%, part of the CO_2 will be vented to the atmosphere with the remaining components in the (flue) gases (e.g. N_2, O_2, Ar, H_2O and trace gases such as SO_2, NO_x, NH_3 and so on). For a post-combustion capture process with a capture efficiency of 95% to >99% the CO_2 concentration in the vented (flue) gases will range between about 0.1 to 1 vol%. In the MRG no uncertainty requirements are given for the amount of CO_2 originating from these vented emissions. In the CATO-2 WP 4.1 deliverable 3 report the amounts and uncertainty associated with these CO_2-emissions is studied in more detail.

$T_{for\ storage}$
The techniques for the determination of the amount of CO_2 transferred to the transport network is described in paragraph 6.3.

Discontinuous or intermittent CO_2 discharges can occur:

- in the case of leakages downstream in the capture installation;
- during the necessary pressure relief on the high pressure side in the case of maintenance work;
- in the case when the capture installation is not in operation and needs to be bypassed (at e.g. post combustion systems or process installations).
- In the case of start-up, shut-down or malfunctioning of the capture installation in which no CO_2 can be captured, but the combustion or process installation continues to operate.

How the CO_2-emissions from these discontinuous CO_2 discharges are determined, needs to be described in the monitoring plan.

6.2 Measurement techniques for CO_2 in flue gases

6.2.1 Requirements from the MRG

Annex XII of the MRG describes the determination of emissions or the amount of greenhouse gases (e.g. CO_2) by continuous measurement systems. For the determination of the gas flow and CO_2-concentration chapter 6 of Annex I in the MRG has to be followed.

Tiers

As already indicated earlier Tier 4 with an 2.5% uncertainty applies for CO_2 streams transferred to the capture installation. However for the case that the capture installation has to be bypassed, then CO_2 is emitted without any capture. Then in principle also the same highest tier (Tier 4) is applicable, except for the reporting period 2008 – 2012. During this period Tier 2 (with an uncertainty level of 7.5%) as minimum may be applied unless technically not feasible.

Uncertainty of CO_2 CEMS systems for flow and concentration are larger than the required 2.5% in the MRG. These uncertainty requirements in the MRG for CO_2 (< 2.5%) are far more stringent than for e.g. NO_x (< 20%), for which NO_x CEMS systems can meet the uncertainty requirement of 20%. So this is a point of further study and is elaborated in the report of the CATO 2 WP 4.1 deliverable 3

Standards

The MRG state that a CEMS according to the ISO 12039: 2001 shall be applied for the analysis of CO_2, in combination with the ISO 10396 for the sampling method. For the determination of the flow with a CEMS the ISO 14164:1999 shall be applied.

Determination of CO_2-concentration

According to Annex XII of the MRG the CO_2-concentration can be determined by two methods (method A and method B). Method A implies the direct measurement of the CO_2-concentration. Method B is applied at high CO_2-concentrations, in which all other components except CO_2 are measured in the gas stream. The CO_2-concentration is then calculated by subtracting the sum of all other components from 100%. Method B is usually not applied for flue gases, due to the complexity and higher uncertainty at lower CO_2 concentrations (10 – 20 vol%)

Determination of flue gas flow

The volumetric flue gas flow can either be determined by means of a mass balance approach, from a calculating the fuel flow and composition (method A) or by a direct measurement of the flue gas flow (method B). In this chapter the focus is laid upon the method B.

6.2.2 CO_2 concentrations

Continuous monitoring with a CEMS

For the determination of CO_2 in flue gases several analysis techniques are suitable. The most common and widely used are NDIR (Non Dispersive Infra Red) or IR (Infra Red) analysis techniques. These instruments measure continuously and are commercially available as in-situ and as extractive versions.

Several types of NDIR/IR techniques exist, such as GFC (Gas Filter Correlation), FTIR (Fourier Transform IR) and classical absorption. When choosing an analysis technique one should focus on the instruments with the lowest uncertainty, which can be calculated according to the EN-ISO 14956. When CO_2 concentrations need to be measured in flue or vent gases, which have been in contact with absorption liquids in the capture process, one should make certain that possible interferences of vapours originating from the absorption liquids on the analysis of CO_2 with the NDIR/IR technique are minimized or absent.

The ISO 12039 indicates that in general CEMS for CO_2-analysis measure up to about 20 vol% of CO_2 which concentrations usually occur in flue gases from combustion. And the ISO 12039 sets out a number of performance criteria to which the CEMS has to comply, of which the most important relating to uncertainty are given below (please refer to ISO 12039 for other performance criteria, such as response time and so on):

Zero drift	< 2% of full scale
Span drift	< 4% of calibrated value
Interferences	< 4% of full scale
Deviation from linearity	< 2% of full scale

As CO_2-concentrations in the vented (flue) gases from post combustion will range between about 0.1 to 1 vol%, it is strongly recommended to install a CO_2-CEMS with a much lower range than usually applied for CO_2 concentrations in flue gases originating from combustion processes (usually about 10 – 20 vol%).

The quality control of the performance of these instruments can be maintained using the EN 14181 (Quality assurance of automated measuring systems)

It is advised to follow the development of new standards within ISO. At this moment two standards for the measurement of greenhouse gases for stationary sources are being developed (in the working draft stage). The ISO 14385-1 will describe the calibration of automated systems and the ISO 14385-2 the ongoing quality control of automated measuring systems.

The impact of the uncertainty of CO_2 measurements is elaborated in more detail in the report of CATO-2 WP 4.1 deliverable 3.

Sampling locations for CEMS in flue gas ducts

For flue gases the EN 15259 describes the procedure for the determination of a representative location for automated systems. This is done by manual sampling of the concentration and velocity at various points in the stack or flue gas duct. The point(s) which have the lowest difference to the weighted average of the whole sampling plane are suited for the sampling location for a CEMS.

Sampling locations for CEMS in process gas

In general a single sampling point in a process gas pipeline (with diameters less than 30 cm) would suffice for the determination of a representative CO_2 gas concentration. For larger diameters representative sampling at more points in the pipeline is performed according to the ISO 10780. Up to diameters of 70 cm one can use four to five sampling points in a cross section of the pipeline. It is recommended to perform an uncertainty analysis of the expected concentration gradient in the pipeline and estimate the overall uncertainty of sampling and CO_2 analysis for one and for additional sampling points. And then decide if additional sampling points are really necessary.

The uncertainty of sampling can be calculated with the following formula:

$$u_s[\%] = \frac{highest\ value - lowest\ value}{4 \times \sqrt{n}} \times \frac{100\%}{average\ value}$$

In which:

u_s	uncertainty (standard deviation) of sampling (%)
highest value	highest CO_2 concentration (vol%) at the 4 or 5 sampling points
lowest value	lowest CO_2 concentration (vol%) at the 4 or 5 sampling points
average value	highest CO_2 concentration (vol%) of the 4 or 5 sampling points
n	number of sampling points (4 or 5 for pipeline diameters up to 0.7m)

With 4 sampling points, an average CO_2-concentration of 95.5% with a highest value of 98% and the lowest value of 93%, the uncertainty equals 0.65%. This should be added to the uncertainty of the determination of the CO_2 concentration.

Discontinuous grab sampling and analysis

When less frequent analysis suffice (e.g. once a week or month) sampling can be performed by means of grab sampling in e.g. gas cylinders, Tedlar bags, metal foil bags. Then the samples can be analysed for CO_2 on a GC (gas chromatograph). In general the uncertainty associated with these techniques are in the range of about 2%.

Quality control procedures should be in place to guarantee reliable results with known uncertainty.

6.2.3 Flue gas flow

For the measurement of flue gas flow in large flue gas ducts or stacks (chimneys) commercial instruments are available, such as ultrasonic techniques and pitot and venturi based probes.

The ISO 14164 describes the various principles and gives performance criteria for the automated measuring systems, including a procedure for selecting a suitable and representative measuring location.

Performance criterion for the uncertainty for flow measurement as stated in the ISO 14164 is less than 10% (95% confidence interval).

The impact of the uncertainty of flow measurements on the total uncertainty of the determination of the CO_2-mass flow and comparison to the required uncertainty is elaborated in more detail in the report of CATO-2 WP 4.1 deliverable 3.

6.3 Measuring techniques for compressed CO_2 flows

6.3.1 Physical states of compressed CO_2

When CO_2 is compressed it can be in different physical states depending on pressure and temperature, such as solid, liquid or gaseous and also mixed states (liquid + gas). The CO_2-phase diagram is shown in figure 6.2 for pure (100%) CO_2.

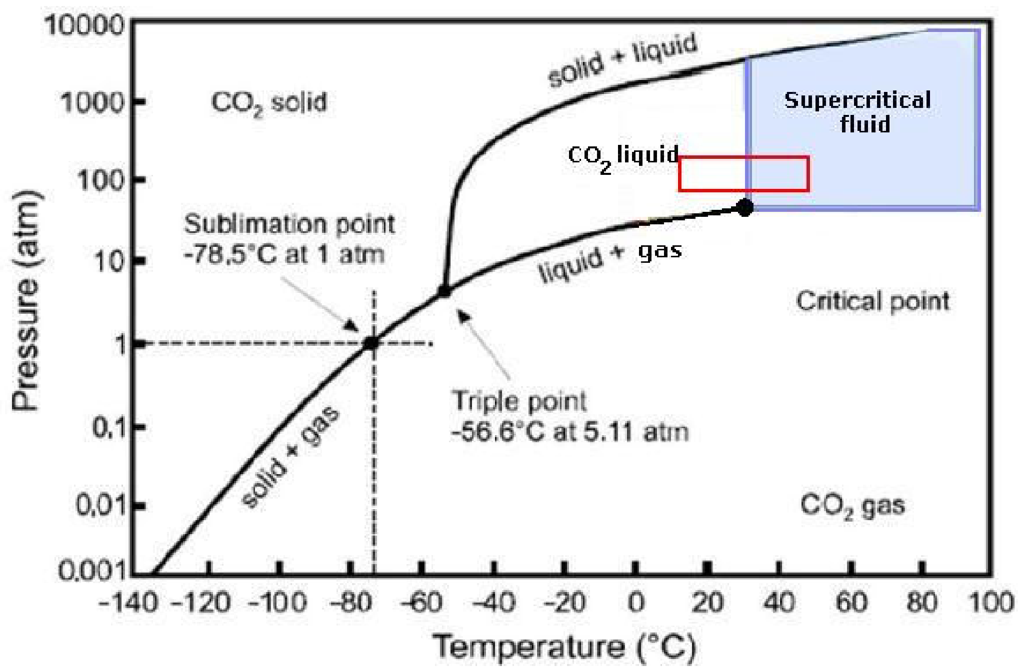

Figure 6.2 Phase diagram for pure (100%) CO_2 (adapted from TUVNEL, 2009). The red box indicates the approximate temperature and pressure ranges applied for CCS.

The physical state of the compressed CO_2 depends on the occurring temperatures and pressures in the pressurized CCS system at the compressor, in the pipelines in the transport network and at the storage site. According to the TUVNEL report (TUVNEL, 2009) full design and operating parameters for CCS are not readily available. From the vast information from pilot or demonstration stages and EOR (Enhanced Oil Recovery) experiences TUVNEL indicates that the approximate temperature and pressure range lies between about 13 – 49 ℃ and about 90 – 230 bar. This range is marked in the red box in figure 6.1. In this range the physical state for CO_2 can be either liquid or supercritical.

However as capture efficiencies will be less than 100%, the compressed CO_2 will contain other gases such as N_2, O_2, Ar and CH_4 as well. The CO_2 content in the compressed CO_2 after capture ranges from about 95% up to 99% (or close to 100%). These other constituents however affect the physical state of CO_2 strongly. As an example the influence of nitrogen (N_2) on the physical state of CO_2 is shown in a phase diagram in figure 6.3.

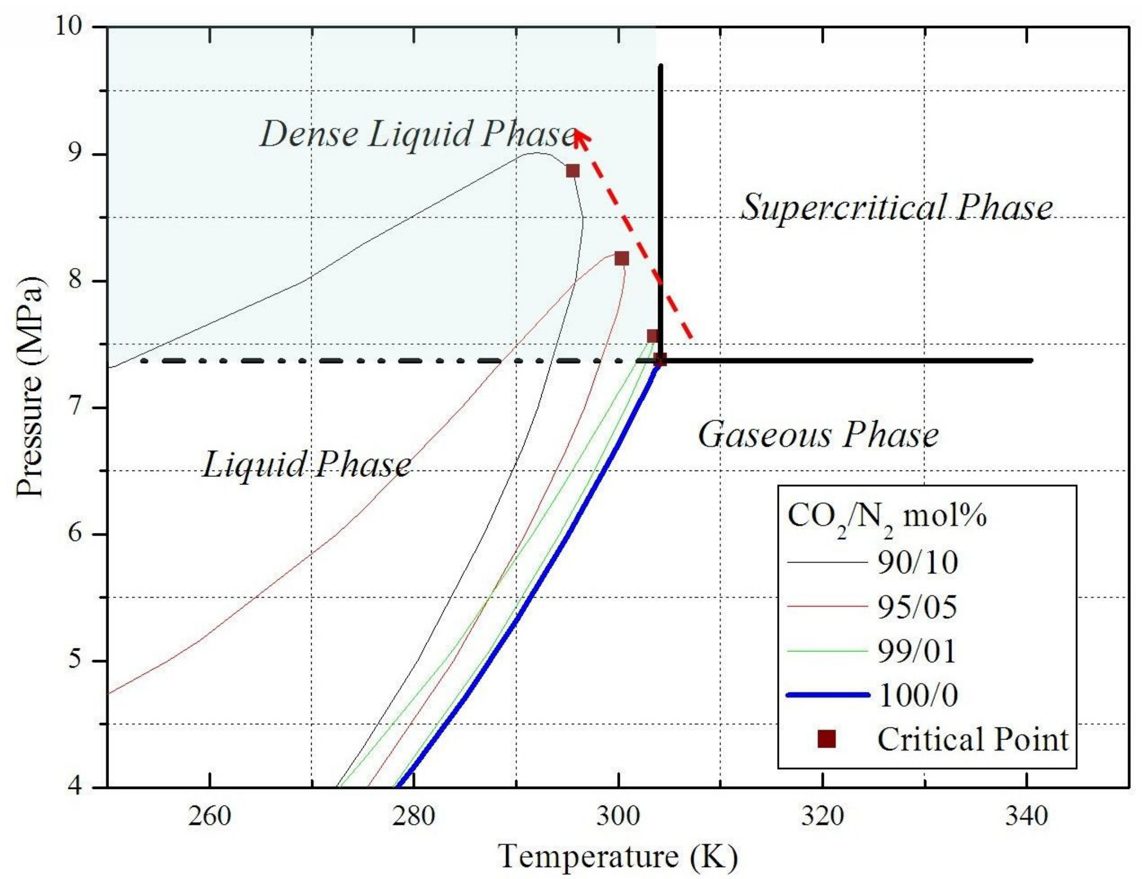

Figure 6.3 Influence of N_2 on the physical state of CO_2 (Yan, 2008)

From figure 6.3 it can be seen that the supercritical point shifts to lower temperatures and higher pressures when the nitrogen content in the compressed CO_2 increases. Another important phenomenon is that the gas+liquid phase envelopes increases with increasing nitrogen content. This implies that at higher nitrogen contents two-phase flow can occur more often at certain temperature and pressure changes. As will become clear in the next paragraphs flow measurements of a two-phase system is very difficult and cumbersome and should be avoided whenever possible at the point of measurement of CO_2 flow.

It should be noted that the data presented in figure 6.3 is based on calculation methods and has not (yet) been fully verified by means of measurements. Also the knowledge of the effect of other constituents such as O_2, Ar, H_2, CH_4 as a binary or ternary component to CO_2 is still scarce. The effect of multi component mixtures is at least unknown.

6.4 Flow measurement techniques for compressed CO_2

TUVNEL (2009) has investigated potential flow measuring techniques for applications for monitoring CO_2 streams of which the main findings are summarized here.

One general but important remark in the TUVNEL report is, that the phase behaviour of CO_2 in the temperature and pressure relevant for CCS applications is much more complex than for many other fluids. It is stressed that a clear knowledge of the density and viscosity of the CO_2 streams is required to assess the influence factors on the meter performance (see paragraph 6.3.3).

Measurement for compressed CO_2 flow can be divided in three types of techniques and instruments:

- Differential pressure meters
- Volumetric meters
- Mass flow meters

These different measuring techniques are elaborated in more detail below.

- **Differential pressure meters**

Differential pressure meters are applied to systems in which a pressure drop is measured over a measurement body mounted in the compressed CO_2 stream. The following three types of measurement bodies are suitable and commercially available:

Orifice Plate meters

At an orifice plate the pressure drop over the orifice is measured, which is a measure for the velocity of the fluid in the orifice. From the combination with the density and cross section of the orifice plate the mass flow can be calculated.

Orifice plate meters are considered suitable for CCS applications under the assumption that the density and viscosity are known at the temperature and pressure of operation. In ordinary steady-state single phase CO_2 flow streams the uncertainty in flow measurement is claimed to be within 1%. This implies that they are installed at locations where the phase is totally predictable.

Design of orifice plates are prescribed in the EN-ISO 5167 part 2. A disadvantage is that the flow range in which the orifice plate can be used is limited.

Venturi meters

Venturi meters have a lower pressure drop than orifice plates but have higher measurement uncertainty. To this day venturi meters have not been used in CCS/EOR applications yet. TUVNEL indicates that venturi meters may be suitable in some CCS applications, but might need individual calibration to achieve an uncertainty to about 1%. Design of venturi tubes are prescribed in the EN-ISO 5167 part 4.

V-Cone

V-cone meters have also a lower pressure drop than orifice plates but have higher measurement uncertainty. With proper individual calibration an uncertainty within 1% is achievable for single phase flows. To this day also V-cone meters have not been used in CCS/EOR applications yet. They are already used in two-phase applications and can operate in multi-phase flows, but there is too few data on uncertainties available under real operating conditions.

- **Volumetric meters**

Turbine meters

Turbine meters have been used for decades in industry for measuring liquid as well as supercritical CO_2 flows in pipelines. In EOR (Enhanced Oil Recovery) uncertainties have been reported as less than 1%. TUVNEL stresses that the turbine meters shall be operated and calibrated under the conditions they are designed for. Turbine meters can be manufactured for any diameter of pipe. The ISO 9951 and EN 12261 give general requirements for the turbine gas meters.

Vortex meters

TUVNEL indicates that the use of vortex meters CCS/EOR applications is unknown and that they are not intended for multiphase flows and require density measurement of the flow.

Ultrasonic meters

Two operating principles are used in ultrasonic meters : Doppler techniques and Time-of-flight (ToF). TUVNEL states that Doppler based techniques struggle to meet an uncertainty of 2% or less under ideal flow conditions. ToF based flow meters show potential for a measurement with sufficient low uncertainty, but extensive development, calibration and proven applications need to be carried out.

- **Mass flow meters (Coriolis)**

The general used mass flow meter is based on the Coriolis principle. The main advantage is that it provides direct measurement of mass flow and density also in CCS (TUVNEL). It stays undamaged by changes in the fluid phase. Two-phase flow measurement is possible, but the uncertainty is not (yet) sufficient (TUVNEL).

A drawback is that pipeline diameter is limited to 150 mm, but sizes up to about 300 mm now become available. Those larger sizes are about sufficient for a full scale carbon capture project at a 600 MWe coal fired power plant. For transport networks with higher capacities a solution could be to install a bank of multiple meters.

Tentative recommendations for flow measuring techniques in CCS

A general recommendation as given in the various measurement standards is to place the meter at a location in the system where the flow velocity profile is fully developed. The ISO 10780 recommends to employ at least 7 hydraulic diameters and that the sampling plane is located at a distance of 5 hydraulic diameters from the inlet.

From the overview of the flow measuring techniques described above it can tentatively be concluded that at present flow measurement techniques by means of orifice plates, turbine meters and coriolis meters looks to be the most promising for CCS applications, which also can fulfil the uncertainty requirements.

It is strongly recommended to choose the pressure and temperature conditions at the measurement location as such, that the compressed CO_2 at the point of measurement is in a single physical phase (either, liquid, gas or supercritical). It is also recommended to choose such a pressure and temperature condition that anticipated temperature or pressure fluctuations occurring during normal operation do not change the physical state of the compressed CO_2 into a two-phase (gas+liquid) flow at the point of measurement. This will reduce complexity of the measurement and uncertainty. Nevertheless the physical state may or could change during transport and at booster stations.

For orifice plates and turbine meters the exact phase conditions (temperature, pressure and density) need to be known.

Development of improved techniques of the other flow measuring principles may proof in near future to be reliable and have a sufficiently low uncertainty.

6.4.1 Determination of CO_2 density and viscosity

One of the key elements in the determination of CO_2 mass flow is the accurate knowledge of the density and viscosity of CO_2 under the local temperature and pressure conditions at the point of measurement.

Most measuring techniques (as described in paragraph 6.3.2 above) are volumetric techniques which need the density and viscosity to calculate the mass flow. The exception is the coriolis flow meter, which determines the mass flow directly. With this techniques no density or viscosity measurement is necessary. The total mass flow could be measured with a full size coriolis mass flow meter or a bench of parallel connected mass flow meters depending on the available sizes of mass flow meters and flow amount to be measured.

Density

It shows that the density of liquid, gaseous and supercritical CO_2 varies strongly with pressure and temperature. Liquid CO_2 is somewhat compressible. Gaseous and supercritical CO_2 do not follow ideal gas properties. This implies that a standard correction formula's based on the ideal gas law cannot be applied. The density for pure CO_2 as function of pressure and temperature is shown figure 6.4.

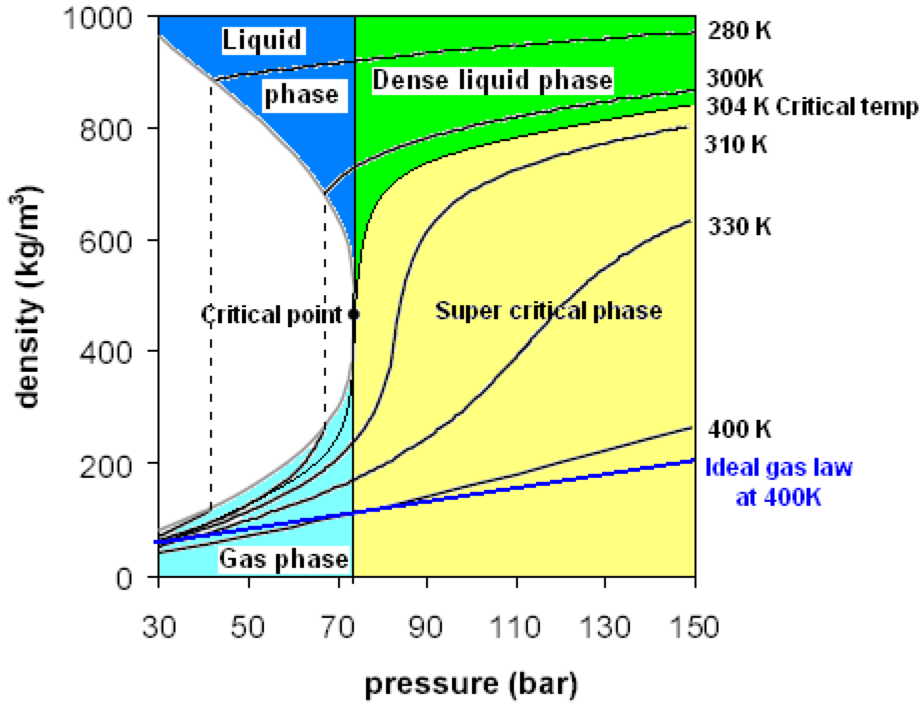

Figure 6.4 Density diagram for pure CO_2 between 30 and 150 bar at temperatures between 280K (7 °C) and 400K (127 °C). Adapted from Jacobs, 2004.

From the diagram in figure 6.4 it shows that especially in the supercritical phase (yellow coloured area) the density is strongly dependent on pressure and temperature. So a small deviation in the actual temperature or pressure at the point of measurement has a strong influence on the uncertainty in the density calculation. This effect will be studied and quantified in future. From about 400K and higher the deviations from ideal gas law starts to decrease. This is shown as the blue line in the diagram.

It is noted that figure 6.4 applies only for pure CO_2 and that viscosity is also dependent on the concentration of other components (e.g. N_2). This should be taken into account as well.

Another cost effective solution could be to determine the density directly in a bypass stream with a small coriolis mass flow meter (density meter).

Viscosity

In figure 6.5 the dependence of temperature and pressure for viscosity is shown.

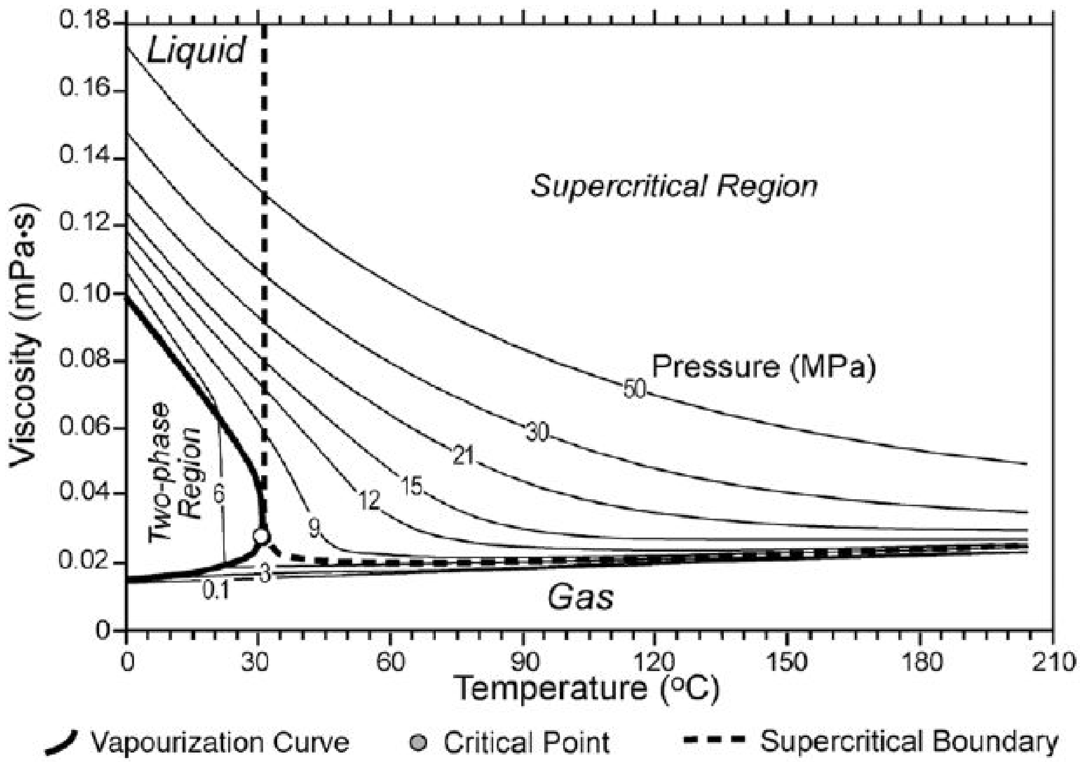

Figure 6.5 Viscosity as function of temperature and pressure (IPCC, 2005)

As can be seen from figure 6.5 the viscosity is strongly dependent on temperature in the temperature range between about 30℃ to about 60℃. So an accurate measurement of the local temperature is important.

Calculation procedures for density and viscosity

At this moment various calculation procedures (UCDAVIS, 2006; Vrabec, 2009, Fenghour, 1998, McCoy, 2008) are described in literature to calculate the density (and other physical parameters) of CO_2 with mixtures of gases (e.g. N_2, O_2) at a given temperature and pressure. These methods are quite complicated and not (yet) easy applicable or general available for density calculations. Therefore further research and standardization of density (but also viscosity) calculations is needed for the use in widely applied monitoring and reporting systems at CCS demonstration plants, which are also easy to use and accepted as a verifiable procedure.

In any case at least temperature and pressure measurements are required at the point of flow measurement when using volumetric flow measuring techniques.

6.4.2 Determination of CO_2 concentration (in compressed CO_2)

Sampling

For compressed CO_2 flows, it is not feasible to measure the CO_2 concentration directly in the pipeline (in-situ). Depending on pressure and temperature the CO_2 will have different densities, which make it rather difficult to perform proper correction calculations for the concentration measurements. Also spectral absorption line broadening in the infrared will result in non-lineair behaviour as function of concentration.

A simple and elegant solution is to perform extractive sampling from the CO_2 stream by means of pressure reduction and subsequently gaseous CO_2 concentration measurements at or near atmospheric pressure. Depending on the quality and uncertainty requirements needed this can be performed continuously or at a lower frequency (e.g. once per week, once per month). The required frequency is elaborated in the CATO-2 WP 4.1 deliverable 3 report.

As already indicated earlier the CO_2 stream should be in a single phase at the point of sampling. Otherwise the uncertainty in the CO_2 content increases due to preferential over-sampling of one of the two phases. The pressure reduction system in the sampling line should be designed in such a way that formation of liquid or droplets in the sampling system is avoided (clogging). This can be done by using a (mild) heated sampling system.

Analysis – method A

For the direct measurement of CO_2 (indicated as Method A in Annex XII in the MRG) several techniques are suitable for continuous analysis with a CEMS or discontinuous grab sampling analysis.

Continuous monitoring with a CEMS

The most common and widely used are NDIR/IR analysis techniques. These instruments measure continuously and are commercially available.

Several types of NDIR (Non Dispersive Infra Red) or IR (Infra Red) techniques exist, such as GFC (gas filter correlation), FTIR (Fourier Transform) and classical absorption. When choosing an analysis technique one should focus on the instruments with the lowest uncertainty, which can be calculated according to the EN-ISO 14569. One should make certain that possible interferences of vapours originating from the absorption liquids originating from the capture process with the NDIR/IR technique are minimized or absent.

At present no standards are available for CO_2-measurement concentrations with these techniques close to 100%, but the ISO 12039 (applicable for flue gases) can be used as a general guidance for performance criteria to be achieved. The most important criteria relating to uncertainty are given below (please refer to ISO 12039 for other performance criteria, such as response time and so on). It is assumed that more or less the same uncertainties apply:

Zero drift	< 2% of full scale
Span drift	< 4% of calibrated value
Interferences	< 4% of full scale
Deviation from linearity	< 2% of full scale

If necessary the uncertainty in the measured CO_2 concentrations can be lowered by calibrating the instrument at or very close to the average measured concentrations (generally between 95% up to 100%). By this the uncertainty due to non-linearity of the instrument (in general at a level of about 1%) can be eliminated.

Quality control and calibration procedures should be in place to guarantee reliable results with known uncertainty.

It is advised to follow the development of new standards within ISO. At this moment two standards for the measurement of greenhouse gases for stationary sources are being developed (in the working draft stage). The ISO 14385-1 will describe the calibration of automated systems and the ISO 14385-2 the ongoing quality control of automated measuring systems.

Discontinuous grab sampling and analysis

When less frequent analysis suffice (e.g. once a week or month) sampling can be performed by means of grab sampling in e.g. gas cylinders, Tedlar bags, metal foil bags. Then followed by CO_2 gas analysis on a GC (gas chromatograph). In general the uncertainty associated with these techniques are in the range of about 2%. Quality control procedures should be in place to guarantee reliable results with known uncertainty

Analysis – method B

The measurement of CO_2 (indicated as Method B in Annex XII in the MRG) can also be performed by the analysis of all other components except CO_2 and then subtracting the sum of the other components from 100%.

In general GC (gas chromatography) is a well-suited and commercial available technique to perform these kind of analysis. This technique can be performed (semi)-continuous by automatic injection of a gas sample onto the GC column, generating analysis data e.g. each 10 – 20 minutes. But this technique can also be applied discontinuous on a less frequent scale employing grab sampling and analysis e.g. once a week or month (the criteria for less frequent sampling are elaborated in the CATO-2 WP 4.1 deliverable 3). In any case quality control procedures should be in place to guarantee reliable results with known uncertainty. It is estimated that the uncertainty in (semi)-continuous GC analysis per component is less than 3 - 5% (relative).

6.5 Monitoring CO_2 emissions from transport networks

In the monitoring plan a description of the transport network including all starting and ending points as well as all bifurcations and national borders is mandatory for the greenhouse gas emission permit. Also intermediate storage facilities should be described.

Setting boundaries and metering for the transport network

It is important to define the boundaries of the transport network very clearly, such as the number and locations of the metering systems and the ownership of these metering systems. The question can be raised if it is sensible and necessary to install a CO_2 flow metering system at the capture plant just before transport as part of the capture system and another CO_2 flow metering system close by downstream at the entrance of the transport system as part of the transport network. Also it should be described if the compressor is part of the capture plant or the transport network.

At the side of the storage complex the Storage Directive (EU, 2009) demands a flow measuring system at the well head. As this will be property of the storage site complex owner and will be often at a remote location, a flow and composition metering system at the exit boundary of the transport network is sensible.

Choice of monitoring method

According to the MRG (EU, 2010) the operator may choose from one of the two monitoring methods (method A and method B) for determination of the CO_2 emissions. As already indicated in paragraph 5.3 in this report, when the operator chooses method B and operates the transport network for commercial reasons, he has to validate method B with method A. So then both methods need to be in place. The impact of uncertainties involved with method A and method B are elaborated in the CATO-2 WP 4.1 deliverable 3 report.

Method A

Method A employs a mass balance calculation in which the own emissions are added to the difference between the received amount of CO_2 and the transferred amount of CO_2:

$$\text{Emissions } [tCO_2] = E_{\text{own activity}} + \Sigma T_{IN,\,i} - \Sigma T_{OUT,\,j}$$

With:

Emissions [tCO_2]	-	Total CO_2 emission of the transport network [tCO_2]
$E_{\text{own activity}}$	-	Emissions from the transport network (e.g. from fuel use in booster stations)
$T_{IN,\,i}$	-	Amount of CO_2 transferred to the transport network at entry point i (in accordance with Annex XII and Section 5.7 Annex I)
$T_{OUT,\,j}$	-	Amount of CO_2 transferred to the transport network at exit point j (in accordance with Annex XII and Section 5.7 Annex I)

$E_{own\ activity}$

For the monitoring plan the standard methodology set out in the MRG for the determination and monitoring of CO_2 emissions from fuel combustion should be set up and put in place. In general combustion units will be rather small and thus fall mostly within class A category (see table 5.1 in this report).

T_{IN} and T_{OUT}

At each entry point and exit point the CO_2-flow and CO_2-concentration can be measured with one of the measuring techniques indicated in subparagraphs under 6.3 in this report.

Total uncertainty

The uncertainty for method A shall be less than 2.5% (Tier 4). The impact of uncertainties involved with method A and method B are elaborated in the CATO-2 WP 4.1 deliverable 3 report.

Method B

Method B quantifies the potential CO_2 emissions from all relevant processes:

Emissions [tCO_2] = $CO_{2\ fugitive}$ + $CO_{2\ vented}$ + $CO_{2\ leakage\ events}$ + $CO_{2\ installations}$

With:

Emissions	-	Total CO_2 emission of the transport network [tCO_2]
$CO_{2\ fugitive}$	-	Amount of fugitive emissions (from seals, valves, intermediate compressor stations and intermediate storage facilities
$CO_{2\ vented}$	-	Amount of vented emissions (from seals, valves, intermediate compressor stations
$CO_{2\ leakage\ events}$	-	Amount of CO_2 transported, which is emitted as a result of failure of one of the components
$CO_{2\ installations}$	-	Amount of CO_2 emitted from combustion or other processes

In Annex XVII of the MRG further requirements are given for Method B how to calculate and monitor the emissions, which are elaborated below.

$CO_{2\ fugitive}$

The Annex in the MRG gives the following items where CO_2-emissions can occur:

- Seals, measurement devices and valves
- Intermediate compressor stations
- Intermediate storage facilities

For each piece of equipment where fugitive emissions can be expected, emission factors (expressed as g CO_2 per unit of time) shall be determined at the beginning of the operation and at latest by the end of the reporting year in which the transport network is in operation. These factors shall be reviewed at least every 5 years in light of the best available techniques.

The total annual fugitive emission is calculated by summing all fugitive emissions from each piece of equipment with their respective emission factors.

In paragraph 6.4.1 of this report possible methods for the determination of fugitive emissions are given.

$CO_{2\ vented}$

The MRG state that in the monitoring plan the operator shall provide an analysis regarding potential situations of venting emissions (including maintenance and emergency) and provide a suitable documented methodology to calculate the amount of CO_2 vented, based on industry best practices.

One of the possibilities is to determine the mass of CO_2 from the volumes of pipeline, compressor and pressure in the parts that are vented. A procedure shall be in place how the vented emissions are calculated.

$CO_{2\ leakage}$

According to the MRG proof shall be given of the network integrity by representative (spatial and time related) temperature and pressure data. When a leaks occurs the operator shall calculate the amount of CO_2, with a suitable methodology documented in the monitoring plan and based on industry best practices. This can be calculated e.g. using pressure drop data and associated volumes in the installations.

$CO_{2\ installations}$

The amount of CO_2 from combustion processes or other processes functionally connected to the pipeline transport shall be monitored according to the Annexes of the MRG.

It is recommended to apply calculation methods (as given in the MRG) based on fuel flows for combustion installations as much as possible. This ensures the lowest possible associated uncertainty.

Total uncertainty

For method B the overall uncertainty of the annual greenhouse gas emissions of the operator's transport network shall not exceed 7.5%. The impact of uncertainties involved with method A and method B are elaborated in the CATO-2 WP 4.1 deliverable 3 report

6.5.1 Determination of fugitive emissions

In this paragraph a number of guidance documents, best available techniques and measuring devices are described.

IPCC

The IPCC has published the 2006 IPPC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) which are an update of the IPCC Good Practice Guidelines (GPG) for the determination of fugitive emissions from oil and gas industry and the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1996).

Pipelines

These guidelines are primarily for National Greenhouse Gas Inventories, but some general guidance can be found how to estimate emission factors for pipelines based on data from natural gas transport (see reference IPCC, 2006a). These emission factors for pipelines could be used as an first estimate and are given in Appendix I in this report. The fugitive emission factors for natural gas are scaled to CO_2 emission factors with a factor 1.66 (by mass)[1], taking into account the molecular weight and the flow properties through a leak.

In the IPCC document it is stated that leakage emissions from pipeline transport are independent of throughput and the number of leaks is not necessarily correlated to the length of pipeline. The best correlation depends on the number and type of equipment components and the type of maintenance. Therefore it is strongly recommended to implement a monitoring plan in which all equipment parts that could potentially leak are monitored, measured and quantified on a regular bases (e.g. maintenance scheme).

Other equipment

In chapter 4 of the 2006 IPCC Guidelines (IPCC, 2006) natural gas emission factors are given for other equipment such as compressor stations, metering and regulator stations and so on. These factors could too be used as a first estimate for fugitive emissions. Those emission factors are shown in Appendix II of this report.

However in an earlier report of IPCC (IPCC, 2005) a gap in knowledge is identified that methodologies for the determination of fugitive emission factors from capture, transport and injection are not available. This shows that monitoring methodologies are not yet available or fully developed and it is recommended to establish a best practice methodology which is agreed upon by the competent authority.

[1] According to IPCC (IPCC, 2006a, page 5.9) the mass leak rates for CO_2 can be estimated from CH_4 leak rates (the IPCC document provides a formula for the leak rate). Assuming the same pressure drop then the mass leak rate is proportional to the square root of density of the gas($\sqrt{\rho}$). Conversion of CH_4 leak rates to CO_2 leak rates is then multiplication by a factor of $\sqrt{44/16} = 1.66$.

EPA Method 21

EPA method 21 describes a method for the determination of leaks of Volatile Organic Compounds (VOC):

"This method is applicable for the determination of VOC leaks from process equipment. These sources include, but are not limited to, valves, flanges and other connections, pumps and compressors, pressure relief devices, process drains, open-ended valves, pump and compressor seal system degassing vents, accumulator vessel vents, agitator seals, and access door seals."

This EPA method 21 can also be applied to determine CO_2 leaks as the method allows any detector applied as long as the detector responds to the compounds to be detected: *"The VOC instrument detector shall respond to the compounds being processed. Detector types that may meet this requirement include, but are not limited to, catalytic oxidation, flame ionization, infrared absorption, and photo ionization."*

The EPA method 21 is regarded and accepted as the best available technique in industry despite discussions about the uncertainty of the method. So for the determination of fugitive emissions it is recommended to follow the procedure in this EPA method 21.

Leak Detection and Repair (LDAR) program

It is strongly recommended to describe and implement a Leak Detection And Repair program. In such a program fugitive emissions are determined (qualitative and quantitative) for all components. The determined emission data can then be reported for the previous period up to the date of measurement. When a certain limit value is exceeded then an immediate maintenance or repair (e.g. tightening of bolts in a flange) is carried out and with a repeated fugitive emission measurement directly after the repair. The new emission data can be used for the coming period and checked against the data when the component is under inspection again.

However there is no hard figure for a limit value at which repair shall take place. One could set a limit value oneself based on a documented estimate of the amount of fugitive CO_2 emitted and costs involved to perform repairs, maintenance and costs of CO_2 emission rights.

Measuring devices

Up to date there is very few CO_2 leak detection equipment on the market, which is readily suited for fugitive CO_2 emission measurement. Some can be found as CO_2 refrigerant leakage detectors.

Nevertheless CO_2 detection and measurement is fairly simple with instruments suited for CO_2 measurement with infrared detectors. For determining fugitive CO_2 emissions it is important that the flow through the instrument is constant but also accurately known. Otherwise it is not possible to determine the CO_2 emission rate (e.g. kg/a). Solely measuring the CO_2 concentration only indicates if there is a leak (thus qualitative) and if it is larger or smaller than another leak.

In this stage no hard data is available about the uncertainties associated with fugitive CO_2 emissions.

6.6 Determining CO_2 emissions from storage

The MRG (EU, 2010) indicate the following potential CO_2 emissions sources at a storage site:

- Fuel use at booster station and other combustion activities
- Vented and fugitive emissions from injection
- Vented and fugitive emissions from enhanced hydrocarbon recovery
- Leakage from the storage Under the EU-ETS

The monitoring and reporting of these four types of emission sources are elaborated in more detail below. For a good general overview of the technologies involved with injection and storage of CO_2 as well as the types of storage sites, reference is made to the special IPCC report "Carbon Dioxide Capture and Storage" (IPCC, 2005).

6.6.1 Emissions at injection and from Enhanced Hydrocarbon Recovery

CO_2 emissions from combustion activities

The CO_2 emissions from above ground activities can be easily determined by means of calculation of the CO_2 emissions from the fuel flow and fuel composition as described in Annex II of the MRG (EU, 2010).

Vented and fugitive emissions from injection

The CO_2 emissions from venting and fugitive emissions shall be determined according Annex XVIII in the MRG (EU, 2010) as follows:

CO_2 emitted = $V_{CO2} + F_{CO2}$

In which:

CO_2 emitted	-	CO_2 emission in tonnes from venting and fugitive emissions
V_{CO2}	-	the vented CO_2 emissions (in tonnes)
F_{CO2}	-	the fugitive CO_2 emissions (in tonnes)

For the determination of vented and fugitive emissions the same methods as described in paragraphs 6.4 and 6.4.1 in this report can be applied.

Vented and fugitive emissions from enhanced hydrocarbon recovery

Enhanced hydrocarbon recovery will most likely produce a number of additional source streams of CO_2, which have to be taken into account. These additional emission sources include:

- fugitive emissions from oil-gas separation units and gas recycling plants
- CO_2 emissions through the flare stack originating from the enhanced hydrocarbon recovery

- CO_2 emissions from the flare stack originating from the necessary additional fuel fed to the flare stack, for prevention of extinguishing the flare
- Any other vented or fugitive CO_2 emissions in the gas conditioning systems

Determination of vented and fugitive emissions

Methods for the determination of vented and fugitive emissions are given in paragraph 6.4 and 6.4.1. in this report.

Determination of CO_2 emissions from the flare stack

The CO_2 emissions from the flare stack comprise of CO_2 from the enhanced oil recovery and additional CO_2 from the burnt fuel to support the flare.

The amount of CO_2 to the flare can be measured using flow meters and a CO_2 gas analyzer (or e.g. a gas chromatograph). The amount of CO_2 from the additional fuel can be calculated using the procedures in chapter 5 of Annex I in the MRG.

The emissions and maximum required total uncertainty of the CO_2-emissions from flares is to be determined according Annex II in the MRG. In Annex I paragraph 5.2 of the MRG the tiers for flares are given.

Table 6.1 Minimum tiers for flares from EHR according to Annexes I and II of the MRG

Category	A		B		C	
CO_2 emission kton/y	< 50		50 < X < 500		> 500	
	Tier	Uncertainty	Tier	Uncertainty	Tier	Uncertainty
Flare	1	< 17.5%	2	< 7.5%	3	< 7.5%

6.6.2 Quantification of leakage from the storage complex

Implications of the requirements from the MRG

The Storage Directive (EU, 2009) requires monitoring of the behaviour of CO_2 in the storage complex, in order to be able to detect any irregularities of leakages in a very early stage. This aspect is not covered by the MRG. The MRG deals with the *quantitative* monitoring of CO_2 when leakage to the atmosphere (or to the water column) occurs. When leakage starts to happen then the monitoring under the MRG shall begin according to Annex XVIII of the MRG (EU, 2010).

Monitoring shall continue until corrective measures pursuant Article 16 of the Storage Directive (EU, 2009) have been taken or that release into the water column can no longer be detected.

The amount of CO_2 released per calendar day shall be determined as the average of mass leaked per hour multiplied by 24. The mass leaked per hour shall be determined according to the provisions in the approved monitoring plan.

Annex XVIII describes that the starting date for calculating the amount of CO_2 released depends at which date it can be proved that leakage has started, or the latest date when no emissions were reported or the date that the CO_2-injection has started. The end date for reporting CO_2 leakage is when corrective measures have been undertaken and that leakage can no longer be detected. It is therefore recommended in this report to start *quantitative* monitoring of the CO_2 leakage to the atmosphere as early as possible in order to avoid the case that the CO_2-emissions are counted back to the starting date of injection.

It is interpreted from the MRG that the overall uncertainty of the sum of all leakage events in a reporting period shall be less than 7.5%. In the case that the uncertainty of the applied quantification approach exceeds 7.5% than a correction shall be made to the quantified CO_2 emission. The reported CO_2 emission is then the quantified CO_2 emission multiplied by a correction factor:

This correction factor equals (1 + (Uncertainty[%]/100%) – 0.075).

In figure 6.6 the correction factor is shown as function of the uncertainty of the quantification method. At 7.5% the correction factor equals 1.

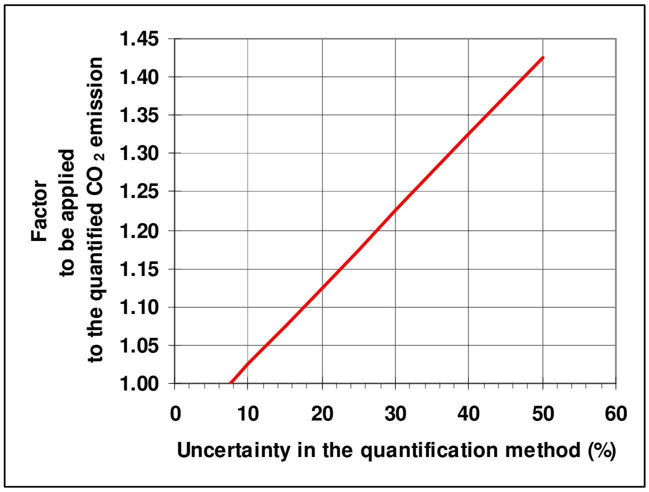

Figure 6.6 Correction factor to be applied to the quantified CO_2 emission as function of the uncertainty in the quantification method.

When the uncertainty of the quantification method is larger than 7.5% then the quantified CO_2-emissions are increased. At an uncertainty of 50% of the quantification method, the CO_2-emissions are raised with 42% (a factor of 1.42).

Monitoring techniques

IPCC reference

A good overview of monitoring techniques is given in the IPCC Guidelines (Volume 2, Chapter 5, Annex 5.1. see reference IPCC, 2006a).

The IPCC gives in several tables an overview of the monitoring techniques with capabilities, limitations and the current technology status for:

- Deep subsurface monitoring technologies
- Shallow subsurface monitoring technologies
- Technologies for determining fluxes from ground or water to the atmosphere
- Technologies for detection of raised CO_2 levels in air and soil (leakage detection)
- Proxy measurements to detect leakage from geological CO_2 storage sites
- Technologies for monitoring CO_2 levels in sea water

Also the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005, in Chapter 5) gives a comprehensive overview of the technologies involved.

IEAGHG reference

Good information can also be found on the website of the Greenhouse Gas Program of the International Energy Agency (see reference IEAGHG, 2010). Their interactive website has a tool under "CO_2 capture and storage" in which monitoring techniques are shown depending on the choices made for:

- Reservoir location : Onshore or offshore
- Reservoir depth : from 500 m to over 4000m
- Reservoir type : Aquifer, Oil, Gas, Coal
- Quantity of CO_2 injected [Mt/y] and duration [years]
- Land use at the proposed storage site: Populated, Agricultural, Wooded, Arid, Protected
- Monitoring phases : Pre-injection, Injection, Post-injection, Closure
- Monitoring aims : Plume, Top-seal, Migration, Quantification, Efficiency, Calibration, Leakages, Seismicity, Integrity, Confidence

A result table with monitoring techniques is then shown in which a ranking is given of which technique is most applicable or recommended. For each technique a description is given, some with some case studies and bibliography.

Overview of the monitoring techniques

Below an overview is given of the monitoring techniques that could be applied. For a detailed description of the techniques reference is made to the already mentioned IPCC reference and the IEAGHG reference.

Applicable monitoring techniques:

- Soil gas concentration measurements
- Bubble stream detection
- Open path CO_2 IR detection
- Bubble stream chemistry
- Long-term downhole pH measurements
- Downhole fluid chemistry
- Fluid geochemistry
- Eddy covariance CO_2 measurements in the open field
- Surface gas flux measurements
- Airborne spectral imaging
- Airborne electro-magnetic techniques
- Ecosystems studies
- Tracer injection and detection

Applicability and uncertainties in the methods

Some of the techniques are suitable for quantification of leakages, whilst others are more suitable for the detection of leaks. Due to insufficient field data and practical experiences it is difficult to indicate which techniques are most suitable for quantification of CO_2 leakages against reasonable costs for onshore and offshore storage sites. Also there is almost no data about the uncertainty in the quantification of these monitoring techniques. Therefore further research and practical experience is needed to establish proven and accepted methodologies for quantifying CO_2 leakages.

Nevertheless when reviewing the techniques at both references, at present the following techniques seems to be the most practical as routine measurements for quantitative determination of CO_2 leakages at **onshore** storage sites:

- Soil gas concentration measurement
- Surface gas flux measurement

These techniques employ grid sampling of CO_2 at many locations in a certain area. However care should be taken with the interpretation of the CO_2 emission data as seasonal variations and humidity of the soil influence bacterial production of CO_2 emissions. For the determination of Soil Gas Concentrations guidelines can be found in the standard ASTM D5314 - 92(2006).

Independent of which monitoring technique is chosen, it is strongly recommended to set-up Standard Operating Procedures (SOPs) for the techniques, with good quality assurance and quality control (QA/QC) procedures around it, to ensure reliable and consistent measured values and monitoring.

7 Remaining issues for further study

During drafting this report for practical guidelines for CCS, a number of issues turned up. These need to be resolved in order to get the methodology for a monitoring and reporting system transparent and unambiguous. Technical monitoring developments for CCS are needed to meet the uncertainty requirements and get commonly accepted and verifiable methodologies.

The following issues need further clarification, study and development:

- Uncertainty requirements for exhaust gases vented from capture or partially bypassed gases from the combustion installation.
- An experimentally verified and accepted (standardized) calculation method for the density and viscosity of compressed CO_2 in a multi component system.
- Development of mass flow measuring techniques for compressed CO_2 flows (either single phase or two phase).
- Assessment of uncertainty estimates for flow measuring techniques for compressed CO_2.
- Accountability and responsibilities for flow and composition metering between the connection point of the capture plant, the transport network and storage sites (e.g. a measuring code for CO_2).
- A standard protocol for the determination of fugitive CO_2-emissions and associated uncertainties.
- An agreed bandwidth and identification of accompanying gases for injection at storage sites, especially trace constituents (such as corrosive components as H_2S, SO_2).
- Protocols for monitoring and verification for the amount of CO_2 stored underground.
- Further development of standardized and accepted quantification techniques for leakage of CO_2 at storage sites, with known uncertainties.

The IPCC Special Report on Carbon Dioxide, Capture and Storage (IPCC, 2005) also identified a number of knowledge gaps for CCS. For monitoring these are quoted below:

- There is strong evidence that storage of CO_2 in geological storage sites will be long term; however, it would be beneficial to have:
    - Quantification of potential leakage rates from more storage sites.
    - Reliable coupled hydrogeological-geochemical-geo–mechanical simulation models to predict long-term storage performance accurately.
    - Reliable probabilistic methods for predicting leakage rates from storage sites.
    - Further knowledge of the history of natural accumulations of CO_2.
    - Effective and demonstrated protocols for achieving desirable storage duration and local safety.
- Monitoring technology is available for determining the behaviour of CO_2 at the surface or in the subsurface; however, there is scope for improvement in the following areas:
    - Quantification and resolution of location and forms of CO_2 in the subsurface, by geophysical techniques.
    - Detection and monitoring of subaquatic CO_2 seepage.
    - Remote-sensing and cost-effective surface methods for temporally variable leak detection and quantification, especially for dispersed leaks.
    - Fracture detection and characterization of leakage potential.

  - Development of appropriate long-term monitoring approaches and strategies.
- The regulatory and responsibility or liability framework for CO_2 storage is yet to be established or unclear. The following issues need to be considered:
  - The role of pilot and demonstration projects in developing regulations.
  - Approaches for verification of CO_2 storage for accounting purposes.
  - Approaches to regulatory oversight for selecting, operating and monitoring CO_2 storage sites, both in the short and long term.

8 Conclusions and recommendations

Depending on ownership of the installations for CCS and issued greenhouse gas emission permits, one to four monitoring plans might be required for the whole CCS chain. Monitoring plans are needed for:

- Combustion or process installation
- Capture installation
- Transport network
- Storage site

Monitoring of CO_2-streams by *calculation* methods from combustion or process installations is a standard methodology as this is common practice for monitoring and reporting of greenhouse gas emissions under EU-ETS. Monitoring of CO_2-streams from combustion or process installations with CEMS however is not common practice. Uncertainty of CO_2 CEMS systems for flow and concentration are larger than the required 2.5% in the MRG. These uncertainty requirements in the MRG for CO_2 (< 2.5%) are far more stringent than for e.g. NO_x (< 20%), for which NO_x CEMS systems can meet the uncertainty requirement of 20%. So this is a point of further study.

Technical monitoring of compressed CO_2-streams within the MRG uncertainty requirements from capture installations and in transport networks shows to be still in the development stage. Only a few measuring techniques are available for monitoring compressed CO_2-streams. The volumetric flow measurement systems with orifice plates, turbine meters and the Coriolis mass flow measurement systems look the most promising at this moment. However all these techniques need to operate in single phase CO_2-flow (gas or liquid or supercritical). For two-phase flow (gas + liquid) experiences still need to be gained and technology developed to meet the MRG uncertainty requirements. To this a development of a measuring code CO_2 (similar to the measuring code natural gas) is recommended. With this measuring code CO_2 quality assurance and quality control can be put into place, for which acceptance by the competent authority is facilitated.

For the orifice plate and turbine measurement systems exact knowledge of the prevailing CO_2 density and viscosity at the point of measurement is needed. The CO_2 density and viscosity are very strongly dependent on temperature, pressure and composition in the anticipated temperature and pressure window for CCS. The impact of a few percent of impurities (e.g. N_2) has a large influence on the density. Theoretical calculation procedures for density and viscosity at a given pressure and temperature are available, but are rather complicated and not easily available or verifiable. Therefore standardization of these calculation procedures are highly recommended for general application and acceptance by the competent authorities and independent bodies.

In order to facilitate and reduce costs for operators of capture installations and storage site operators, transport network operators could be made responsible for monitoring and accounting of the transferred CO_2 received from the capture installations and the transferred CO_2 to the storage sites. The transport network operators then can monitor according the measuring code CO_2, which avoids monitoring and quality control by the operators of the capture installations and storage sites. This is similar to to common practice of commercial deliverable feedstocks

For the quantification of fugitive emissions from capture installations, transport networks and at storage sites the EPA method 21 is regarded as the best practice technology. However no hard data is available about the uncertainties associated with the quantification of fugitive CO_2 emissions. There is very few CO_2 leak detection equipment on the market, which is readily suited for fugitive CO_2 emission measurement. When fugitive emissions are being determined it is recommended to have a Leak Detection And Repair (LDAP) in place and referred to in the monitoring plan, in order to minimize fugitive CO_2 emissions. Further development and standardization of measurement methodologies is recommended.

For onshore and offshore storage sites it is difficult to indicate which techniques are most suitable for quantification of CO_2 leakages. Some are suitable for quantification of leakages, whilst others are more suitable for the detecting of leaks. At present for onshore storage sites the soil gas concentration measurement and the surface gas flux measurement seems to be the most practical as routine measurements for quantitative determination of CO_2 leakages.

There is almost no data about the uncertainty in the quantification of these monitoring techniques. Therefore further research, practical experiences and standardization of methods needed to establish proven and accepted methodologies for quantifying CO_2 leakages.

It is recommended to set up a study project to draft monitoring plans for the whole CCS chain of a real full scale CCS project. In this study project all relevant parties should be involved to discuss, implement and technically make the monitoring possible. Parties to be involved should be the operators of a capture plant, transport network and storage site, CEMS equipment manufacturers, representatives of the competent authorities and verification bodies. With such a project all the issues that need to be resolved can be discussed and the results can set an example for future CCS projects.

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APPENDIX I IPCC CO_2 EMISSION FACTORS FOR PIPELINE TRANSPORT

Table from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
(Volume 2: Energy. Chapter 5: Carbon Dioxide Transport, Injection and Geological Storage. Page 5.10).

TABLE 5.2
DEFAULT TIER 1 EMISSION FACTORS FOR PIPELINE TRANSPORT OF CO_2 FROM A CO_2 CAPTURE SITE TO THE FINAL STORAGE SITE

Emission Source	Value			Uncertainty	Units of Measure
	Low	Medium	High		
Fugitive emissions from CO_2 transportation by pipeline	0.00014	0.0014	0.014	± a factor of 2	Gg per year and per km of transmission pipeline

Please note the comments in paragraph 6.4.1. in this report that leakage emissions from pipeline transport are independent of throughput and that the number of leaks is not necessarily correlated to the length of pipeline. The best correlation depends on the number and type of equipment components and the type of maintenance. So these emission factors should only be used as a first estimate.

APPENDIX II IPCC NATURAL GAS EMISSION FACTORS FOR SELECTED FACILITIES

Table from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. (Volume 2: Energy. Chapter 4: Fugitive Emissions. Page 4.71).

TABLE 4.2.8
CLASSIFICATION OF GAS LOSSES AS LOW, MEDIUM OR HIGH AT SELECTED TYPES OF NATURAL GAS FACILITIES

Facilities	Activity data	Yearly emission factors			
		Low	Medium	High	Units of Measure
Production and Processing	Net gas production (i.e. marketed production)	0.05	0.2	0.7	% of net production
Transmission Pipeline Systems	Length of transmission pipelines	200	2 000	20 000	m^3/km/yr
Compressor Stations	Installed compressor capacity	6 000	20 000	100 000	m^3/MW/yr
Underground Storage	Working capacity of underground storage stations	0.05	0.1	0.7	% of working gas capacity
LNG Plant (liquefaction or regasification)	Gas throughput	0.005	0.05	0.1	% of throughput
Meter and Regulator Stations	Number of stations	1 000	5 000	50 000	m^3/station/yr
Distribution	Length of distribution network	100	1 000	10 000	m^3/km/yr
Gas Use	Number of gas appliances	2	5	20	m^3/appliance/yr

Source: Adapted by the authors from currently unpublished work by the International Gas Union, and based on data for a dozen countries including Russia and Algeria.

Please note that these natural gas emission factors in this table have to be converted to CO_2 emission factors by first converting the m^3 to kg by multiplying with 0.7 kg/m^3 (for CH_4) and then with a factor 1.66. (Overall thus multiplying with a factor 0.7 x 1.66 = 1.16).

APPENDIX III THE REQUIRED CONTENT OF A MONITORING PLAN ACCORDING TO THE MONITORING AND REPORTING GUIDELINES

In this appendix chapter 4.3 of Annex I in the MRG (EU, 2010) has been copied, in which the required content of a monitoring plan is described.

From the MRG (EU, 2010):

4.3 THE MONITORING PLAN

Pursuant to Article 6(2)(c) of Directive 2003/87/EC greenhouse gas emissions permits shall contain monitoring requirements, specifying monitoring methodology and frequency.

The monitoring methodology is part of the monitoring plan which shall be approved by the competent authority in accordance with the criteria set out in this Section and its subsections. The Member State or its competent authorities shall ensure that the monitoring methodology to be applied by installations shall be specified either under the conditions of the permit or, where consistent with Directive 2003/87/EC, in general binding rules.

The competent authority shall check and approve the monitoring plan prepared by the operator before the start of the reporting period, and again after any substantial changes to the monitoring methodology are applied to an installation as listed three paragraphs below.

Subject to Section 16, the monitoring plan shall contain the following contents:

(a) the description of the installation and activities carried out by the installation to be monitored;

(b) information on responsibilities for monitoring and reporting within the installation;

(c) a list of emissions sources and source streams to be monitored for each activity carried out within the installation;

(d) a description of the calculation-based methodology or measurement-based methodology to be used;

(e) a list and description of the tiers for activity data, emission factors, oxidation and conversion factors for each of the source streams to be monitored;

(f) a description of the measurement systems, and the specification and exact location of the measurement instruments to be used for each of the source streams to be monitored;

(g) evidence demonstrating compliance with the uncertainty thresholds for activity data and other parameters (where applicable) for the applied tiers for each source stream;

(h) if applicable, a description of the approach to be used for the sampling of fuel and materials for the determination of net calorific value, carbon content, emission factors, oxidation and conversion factor and biomass content for each of the source streams;

(i) a description of the intended sources or analytical approaches for the determination of the net calorific values, carbon content, emission factor, oxidation factor, conversion factor or biomass fraction for each of the source streams;

(j) if applicable, a list and description of non-accredited laboratories and relevant analytical procedures including a list of all relevant quality assurance measures, e.g. inter-laboratory comparisons as described in Section 13.5.2;

(k) if applicable, a description of continuous emission measurement systems to be used for the monitoring of an emission source, i.e. the points of measurement, frequency of measurements, equipment used, calibration procedures, data collection and storage procedures and the approach for corroborating calculation and the reporting of activity data, emission factors and alike;

(l) if applicable, where the so-called 'fall-back approach' (Section 5.3) is applied: a comprehensive description of the approach and the uncertainty analysis, if not already covered by items (a) to (k) of this list;

(m) a description of the procedures for data acquisition, handling activities and control activities as well as a description of the activities (see Section 10.1-3);

(n) where applicable, information on relevant links with activities undertaken under the Community ecomanagement and audit scheme (EMAS) and other environmental management systems (e.g. ISO14001:2004), in particular on procedures and controls with relevance to greenhouse gas emissions monitoring and reporting;

(o) where applicable, the location of equipment for temperature and pressure measurement in a transport network;

(p) where applicable, procedures for preventing, detecting and quantification of leakage events from transport networks;

(q) in the case of transport networks, procedures effectively ensuring that CO_2 is transferred only to installations which have a valid greenhouse gas emission permit, or where any emitted CO_2 is effectively monitored and accounted for in accordance with section 5.7 of this Annex;

(r) where CO_2 is transferred according to section 5.7 of this Annex, an identification of the receiving and transferring installations. For installations holding a greenhouse gas emissions permit, this is the installation identification code as defined by the Regulation pursuant to Article 19 of Directive 2003/87/EC;

(s) where applicable, a description of continuous measurement systems used at the points of transfer of CO_2 between installations transferring CO_2 according to section 5.7 of this Annex;

(t) where applicable, quantification approaches for emissions or CO_2 release to the water column from potential leakages as well as the applied and possibly adapted quantification approaches for actual emissions or CO_2 release to the water column from leakages, as specified in Annex XVIII.

APPENDIX IV THE REQUIRED CONTENT OF A MONITORING PLAN ACCORDING TO THE STORAGE DIRECTIVE

In this appendix the key elements of chapter 1.1 of Annex II in the Storage Directive (EU, 2009) have been copied, in which the required content of a monitoring plan is described. Reference is made to that Annex how to update the plan and to perform post-closure monitoring (this in not given in this Appendix below).

From the Storage Directive (EU, 2009):

1.1. Establishing the plan

The monitoring plan shall provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring. The following shall be specified for each phase:

(a) parameters monitored;

(b) monitoring technology employed and justification for technology choice;

(c) monitoring locations and spatial sampling rationale;

(d) frequency of application and temporal sampling rationale.

The parameters to be monitored are identified so as to fulfil the purposes of monitoring. However, the plan shall in any case include continuous or intermittent monitoring of the following items:

(e) fugitive emissions of CO_2 at the injection facility;

(f) CO_2 volumetric flow at injection wellheads;

(g) CO_2 pressure and temperature at injection wellheads (to determine mass flow);

(h) chemical analysis of the injected material;

(i) reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

The choice of monitoring technology shall be based on best practice available at the time of design. The following options shall be considered and used as appropriate:

(j) technologies that can detect the presence, location and migration paths of CO_2 in the subsurface and at surface;

(k) technologies that provide information about pressure-volume behaviour and areal/vertical distribution of CO_2-plume to refine numerical 3-D simulation to the 3-D-geological models of the storage formation established pursuant to Article 4 and Annex I;

(l) technologies that can provide a wide areal spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO_2 out of the storage complex.