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Monitoring system for an integrated CO_2 buffer and permanent CO_2 storage project

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Contents

1 Executive summary

The ENOS (ENabling Onshore CO_2 Storage) project (www.enos-project.eu), addresses the challenges to deploy the CCS technology onshore in Europe, with its unique geological and socio-economic context. The advantages of local onshore storage include empowering communities to steer the process, supporting local jobs and industries and enabling sustainable development. Onshore storage is needed to meet climate targets and offer opportunities for EU Member States that do not have easy access to storage potential in the North Sea (where CO_2 storage has been demonstrated for over two decades). In addition, the costs for transport and storage onshore are much lower than offshore.

The ENOS consortium includes more than 100 professionals (scientists and engineers, experts in geology, monitoring and social sciences and many others) from 29 organisations based in 17 European countries. The main objective of the project is to enable the development of CO_2 storage onshore in Europe by:

- Developing, testing and demonstrating in the field, under “real-life conditions”, key technologies specifically adapted to onshore contexts (for example tools to monitor CO_2 storage sites);
- Involving local communities in CO_2 geological storage development (e.g. establishing dialogue groups with researchers, citizens and civil society representatives);
- Sharing experience and knowledge across Europe to contribute to the creation of a favourable environment for onshore storage.

This report outlines a proposed monitoring system for an integrated CO_2 buffer (temporary storage with the aim of CO_2 back-production and re-use) and combined permanent CO_2 storage project specifically for CO_2 accounting purposes. In addition, the monitoring of CO_2 quality after back-production according to the required specifications for re-use is addressed. The report describes the design of a monitoring system in a temporary storage scenario where only a portion of the CO_2 will be permanently stored. The monitoring system has been designed in line with EU regulatory requirements regarding the quantification of permanently stored CO_2 for climate change mitigation purposes.

This report has demonstrated that the monitoring of an integrated buffer and storage site should be feasible within current EU regulation although no projects have yet been undertaken. Given the inclusion of enhanced hydrocarbon recovery (EHR) within legislation it would be unlikely that a buffer site could not also be included. Current CO_2-EHR experience (outside of Europe) has extensive literature regarding separation technologies and metering of CO_2 both at injection and back-production. A review of current monitoring technologies and their ability to meet currently regulatory uncertainty requirements is included in this report. The European CCS Directive will have many of the same monitoring requirements for pure CO_2-storage, CO_2-EHR and buffering projects given it focus on environmental impact. The main challenge for future CO_2 storage projects in Europe will be in meeting specific regulatory requirement to gain ETS credits and accurately quantify the amount of CO_2 permanently stored in the reservoir.

A review of current literature regarding monitoring technologies and their associated uncertainties in quantifying CO_2 has demonstrated that leakage quantification may currently be difficult. Reaching the European requirements for leakage quantification is not specific to buffer sites but will also apply to permanent storage sites and CO_2-EHR projects seeking ETS credits, should a leakage occur.

2 Introduction

This report outlines a proposed monitoring system for an integrated CO_2 buffer (temporary storage with the aim of CO_2 back-production and re-use) and combined permanent CO_2 storage project specifically for CO_2 accounting purposes. In addition, the monitoring of CO_2 quality after back-production according to the required specifications for re-use is also addressed. The report describes the design of a monitoring system in a temporary storage scenario where only a portion of the CO_2 will be permanently stored. The monitoring system has been designed in line with EU regulatory requirements regarding the quantification of permanently stored CO_2 for climate change mitigation purposes.

In comparison to storage projects without a buffering component, an accurate knowledge of the volume of CO_2 in the reservoir and of the total volumes injected and produced is a first priority in regulations allowing combined buffering and storage activities. For the purpose of re-use, the quality of the CO_2, i.e. the composition of the back-produced stream, is key. The required specifications for the back-produced CO_2 will depend on the type of re-use. This report prepares for such future activities by designing a monitoring system for accounting and quality monitoring purposes in a scenario in which only part of the CO_2 is to remain permanently in storage (and is therefore only partially suitable for emission reduction credits). The approach in this report is to review existing CCS monitoring techniques to design a system that produces the required information in a buffering scenario.

This report has defined generally applicable guidelines on the design of a monitoring system for combined buffering and permanent storage project. The focus of the report is a case study on the Q16-Maas field in the Dutch North Sea where a temporary storage project may be required to meet seasonal, fluctuating CO_2 demand for industry. A key part of this evaluation is an investigation on the monitoring requirements for accounting as part of the regulatory framework. In particular, considerations with regard to monitoring and measurement for accounting purposes will be taken into account in a scenario in which part of the CO_2 is to remain permanently in storage.

The main outcomes of this report are:

- Review of the technical feasibility of combining CO_2 buffering and permanent storage activity within the current regulatory framework;
- Quantification of mass balance and quality of the delivered end-products (back-produced CO_2), including a description of additional separation methods.
- Potential solution for adapting current regulatory regime to accept the combination of buffering and enhanced production activities.
- Detailed description of an adequate monitoring system that suits the regulatory requirements

The regulation covered in this study includes the European CCS Directive (hereinafter referred to as the CCS Directive) which covers the permanent storage aspect of CO_2 in the EU. The EU Emissions Trading System (hereinafter referred to as the ETS Directive) is also covered with regards to accounting and the monitoring standards required to gain credits by quantifying the amount of CO_2 permanently stored and extracted in the buffering scenario. A review of Dutch regulatory requirements is also included for the Q16-Maas case study, where a buffering scenario has been proposed in offshore Rotterdam, to provide CO_2 to meet seasonal demand by the greenhouses in the Westland area.

A buffering scenario is not directly referenced in current EU legislation and the first combined CO_2 storage and buffering project has yet to be conducted. The current regulatory framework in the EU for CCS has included EHR project examples and hence the extraction of CO_2 for industrial use is thought to be feasible within current legislation as it will likely fall within a similar framework to EHR (see ENOS deliverable D4.7 (Rycroft and Mikunda, 2019)).

3 Regulatory Requirements for CO_2 Accounting

The European regulatory requirements and related guidelines regarding the monitoring of CO_2 storage sites are from 4 main sources:

CCS Directive
The directive provides general guidance on the monitoring requirements of sites and outlines the objectives that should be considered. The CCS Directive requires containment within the reservoir to be monitored and demonstrated but does not require any quantification of leakages should they occur. The Directive does not specify the measurement methods or technologies that should be considered or utilised for monitoring.

ETS Directive and associated Monitoring and Reporting Regulations (MRRs)
The ETS Directive awards credits for any emissions avoided from entering the atmosphere and therefore requires the amount of CO_2 stored to be monitored and quantified. The ETS Directive also requires the quantification of any leakages in order for the credits to be adjusted accordingly. The ETS Directive is focused on credits per tonne of CO_2 stored, and the climate mitigation associated with the project and therefore have more stringent guidelines regarding accounting and quantification.

IPCC Guidelines for National Greenhouse Gas Inventories (2006)
These guidelines consist of a number of steps leading to the inventory and quantification of emission terms during injection and storage of CO_2 for national greenhouse gas inventories.

OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (2007),
OSPAR is only applicable for offshore areas. The guidelines provide generic guidance for Contracting Parties when considering applications for CO_2 storage permits.

It is generally considered that by meeting the European regulatory requirements (CCS Directive and ETS Directive) the older international guidelines (IPCC, OSPAR, London Protocol) are also covered, as demonstrated in Figure 1 below (Hannis et al. 2017).

The main focus of the CCS directive is to ensure the safety of CCS projects including the geological storage of CO_2. The monitoring requirements of the directive can be categorised into 3 key objectives: monitoring the containment of CO_2, the conformance of reservoir behaviour with model predictions and finally contingency monitoring should a leakage occur. The requirements of contingency monitoring focus on the environmental impact the leakage may have but there are no requirements for quantification or accounting of the CO_2.

The focus of the CCS Directive is to ensure that CO_2 is stored safely in the long-term by conforming with the predicted modelled behaviour and ensuring containment is maintained. These aspects would cover both the permanent storage and buffering/ temporary storage elements of a project. The main difference between the two scenarios is the amount of CO_2 stored that would qualify for ETS Directive credits. Temporary storage of CO_2 would not quality for credits as it would not prevent CO_2 emissions to atmosphere as permanent storage does. Therefore, the regulatory requirements for CO_2 quantification outlined in the ETS Directive will be the focus of this report.

The use of geological CO_2 storage to provide a 'buffer' for the temporary storage of CO_2 has, to the best of our knowledge, never been undertaken either internationally or in Europe. The ETS Directive also has yet to be applied to an active CCS operation or EOR site, although Norwegian projects have already operated under their own CO_2 tax system. The content of this review is therefore based on an interpretation of current legislation.

		OSPAR	EU Directive	EU ETS	
Shallow-focussed monitoring actions	Verification of no leakage	✓	✓		Containment
	Leakage detection	✓	✓		Containment
	Emissions quantification	✓		✓	Contingency
	Environmental impacts	✓	✓		Other
	Testing remedial actions		✓		Contingency
Deep-focussed monitoring actions	Migration in overburden	✓	✓		Containment
	Containment integrity	✓	✓		Containment
	Migration in reservoir		✓		Conformance
	Performance testing, calibration and identification of irregularities	✓	✓		Conformance
	Calibration for long-term prediction		✓		Conformance
	Testing remedial actions		✓		Contingency

Figure 1: Summary of regulatory requirements for monitoring.
(Hannis et al. 2017)

3.1 The EU Emissions Trading System (ETS)

The EU Emissions Trading System (Directive 2003/87/EC) works on the 'cap and trade' principle where a cap is set on the total amount of greenhouse gases that can be emitted in the EU by large industry installations (not all installations fall under the ETS Directive). A monetary value is assigned to emissions providing a financial incentive for projects to reduce their greenhouse gas emissions. In 2007 the EU Commission made an amendment to the ETS Directive (amending Decision 2007/589/EC) which allowed for the inclusion of greenhouse gas emission mitigation from the capture, transport and geological storage of carbon dioxide to be credited under the ETS Directive. From then on, CCS projects could gain ETS credits by avoiding emissions via capture processes and storing the CO_2 permanently.

The ETS Directive has specific monitoring requirements which are implemented under the “Monitoring and Reporting Regulations (MRRs)” (Commission Regulation (EU) No. 601/2012). The MRR document outlines the monitoring requirements that need to be met for a project to qualify for ETS credits. The EU have also published a series of guidance documents on the monitoring and reporting regulation (MRR) (referred to as the Monitoring and Reporting Regulation Guidance or MRGs) which provide further details on the monitoring uncertainty requirements that operators must meet.

3.1.1 Emissions from installations in the CCS chain

The first MRG, “MRR Guidance document No. 1 - general Guidance for Installations” (November 2017) is directed at monitoring, reporting and verification of greenhouse gas emissions, needed to create the trust required for emissions trading. The latest ETS Directive developments have now taken into account the ‘transfer’ of CO_2 between CCS installations with the MRGs Guidance document No. 1 having a specific section on “transferred and inherent CO_2 and CCS”. According to the document, the transfer of CO_2 from one installation to the other needs to be monitored using a mass balance approach. *“The receiving installation has to add that CO_2 to its emissions, before it may again subtract the amount transferred to the next installation or to the storage site”.* If the CO_2 is transferred to a non-ETS installation, the CO_2 has to be accounted for as emitted.

The ETS Directive refers to emissions from and between “*installations*” which are “*a stationary technical unit where one or more activities listed in Annex I are carried out and any other directly associated activities which have a technical connection with the activities carried out on that site and which could have an effect on emissions and pollution*”. The capture, transport and storage of CO_2 are all now included in Annex I and are therefore considered their own separate installations that emissions are transferred between.

A ‘buffering scenario’ is not explicitly outlined in the ETS Directive and hence the findings of this report are solely an interpretation of how monitoring may be conducted to meet current regulations. The ETS Directive does however explicitly cover the monitoring requirements for enhanced hydrocarbon recovery (EHR) operations using CO_2. It is therefore expected that a buffering scenario can qualify for credits under the ETS Directive as similar CO_2 emissions from EHR activities such as the use of oil-gas separation units and CO_2 breakthrough/ production are already covered in the ETS Directive documents:

> *“Each operator of a geological storage activity shall consider at least the following potential emission sources for CO_2 overall: fuel use by associated booster stations and other combustion activities including on-site power plants; venting from injection or enhanced hydrocarbon recovery operations; fugitive emissions from injection; breakthrough CO_2 from enhanced hydrocarbon recovery operations; and leakages.”*
> (ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

The MRRs outline the maximum uncertainties allowed when quantifying the CO_2 emissions throughout the CCS chain. This covers a variety of scenarios including transfer points, injection for storage and leakage. Within the CCS chain the transfer of CO_2 between each installation must meet the continuous emission measurement systems (CEMs) requirements, this will include the injection and production of CO_2 in a buffering scenario. CEM requirements are published in a separate guidance document (MRR Guidance Document No. 7).

3.1.2 Monitoring of back-production

Breakthrough of CO_2 is mentioned as potential CO_2 emission source in MRRs but it is unclear how CO_2 breakthrough in EHR should be monitored and breakthrough is not mentioned in MRGs. The back-production of CO_2 in the buffering scenario is unlikely to be classified as leakage as it is planned and will therefore be more likely to fit into the CEM requirements rather than the requirements of monitoring for leakage. The transfer of CO_2 from the oil-gas separations unit into the transport pipeline to the greenhouses would be considered as emitted, as the greenhouses are not considered an ETS-installation.

3.1.3 Monitoring of leakage

Most monitoring requirements in the MRRs regarding storage refer to ‘leakage’. These requirements will be the same for permanent storage as they will be for the CO_2 to be permanently stored in the buffering scenario. The EU CCS Directive defines leakage as “*any release of CO_2 from the storage complex*.”

The MRGs outline how a monitoring plan should be developed to meet ETS requirements. How this may be applied to the Q16-Maas case study in the Netherlands is outlined in Section 8. Overall this report highlights the monitoring that would need to be undertaken to quantify CO_2 within the storage site to meet European requirements.

4 CO_2 Injection and Production Quantification

Compared to permanent storage, a key element for the buffering concept is quantifying the amount of CO_2 produced for resale and keeping records of the amount of CO_2 injected versus produced to allow the total mass of stored CO_2 to be calculated. The CCS and ETS Directives cover the permanent storage aspect but current regulations do not refer to a ‘buffering’ style scenario.

For permanent CO_2 storage sites the CCS Directive states that the flowrate, pressure, temperature and a chemical analysis of the injected material must be undertaken at the wellhead during CO_2 injection for storage. The quantification of injected CO_2 is also required under the ETS Directive following the CEM regulations.

As discussed in Section 3, for the quantification of injected and produced CO_2 the uncertainty thresholds required under the ETS Directive are outlined in the MRRs and MRGs. The MRGs state that:

> *“CCS installations are monitored using a form of mass balance approach, where some of the CO_2 entering or leaving the installation (i.e. at the transfer points) is monitored using continuous measurement systems… The application of CEMS (Continuous Emission Measurement Systems) always requires two elements:*
>
> - *Measurement of the GHG concentration; and*
> - *Volumetric flow of the gas stream where the measurement takes place.*
>
> *According to Article 43 of the MRR, the emissions are first to be determined for each hour of measurement from the hourly average concentration and the hourly average flow rate. Thereafter all hourly values of the reporting year are summed up for the total emissions of that emission point”*
> (ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

The accuracies required for monitoring injection and production are dependent on how the storage complex ‘installation’ as a whole is categorised under the defined ETS Directive Tier Levels. CO_2 production from a storage installation is not explicitly mentioned in any ETS regulation but is likely to have to meet the same quantification requirements as injection and the requirements of the storage installation as a whole.

Emission sources are tiered (allocated between tiers 1 and 4) dependent on their total emissions size (larger emissions are required to undertake more accurate monitoring):

	Tier 1	Tier 2	Tier 3	Tier 4
CO_2 emission sources	± 10%	± 7.5%	± 5%	± 2.5%
N_2O emission sources	± 10%	± 7.5%	± 5%	N.A.
CO_2 transfer	± 10%	± 7.5%	± 5%	± 2.5%

Table 1: Tiers defined for CEMS, expressed using the maximum permissible uncertainties for the annual average hourly emissions
(ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

To calculate which tier requirement must be met, the installation (i.e. in this scenario storage site) is first categorised dependant on its total average emissions:

- Category A: Annual average emissions are equal to or less than 50 000 tonnes of CO_2(e);
- Category B: Annual average emissions are more than 50 000 tonnes of CO2(e) and equal to or less than 500 000 tonnes of CO_2(e);
- Category C: Annual average emissions are more than 500 000 tonnes of CO_2(e).

For a permanent storage scenario the annual average emissions would be very low, only associated with the emissions from the injection process (compressors etc.) For a buffering scenario the storage installation will have larger emissions as CO_2 produced will be quantified as an emission being transferred to a non-ETS installation.

Dependent on the category assigned the following tier rules then apply:

Source stream	Category A	Category B	Category C
Major	Annex V	Highest	Highest
Major, but technically not feasible or unreasonable costs	up to 2 tiers lower with a minimum of tier 1	up to 2 tiers lower with a minimum of tier 1	1 tier lower with a minimum of tier 1
Major, but still technically not feasible or unreasonable costs; improvement plan (max. 3 year transition)	Minimum tier 1	Minimum tier 1	Minimum tier 1
Minor	highest tier technically feasible and without unreasonable costs (minimum tier 1)		
De-minimis	Conservative estimation, unless a defined tier is achievable without additional effort		

Table 2: Summary of tier requirements for calculation approaches.
(ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

The differences between the associated emissions with processes such as injection versus the production of CO_2 back-produced from the reservoir is that one is classified as a source stream and the other as an emissions source.

An emissions source is defined as a separately identifiable part of an installation or a process within an installation, from which relevant greenhouse gases are emitted, e.g. the back-production of CO_2.

A source stream is defined as the product (e.g. fuel or raw material) that gives rise to GHG emissions at one or more emission sources as a result of its consumption or production:

Source streams[30]: This term refers to all the inputs and outputs which have to be monitored when using a calculation based approach (→see 4.3). The wording is the result of the attempt to quickly express “fuel or material entering or leaving the installation, with a direct impact on emissions”. In the simplest case it means the fuels “streaming” into the installation and forming a “source” of emissions. The same is true for raw materials which give rise to process emissions. In some cases, process emissions are calculated based on a product, such as burnt lime. In this case this product is the source stream. Furthermore the term includes also mass streams going into and coming from the system boundaries of mass balances. This is justified by the fact that mass streams entering and leaving the installation are treated in principle by applying the same requirements[31] as for other source streams, as can be concluded from sections 4.3.1 and 4.3.2 below.

Figure 2: Source Emission definitions as given in ETS Directive’s MRGs.
(ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

The source streams highlighted in Figure 2 classify minor sources are defined as less than 5000 tonnes of CO_2 or less or less than 10% of total emitted items. De-minimis is defined as less than 1000 tonnes or less than 2%. And anything larger is defined as major. The smaller the installation emissions as a whole and the smaller the source stream the higher uncertainties in quantification that are allowed.

For example, if the installation as whole emits 20,000 tonnes per year (Category A), a di-minimis source would be classified as anything lower than 400 tonnes (2%). For this emission a conservative estimation can be made for its quantification unless Tier 1 of 10% uncertainty can easily be met. For an installation with much larger emissions, 800,000 tonnes a year (Category C) a major source would be anything larger than 80,000 tonnes per year and would have to meet Tier 4 uncertainty requirements of 2.5%.

The overarching rule stated in the MRGs is that the operator should apply the highest tier defined for each installation. For the large-scale production of CO_2 from a storage site this will therefore have to meet 2.5% uncertainty requirement. But as demonstrated in Table 2 for smaller sites and if unreasonable costs or technical requirements can be demonstrated this uncertainty requirement may be widened.

4.1 Flow Meters and Sensors

In order to calculate the total mass of CO_2 being injected and produced a flow-meter is required for continuous measurement. The measurement for compressed CO_2 flow can be divided in three types of techniques and instruments:

- Differential pressure meters
- Volumetric meters
- Mass flow meters

Assuming the most stringent tier assignment the accuracy required in the ETS Directive for CO_2 flow metering would need to be in the range of ±2.5% by mass (Table 1). A review of CO_2 storage literature shows for flow metering the Coriolis Flow meter (OPTIMASS 6000-S08 provided by KROHNE Ltd) is regularly used in EHR applications. The Coriolis meter has also been regularly researched in relation to CCS applications and experimental demonstrations have met the accuracy requirements of the ETS Directive (Nazeri et al., 2017). For accurate flow measurements the pressure, temperature and chemical composition of the CO_2 at the well head will have to monitored, as required by the CCS Directive (Annex II). Experiments have shown that impurities in the CO_2 stream can increase the uncertainty of the flow meter and hence knowing the chemical composition of the stream is beneficial. A benefit of the Coriolis technique is that density and viscosity measurements are not required to calculate mass flow which other techniques require.

Various measurement standards advise to place the meter at a location in the system where the flow velocity profile is fully developed (i.e. in order for this to occur the fluid must travel through a length of a straight pipe). The ISO 10780 regarding stationary source emissions 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. (CATO, 2010).

An international standard has been published for the quantification and verification of CO_2 storage (ISO 27915) which also includes detailing on the metering required for a CO_2 storage system. As with the CCS Directive it advises measurement of the temperature, pressure, fluid composition of CO_2, injection rates, mass of CO_2 injection and re-injection when qualifying for CO_2 emissions reduction. No specific recommendations are given on metering equipment. (ISO 27915, 2017)

Although experimental results demonstrate suitable accuracies, some issues have been experienced in the oil and gas industry with the recycling and quantification of CO_2 injection and production. Based on EHR operator experience (verbal communication), the sum of CO_2 injection volumes from wellhead flow meters does not conform exactly to the total volume of purchased CO_2. This inconsistency not only comes from equipment errors in CO_2 volume calculations that are intrinsic to the flow meters used in oil and gas operations but also from equipment calibration issues (US DOE, 2016), although no exact uncertainties are stated.

The MRGs also state that:

> *"Concentration measurements may be difficult in gas streams of very high CO_2 concentrations. This is in particular important for measurement of CO_2 transferred between installations for the capture, pipeline systems for the transport and installations for geological storage of CO_2. In such cases CO_2 concentrations may be determined indirectly, by determining the concentration of all other constituents of the gas and subtracting them from the total"*
> (ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

Instead of measuring the CO_2 concentration this allows instead for a measurement of the concentration of the impurities to be taken. This is an easier but less accurate technique as you only know the impurities that you measure. There might be impurities for which the measurement device is not suitable and are then unaccounted for.

Experimental results using flow meters have demonstrated the most stringent ETS Directive requirements can be met. In practice, a review of oil and gas literature has demonstrated that calibration errors and varying parameters such as impurities can lead to larger uncertainty measurements.

4.2 Chemical Analysis

A chemical analysis must be undertaken of the injected CO_2 under the CCS Directive. The chemical composition is required at injection to improve flow meter accuracy. For the buffer concept, it is useful to measure the composition after back-production, to validate the modelled CO_2 behaviour in the reservoir due to chemical interactions within the reservoir. Furthermore, it is necessary to measure the composition after cleaning up of the contaminated back-produced CO_2 stream for re-use purposes (see section 8.2).

As with accurate metering, accurate sampling will also require the CO_2 to be in a single phase to prevent preferential sampling of one phase. For compressed CO_2 flows, it is not feasible to directly measure the CO_2 concentration in-situ (from the pipeline). Depending on pressure and temperature, the CO_2 will have different densities, which makes it difficult to perform proper correction calculations for the concentration measurements. Also spectral absorption line broadening in the infrared will result in non-linear behaviour as a function of concentration. A 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 (CATO, 2010). The 2010 CATO report goes into more detail regarding specific techniques for analysis but in summary there two methods. Firstly, infrared techniques, which are commercially available and measure continuously, but this is not relevant for compressed CO_2 as explained above. Secondly, for intermittent (non-continuous) requirements, grab sampling (i.e. at one location and one point in time) followed by gas analysis on a chromatograph can be used. A gas chromatograph analysis for natural gas in accordance with ISO 6974 will measure the typical components of natural gas and is not applicable to CO_2 concentrations above 8.5% (ISO 6974-5). Either proper standardization of gas with high CO_2 concentration, or dilution by CH_4 and back-calculation needs to be applied.

It is also important to know the chemical composition of the back-produced CO_2 stream as this data will help improve the flow metering accuracy. The quality of the CO_2 required for re-sale will be dependent on the end-use of the product, e.g. food grade CO_2 will have to be of a higher quality than that required for enhanced hydrocarbon recovery use, and will also impact the quality monitoring requirements.

The ENOS deliverable D4.3 (Koenen and Hofstee, 2017) reported on the expected chemical processes that would take place in a 'buffering' storage scenario in a depleted hydrocarbon field and the predicted composition of the back-produced CO_2. The findings of the study are given in more detail in Section 8.2 of this report with regards to the Q-16 Maas case study. In summary the main factors impacting the chemical composition of the back-produced CO_2 will be the interaction with remaining condensates within the reservoir (if injecting into a depleted hydrocarbon field). Temperature will also have a large impact with low temperature conditions increasing the risk of H_2S formation due to increased microbial activities. Metals are not likely to be a problem for the composition of the CO_2 post separation as the metals will precipitate when the CO_2 transitions from gas to liquid phase. The separation technologies required to filter the CO_2 will depend on the composition of the extracted CO_2 and the desired end-use of the product.

4.3 Separation Technologies

In order for CO_2 to be produced and sold a separation process must be undertaken which will remove the impurities in the produced CO_2 and separate CO_2 from and residual hydrocarbon gases. The requirements for the separation of CO_2 and the end quality necessary will be case specific dependant on the end use, e.g. for food production purposes. The separation technology process is also important for the accounting process as dependant on the technique used it can be energy intensive and have associated emissions that would need to be taken into account.

Separation is already undertaken during EHR projects where CO_2 is separated from the produced gas stream and separated for recycling and reinjection. During EHR the process of recovering, separating, recompressing, and reinjecting the CO_2 in an EHR operation is often referred to as 'CO_2 recycle'. For the re-injection of CO_2 in EHR product the main focus is the removal of hydrocarbons for sale and the purity of the CO_2 for re-injection is not paramount. Because there are energy requirements and potential losses of CO_2 during the CO_2 recycle process, the GHG emissions associated with CO_2 EHR/CCS need to account for the energy use and fugitive emissions inherent in the operation (Allinson et al, 2017).

There are three main techniques for separation:

1. Amine Gas Sweetening
2. Membrane Separation
3. Ionic Liquids

Amine gas sweetening is most commonly used with a long history in the oil production industry and has been utilised at Sleipner in the Norwegian North Sea for over 15 years. CO_2 is absorbed by the amine (reducing the initial CO_2 content from 9 mole % to 3 mole % to meet required pipeline specifications) and then released via a heating process known as regeneration. Previously the captured CO_2 was released to the atmosphere but following increasing carbon taxes Equinor decided to develop the field with re-injection of the CO_2 back into the subsurface. At the Sleipner amine facility the CO_2 removal and injection system requires 160MW for heating, cooling, pumping and compression. This energy requirement is around 41% higher than was originally planned. Of the total160MW energy demand, 75% is used for CO_2 removal and amine regeneration. (SCCS, 2014)

ENOS deliverable D4.3 (Koenen and Hofstee, 2017) and D4.4 (Koenen et al., 2018) regarding reactive transport Q16-Maas buffering scenarios concluded that the main contaminants from the reservoir being back-produced with the CO_2 were hydrocarbons, primarily methane. An evaluation of the proposed separation technologies for the CO_2 buffer case for re-use in greenhouses is reported in ENOS deliverable 4.9 (to be finalized).

4.4 Emissions During Injection and Production

The ETS Directive's MRGs state:

> *"the description of the installation in the monitoring plan should list all emission points by describing the points where the greenhouse gases are actually released from the installation, including for fugitive emissions, if applicable."*
> (ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

Aside from the deliberate back-production of CO_2, the emissions in a buffering scenario may come from the following sources:

- Compression at injection site (i.e. from fuel required to power facility)
- Production process (e.g. artificial lift)
- Gas separation
- Leakage from equipment prior to and during injection, and during and after back-production (fugitive emissions)
- Leakage from the storage reservoir

Leakage from the storage reservoir is addressed separately in Section 6. Regarding the injection and back-production processes the CO_2 emissions from above ground activities requiring energy production (e.g. compression) 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 MRGs (EU, 2010 & CATO 2010).

CO_2 compression is the most energy intensive component of any CO_2-EHR operation and will therefore provide a significant contribution to emissions in the CCS process. In US CO_2-EHR projects compression is thought to use around 60-80% of the electricity demanded by operations (SCCS, 2013). The production process energy requirements are highly site specific and driven by reservoir conditions. Lower pressure in the reservoir and higher viscosity production fluids will increase the energy required to produce the CO_2 and artificial lifting to draw reservoir fluids to the surface may be required.

Fugitive emissions arise from unintentional leaks from compressor seals, leaking pipes, turbines, and valves on many different pieces of operational equipment. Very little data is currently available relating to fugitive emissions from CO_2-EOR or CCS projects, especially offshore.

5 Storage Quantification and Monitoring during Production

For a permanent storage scenario the amount of CO_2 injected is the same amount that would qualify for ETS credits (if no leakage occurs). In a buffering scenario, in order to qualify for ETS credits, the amount of CO_2 back-produced must be subtracted from this total as it does not qualify for credits. As stated in the ETS Monitoring and Reporting Regulations:

> *"…in the case of a "CCS chain" (i.e. several installations together performing the capture, transport and geological storage of CO_2), the receiving installation has to add that CO_2 to its emissions … before it may again subtract the amount transferred to the next installation or to the storage site. Thus, CCS installations are monitored using a form of mass balance approach, where some of the CO_2 entering or leaving the installation (i.e. at the transfer points) is monitored using continuous measurement systems."*
> (ETS Directive MRR Guidance document No. 1, 2017 (MRGs))

Naturally, a storage permit needs to be obtained under the CCS Directive and the operator needs to fulfil all requirements related to permanent storage in order to quality for ETS credits. In order for a temporary storage reservoir to gain credits for the associated permanent storage of CO_2, it must accurately quantify how much of the total CO_2 injected has been permanently stored. This means that the amount of CO_2 injected and produced at the wellheads needs to be quantified (as outlined above) so that the difference between the two calculates the amount of CO_2 permanently stored.

5.1 Quantification

To calculate the quantity of CO_2 stored in the reservoir the data from injection and production is required as outlined in Section 4. The net CO_2 retained can be computed for a buffer field as a percentage of total injection:

$$\text{CO2 Stored} = \frac{\text{Cumulative CO2 Injected} - \text{Cumulative CO2 Produced} - \text{Cumulative CO2 vented}}{\text{Cumulative CO2 Injected}}$$

This technique is outlined by the World Bank for enhanced oil recovery calculations and outlines the metrics required to make calculation which are (World Bank, 2016):

- Fluid Production and Injection by Field – this is a key metric for performance including production of oil, brine, natural gas, and CO_2 over specific periods, such as daily, weekly and yearly since start;
- Pure CO_2 (purchased or make-up CO_2) compressed at a CO_2 compression facility;
- Produced, vented and recycled CO_2;
- Injected CO_2 by well and by field ;
- Composition analysis of recycled gas streams through periodic sampling.

The amount of fluid injected and produced at the site needs to be quantified and monitored as outlined in Section 4. A buffering style scenario is similar to an EHR scenario as CO_2 is back-produced, the amount of which has to be subtracted from total injected CO_2.

The international standard "ISO 27915 Carbon dioxide capture, transportation and geological storage: Quantification and verification" also outlines best practices for the quantification of CO_2 in the storage system. It states that the following surface equipment emissions should also be quantified:

- fuel consumed in the operation of surface injection or re-injection (and possibly production) equipment;
- fugitive emissions including: leaks and venting in the injection or re-injection system such as at the distribution manifold at the end of pipeline; distribution pipelines to wells and compression or pumping apparatus; leakage at the production well head;
- fuel consumed/energy used for monitoring and measurement devices.

Figure 3 (below) summarises the CO_2 flow in a closed-loop EHR cycle. This is a similar analogy to the 'buffer' style scenario with some minor differences. As the legislation is already in place for EHR purposes the monitoring requirements for a buffering scenario are likely to be very similar.

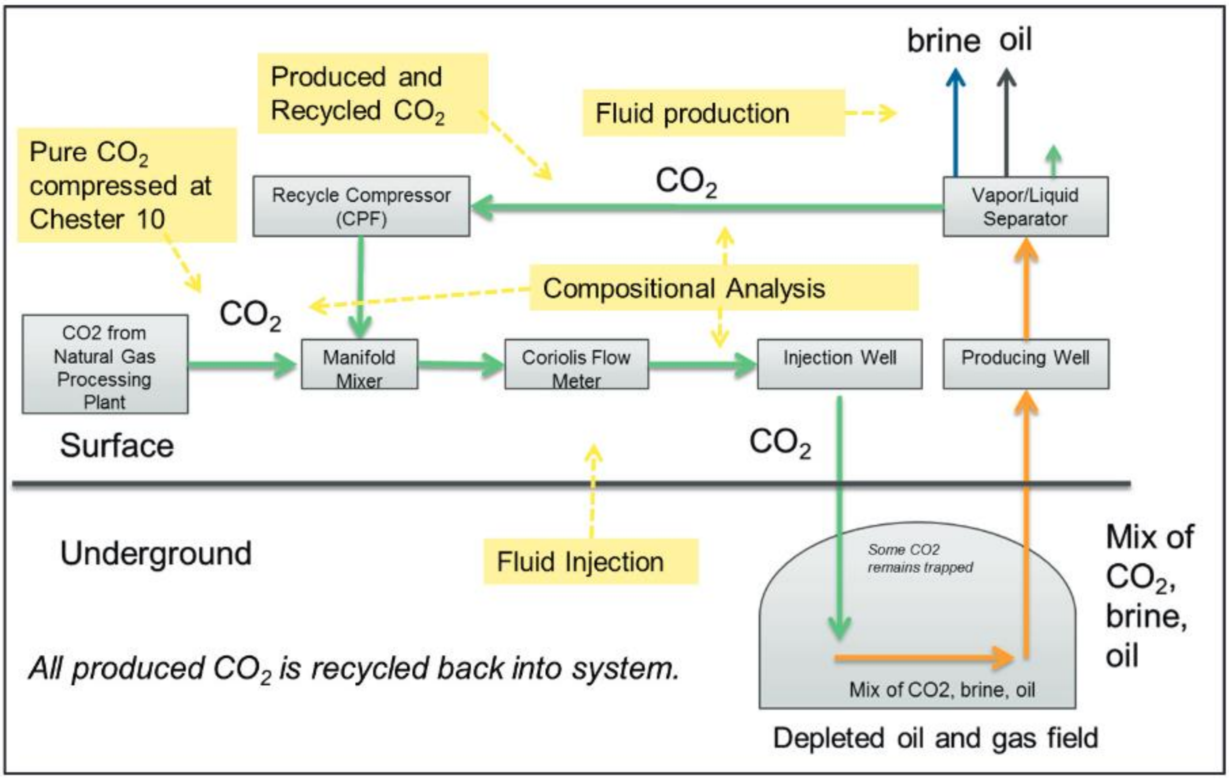

Figure 3: Example diagram of closed loop CO_2-EOR cycle (source: Gupta et al., 2014)

The monitoring of stored CO_2 in the reservoir would not be undertaken any differently to that required for a permanent storage project. Should leakage occur this will need quantifying as outlined in Section 6 but demonstrating that no leakage is occurring falls under the CCS Directive requirements which would apply in the same manner to both buffering and permanent storage projects.

6 CO_2 Leakage from the Storage Reservoir

The CCS Directive requires monitoring of the CO_2 storage complex in order to detect any leakage from the complex as early as possible and assess any potential environmental impacts. Monitoring requirements to indentify potential leakage are often categorised into two areas, to demonstrate conformance and containment. If a leakage occurs a contingency monitoring plan to assess the environmental impact is required under the CCS Directive, often referred to as the contingency monitoring plan. Once a leakage has been identified the ETS Directive requires for monitoring to quantify the amount of CO_2 leakage occurring. The early detection technologies are not covered by the ETS Directive's MRGs but the guidelines do cover how to quantify the amount of CO_2 leakage once it has already started to occur.

Containment monitoring technologies required to meet CCS Directive requirements are unlikely to differ between permanent storage and a buffering style scenario. The monitoring techniques required to demonstrate containment are usually driven by site specific risks. A risk assessment for either a permanent storage or a buffering scenario is likely to highlight the same risks for the same storage site. The main difference is the inclusion of a production well although these will be present on EHR sites and will be integrated into the containment monitoring plan in the same way.

Conformance monitoring (to check that modelled behaviour is conforming with operational data) will have a slight variation as modelled behaviour of the reservoir will differ for a buffering scenario where CO_2 is being back-produced. Large quantities of CO_2 leaving the reservoir will affect the fluid behaviour in the reservoir and conformance modelling may therefore need to be adapted accordingly.

The CCS directive requires for the pressure and temperature of the reservoir to be monitored as these parameters help improve monitoring accuracy. For example, at the Ketzin site in Germany, a vital part of the operational pressure and temperature data came from the downhole P-T measurements, which the project subsequently recommended for any CO_2 storage site. Without this downhole information, it would not have been possible to provide the complete picture of CO_2 injection.

Under the ETS Directive if leakage does occur it must be monitored and quantified and the credits will be deducted for the CO_2 no longer stored. For both a permanent storage and buffering scenario, should a leakage occur, the same requirement for leakage quantification would need to be met. This contingency monitoring plan for when leakage does occur will be site specific and most importantly depend on how and where the leakage is occurring.

6.1 Leakage Quantification

The ETS Directive requires leakage of CO_2 to be quantified and credits surrendered for any leakage that occurs outside of the 'storage complex'. 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.

The MRR's state the following regarding CO_2 leakage from the storage reservoir (Figure 4):

Emissions and release to the water column shall be quantified as follows:

$$CO_2 emitted\ [t\, CO_2] = \sum_{T_{Start}}^{T_{End}} L\, CO_2 \left[t\, CO_2/d\right]$$

Where:

L CO_2 = the mass of CO_2 emitted or released per calendar day due to the leakage in accordance with all of the following:

(a) for each calendar day for which leakage is monitored, each operator shall calculate L CO_2 as the average of the mass leaked per hour [t CO_2/h] multiplied by 24;

(b) each operator shall determine the mass leaked per hour in accordance with the provisions in the approved monitoring plan for the storage site and the leakage;

(c) for each calendar day prior to commencement of monitoring, the operator shall take the mass leaked per day to equal the mass leaked per day for the first day of monitoring ensuring no under-estimation occurs;

T_{start} = the latest of:

(a) the last date when no emissions or release of CO_2 into the water column from the source under consideration were reported;

(b) the date the CO_2 injection started;

(c) another date such that there is evidence demonstrating to the satisfaction of the competent authority that the emission or release into the water column cannot have started before that date.

T_{end} = the date by which corrective measures in accordance with Article 16 of Directive 2009/31/EC have been taken and emissions or release of CO_2 into the water column can no longer be detected.

Figure 4: Excerpt from MRR regarding leakage (ETS Directive Monitoring and Reporting Regulations, 2018 (MRRs)).

The ETS MRRs state that *“The operator shall quantify the amount of emissions leaked from the storage complex for each of the leakage events with a maximum overall uncertainty over the reporting period of 7.5 %”.* The ‘storage complex’ means the storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations.

To date, no leakage has occurred at any offshore CO_2 storage site meaning the monitoring of leakages has yet to be tested at an actual commercial site. The techniques available for CO_2 leakage quantification were extensively reviewed by IEAGHG in 2012 (IEAGHG, Korre et al., 2011). The review concluded that for offshore sites, for a leakage underground in the reservoir and overlying formation that 4D seismic methods currently offer the best potential for quantification although large uncertainties are involved. It was hypothesised that uncertainties could be reduced though with the use of supplementary techniques such as gravimetry and EM and more downhole sensors.

For leakage at the seabed (the focus for quantification regarding the ETS credits) the IEAGHG report reviewed hydroacoustic methods, seawater chemistry methods and bubble stream chemistry methods. The report concluded that hydroacoustic techniques (e.g. sidescan sonar and echo-sounding) were suitable to detect leakages and were cost effective at covering large areas in short periods of time. For quantification the accuracy was thought to be more of a rough estimate with other technologies needed to improve uncertainties. Seawater chemistry monitoring was also highlighted as having the potential to quantify CO_2 leakages but also with high uncertainties mostly relating to the potentially large variabilities in the background corrections required. Bubble stream chemistry can also be used, where streams detected by hydroacoustic methods are then directly sampled. Further work is required to develop reliable quantitative monitoring systems for CO_2 leakages, incorporating dissolved gas sensors in addition to pH probes, and active and passive acoustic instruments for bubble stream detection. The new systems should be tested on mobile devices (ROVs and AUVs), and verified for use at sites with lower emission rates (IEAGHG, 2012).

As no offshore leakage has occurred, the majority of data available regarding the quantification of CO_2 leakages has been obtained from experimental and research projects. For example, the STEMM-CCS project is currently undertaking experimental work in the North Sea to detect, trace and quantify CO_2 leakage by creating a deliberate release and injecting CO_2 into the shallow subsurface. Quantification of CO_2 leakage at the seabed has also been undertaken at natural seepage sites to simulate CO_2 storage scenarios. For example Gros et al., 2019 studied Italian seepages at the Aeolian Islands and developed a new reaction model to help quantify temporarily variable plumes of dissolved CO_2. The potential of this technique has been demonstrated at the natural analogue site near Panarea in the South Tyrrhenian Sea (Caramanna et al., 2011).

There is limited data regarding the uncertainties of these quantification techniques and generally the methodologies are still being researched and in the process of development. The ETS Directive requirement of 7.5% for leakage quantification may therefore be difficult to ascertain at present.

The ETS Directive has taken into account that some accuracy requirements may not be achievable in certain circumstances either due to costs or technical feasibility:

> "…*it has been recognised that special circumstances may exist in installations under which applying the tier system is technically not feasible, or leads to unreasonable costs for the operator. Although there might be other reasonably precise methods of monitoring, these circumstances would render the operator non-compliant with the MRR….In order to avoid such unwanted "pseudo-non-compliance", the MRR (Article 22) allows the operator to apply non-tier methodology (also known as "fall-back methodology".)"*
> (ETS Directive, 2003)

If it can be proved the 7.5% is not technically feasible it may be possible for the operator to prove that the total installation quantification is below 7.5% once the larger uncertainty of leakage quantification has already been taken into account.

> *"Where the above conditions are met, the operator may propose in the monitoring plan an alternative monitoring methodology, for which he can demonstrate that it allows achieving the required overall uncertainty level for the emissions of the total installation."*
> (ETS directive, MRR Guidance document No. 1, 2017 (MRGs))

7 Developing a Monitoring System for Accounting Purposes

Many reviews have been conducted outlining how to develop a monitoring plan for a permanent CO_2 storage site (e.g. published by IEAGHG, US DOE, GCCSI). The aim of this report is to highlight the specific requirements for monitoring a combined permanent storage and buffering scenario project, especially for accounting purposes. This section outlines generally applicable guidelines to design a monitoring system for combined buffering and storage projects. The key attributes of a monitoring plan for a buffering style scenario are outlined below, also highlighting key areas where CO_2 quantification is required for accounting purposes. A case study on how to develop a site specific monitoring plan is presented in Section 8 on the Q16 Maas site in the Netherlands.

For shallow subsurface monitoring, baseline monitoring is the first monitoring to be undertaken at a site prior to CO_2 injection. Baseline data is key for establishing natural CO_2 fluctuations to prevent false leakage attribution once injection has begun. The best practice for baseline monitoring plans developed for permanent storage projects will also be appropriate for a site planning to undertake buffering. Baseline monitoring plans are especially important in marine environments where large variations occur naturally. Seabed morphology and CO_2 variations need to be well characterised to allow for more accurate CO_2 quantification at the seabed should leakage occur. Depleted oil and gas reservoirs and EHR projects will typically require greater assessment of baseline conditions to establish reservoir conditions before injection starts. This is due to their altered state (e.g. pressure changes) which may not have reached equilibrium by the time of the project start (SCCS, 2015). No CO_2 accounting is required at this stage.

Injection phase monitoring during the operation of a buffering project will require continuous monitoring and quantification of CO_2. This is the most important stage for CO_2 quantification where mass balances must be conducted to calculate the CO_2 injected that is being permanently stored versus how much CO_2 has been back-produced for sale. Compared to permanent storage CO_2 quantification monitoring will also be required at the production well (should one be used) to account for CO_2 losses from the reservoir in a buffering scenario. This will require flow meters at the production well and the quantification of CO_2 produced in the separation process. Periodic calculation of net CO_2 retained will aid in tracking CO_2 storage performance. Fugitive emissions and emissions from the injection processes will also need to be quantified, which would also be the case for a permanent storage project, e.g. from compression units. A buffering scenario will have additional fugitive emissions from the separation technology utilised to separate pure CO_2 from the back-produced material. The injection phase will also require conformance and containment monitoring in line with the CCS Directive. This will predominantly be the same as best practices for a pure storage project where geophysical methods will be required to prove leakage is not occurring. The main difference is the presence of a CO_2 producing well which need monitoring, which has been conducted in many CO_2-EHR projects.

Post closure monitoring will follow the same procedure as pure CO_2 storage project. In a buffering scenario injection for permanent storage may finish whilst production in the buffering scenario continues, or vice versa.

A summary of monitoring requirements as different project phases is given below in Table 3.

Aspect to be Monitored	EU Regulatory Requirements		
	Permanent Scenario	**Buffering & Permanent Storage Scenario**	**EHR & Permanent Storage Scenario**
CO_2 flow entering storage site	All scenarios require CO_2 to be delivered to site and monitoring requirements will be the same for all projects. Chemical composition analysis is required as the CO_2 flow enters the site under the CCS Directive and accurate metering is required under both the CCS and ETS directives.		
Injection operations	All scenarios will require flow metering to quantify CO_2 injected into the reservoir. Continuous pressure and temperature monitoring is required by the CCS Directive and accurate quantification is required under the ETS Directive.		
Production operations	N/A	CO_2 produced from the reservoir must be quantified via metering for the mass balance required under the ETS Directive.	CO_2 produced from the reservoir during breakthrough must be quantified via metering for the mass balance required under the ETS Directive. Additional metering of the amount of CO_2 separated and re-injected must also be quantified.
Surface facilities	The only surface facilities will be those associated with injection. For quantification under the ETS directive fugitive emissions from compressing and injecting CO_2 must be calculated.	For quantification under the ETS directive fugitive emissions from injection and production operations must be calculated. Additional production emissions which must be monitored will include artificial lift technologies (if used) and CO_2 separation technologies.	For quantification under the ETS directive fugitive emissions from injection and production operations must be calculated. Additional production emissions which must be monitored will include artificial lift technologies (if used) and CO_2 separation technologies. Venting may also occur during hydrocarbon production which will require metering.
CO_2 flow exiting storage site	N/A	CO_2 composition monitoring will be required to confirm CO_2 is at quality specified for re-sale purposes.	N/A
CO_2 in the reservoir	Conformance and containment monitoring will be required under the CCS Directive for any projects storing CO_2 underground to ensure storage has no impact to the environment and any potential leakage is identified. The ETS Directive requires quantification of the CO_2 in the reservoir. This will be done via mass balance calculations and monitoring of CO_2 production and injection.		
Potential Leakage	Contingency Environmental monitoring (if a leakage is detected) is required under CCS Directive for all projects storing CO_2 underground. This is to ascertain any environmental impact caused by an identified leakage to groundwater, water column or atmosphere. Quantification of the leakage will also be required under EU ETS for all projects.		

Table 3: Overview of Requirements

The World Bank (2016) also published the following accounting recommendations (in a study regarding potential CO_2-EHR with permanent storage in Mexico) outlining further detail on how monitoring could need to be conducted and improved on given current best practices:

- **Review CO_2 flow metering equipment and flow circuit to ensure all streams are tracked adequately and reliably.** This may include metering CO_2 flow rates at injection wellheads, periodic measurements of CO_2 density, CO_2 produced with EOR, and recycled CO_2. Develop a process flow diagram illustrating metering locations, equipment, pipelines, CO_2 recirculation, and interconnections for the CO_2 -EOR system. Plan for periodic measurements of CO_2 flow stream chemistry at key locations. Plan for annual calibration of metering equipment.
- **Develop plan for accounting for CO_2 net balance based on relevant metrics**. This plan should identify key locations where CO_2 is metered for both injection wells and production. The plan may also include options for examining leakage/fugitive emissions at wellheads, and how this relates to CO_2 storage accounting. The plan should examine accuracy of flow metering equipment in relation to accounting goals. Periodic calculation of net CO_2 retained will aid in tracking CO_2 storage performance and CO_2 -EOR operations.
- **Plan for periodic (monthly) reports on CO_2 storage volumes**. Develop reporting template for accounting CO_2 storage volumes, injection pressures, monitoring well data, CO_2 composition, and operational parameters. Based on net CO_2 retained in the reservoir, track the total CO_2 retained in the reservoir over time to help determine any anomaly in the CO_2 storage process, such as migration out of the storage zone.
- **Consider CO_2 leakage potential in surface EOR system (pipelines, oil processing, wellheads).** This effort may be necessary to fulfil CO_2 storage credits. Leakage monitoring may include analysis of fugitive emissions.

7.1 EOR Midwestern USA (MRCSP) Case Study

The Midwest Regional Carbon Sequestration Program (MRCSP) have conducted CO_2 accounting at an active CO_2-EHR site. The project have published their learnings regarding monitoring of depleted oil fields as part of CO_2 injection for EHR (Gupta et al., 2017).

As shown in Figure 2 the parameters of the project monitored for accounting purposes were (Gupta et al., 2017):

- Daily pure CO_2 availability from gas processing plant;
- Daily production of recycled CO_2 gas from active EHR reefs;
- Daily injected quantity of pure and recycled CO_2 in all EHR reefs;
- Production of oil and brine;
- CO_2 composition, tubing/casing pressures, compressor station parameters, etc.

The project reported a small discrepancy in their accounting method of 3% between calculated CO_2 and measured CO_2 leaving the central processing facility (where numerous sites are interconnected). This could be attributed to measurement uncertainties and system losses during processing.

8 Q16-Maas Case Study

The Dutch gas and condensate field Q16-Maas is currently under consideration for the development of a CO_2 buffer for CO_2 utilisation in greenhouses to enhance crop growth. The site is in the final stages of operation and has the optimal location and size for the planned CO_2 buffering for use in greenhouses in the Westland area. The field was operated by OranjeNassau Energie (ONE) with Energie Beheer Nederland B.V. (EBN), TAQA offshore B.V. (TAQA) and Energy Investments B.V. (EN) as joint venture partners and production began in 2014.

The site is a condensate-rich gas reservoir located just offshore from the Rotterdam Port area and has an estimated storage capacity of about 1.8 Mt CO_2. This large buffer will offer storage for industrially produced CO_2 in the wintertime and back-production in summertime for greenhouse horticulture companies and thus guarantee the security of supply with increasing demand for CO_2.

Underground buffering is the only solution considering the scale of the buffer capacity needed. A similar buffer for CO_2 storage could also be necessary for other uses and for collecting emissions before sending them to larger storage sites, including offshore storage locations. Deliverable D4.4 (Koenen et al., 2018) of the ENOS project concluded from reservoir and well dynamics simulations that a maximum flow rate of 20 kg/s of CO_2 from the reservoir could be feasible. This would allow the buffering scenario to provide 250-315 ktonne extra in summertime compared to current supply, an increase of 50-63%.

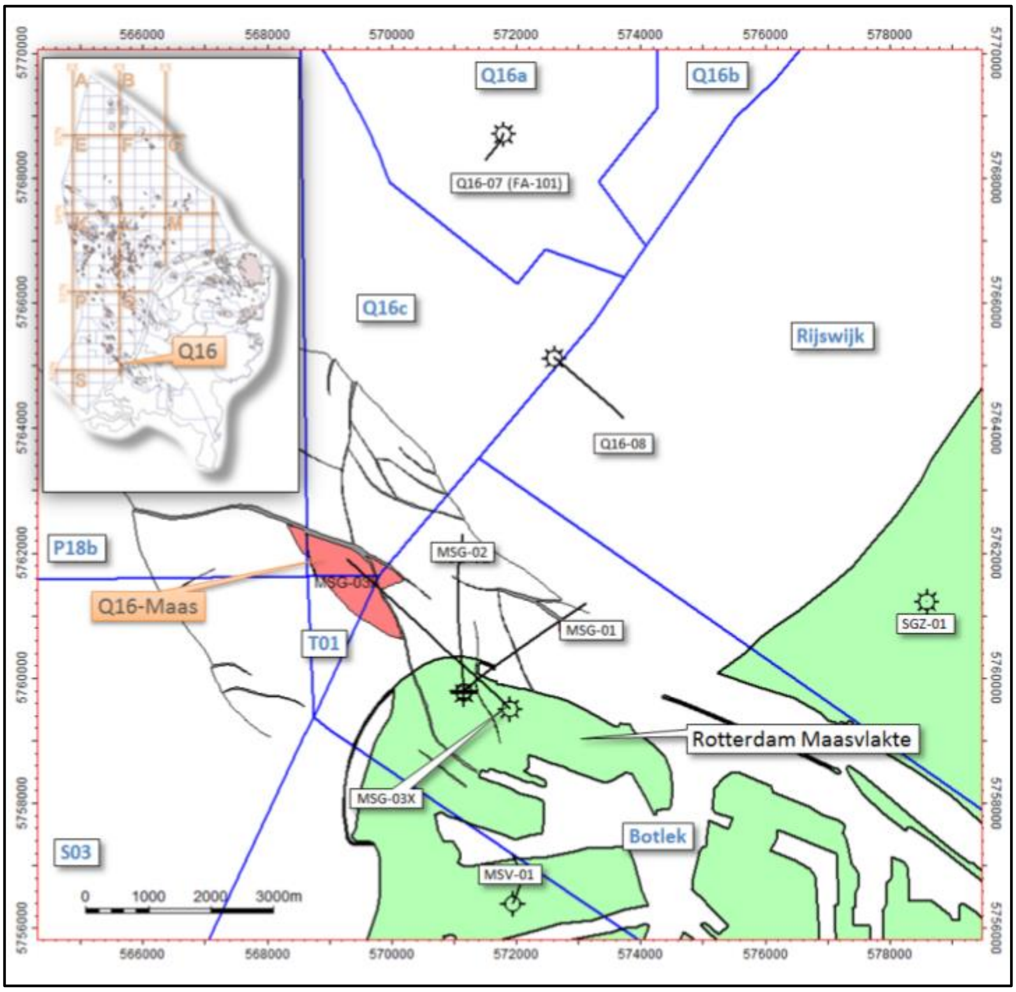

Figure 5: Location of the Q16-Maas Field (J. Schut, 2017)

Figure 6 blow shows the buffer chain for temporary CO_2 storage in the Q16-Maas and back-production for re-use in the greenhouses. The locations along the chain for monitoring equipment for accounting purposes related to back-production are shown as well as sampling locations for chemical analysis for the CO_2 composition.

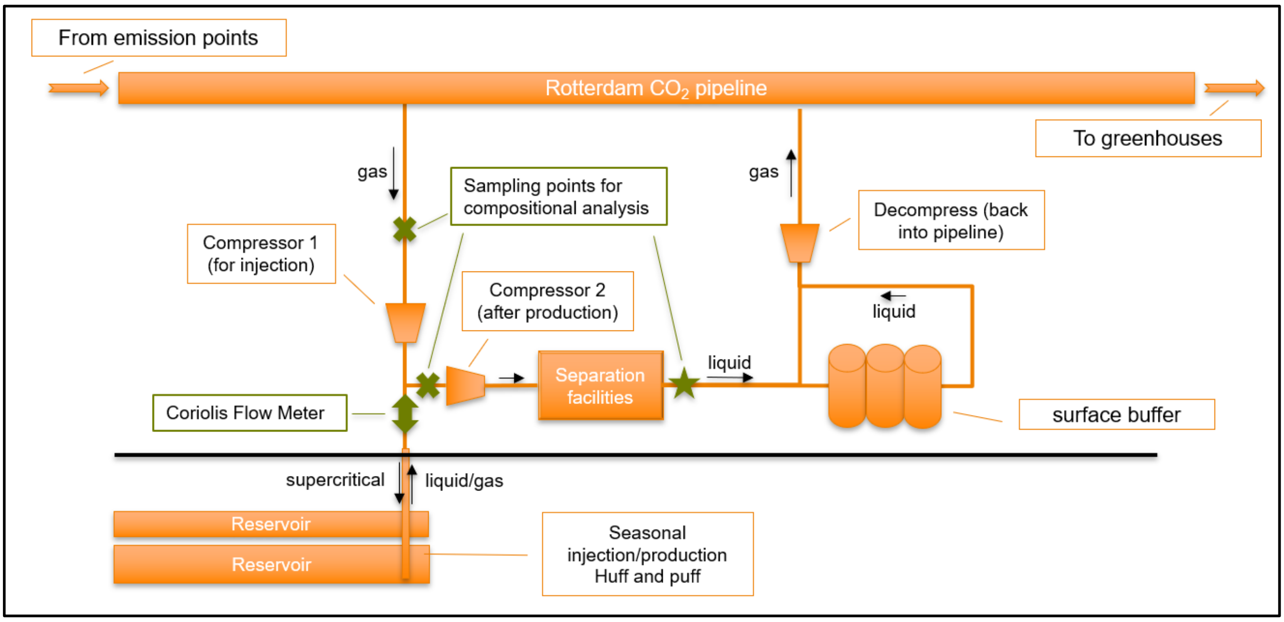

Figure 6: Schematic representation of the buffer chain for re-use in greenhouses. The Coriolis flow meter measures the CO_2 flow during injection in winter and during back-production in summer. The green crosses represent sampling points for chemical analysis required for accounting purposes. The green star represents a sampling point for chemical analysis required to demonstrate compliance with greenhouse specs. (Additional information on the buffer chain can be found in ENOS deliverables D4.4 (Koenen et al., 2018) and D4.9 (to be finalized).)

8.1 Monitoring Plan for Q-16 Maas CO_2 Buffering and Storage

CATO proposed a monitoring plan for the Q16-Maas site for permanent CO_2 storage for the now ended ROAD project. The report focuses on a permanent storage and does not consider a buffering scenario. This included an initial brief risk assessment associated with the major potential fluid migration pathways: the faults, caprock and well integrity. Reservoir model simulations were also undertaken to assess the behavior of CO_2 for various potential injection scenarios. Overall the report concluded:

- Storage of CO_2 in Q16-Maas is feasible and no fundamental problems were identified;
- CO_2 can be stored safely and securely in the field, provided injection pressure and temperature are within safe limits. (The limits are discussed in detail within the report);
- Due to the active aquifer, monitoring the behavior of CO_2 in the reservoir is more challenging than in fields without such an aquifer.

In this report, these plans are developed a step further, for the case of a buffering scenario. A step-by-step approach for developing a monitoring plan is outlined in the ETS Directive's MRGs. This is included below (original text from the MRGs highlighted in blue) with suggestions of how the Q16-Maas could meet the ETS Directive's requirements in a combined buffering and permanent storage scenario.

1. Define the installation's boundaries. Operators of incumbent installations should be aware that the scope of the EU ETS Directive (its Annex I) has been updated during the EU ETS review. Therefore the boundaries should be re-evaluated before the start of the new ETS period in 2013.

The spatial boundaries of plants, equipment and geological formations for CCS are outlined in ISO 27915:

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

Defining the geological storage complex, the ISO TR 27915 states:

> *"The storage system primarily includes the storage complex, composed of two main underground geological elements: a) the reservoirs or geological systems where CO_2 is injected and b) the caprock (or seals) that is (are) necessary to maintain the safety and integrity of the storage. Overlying geological and underlying geological layers are typically outside the storage complex …. however, they may be considered for monitoring activities or for the purpose of measurement of leakages/emissions."*

Detailed geological evaluation combined with reservoir simulations are needed to define the boundaries of the storage complex according to the definition of the CCS Directive. ENOS deliverable D4.4 (Koenen et al., 2018) reports on reservoir simulations for the purpose of evaluating the composition of the back-produced stream. An assessment of the storage complex needs to be performed for the purpose of a monitoring plan.

For the overall buffer concept, the surface facilities should be included in a full chain assessment, starting at the capture plant and ending at the greenhouses. Along the entire chain the required installations need to be identified and monitored in accordance to the ETS Directive's "MRR Guidance document No. 1 - general Guidance for Installations" and "MRR Guidance document No. 7 - Continuous Emissions Monitoring Systems (CEMS)". This is out of the scope for the current study.

2. Determine the installation's category based on an estimate of the installation's annual GHG emissions. Where the boundaries of an incumbent are unchanged, the average verified annual emissions of the previous years can be used. In other situations, a conservative estimate is needed.

Assuming that back-production would be considered as continuous emission from an installation, for the buffering scenario proposed at Q16-Maas the emissions per year would be between 50,000 to 500,000 tonnes with 250-315,000 tonnes expected to be produced and sold. This would make the storage complex 'installation' a Category B but would be dependant on the amount of CO_2 the project plans to extract in the buffering scenario.

3. List all emission sources and source streams in order to decide on calculation or measurement based approach. Classify the source streams as major, minor and de-minimis as appropriate.

A potential list of sources and streams could be:

Emission sources:

- Back-produced CO_2
- Leakage from the storage complex
- Vented and fugitive emissions from surface operations

Source streams:

- Fuel use at booster station
- Fuel use from oil-gas separation units and gas recycling plants

The source streams then need to be defined as major, minor or de-minimis:

The operator may select as **minor source streams**: source streams which *jointly* correspond to less than 5 000 tonnes of fossil CO_2 per year or to less than 10% of the “total of all monitored items”, up to a total maximum contribution of 100 000 tonnes of fossil CO_2 per year, whichever is the highest in terms of absolute value.

The operator may select as **de-minimis source streams**: source streams which *jointly* correspond to less than 1 000 tonnes of fossil CO_2 per year or to less than 2% of the “total of all monitored items”, up to a total maximum contribution of 20 000 tonnes of fossil CO_2 per year, whichever is the highest in terms of absolute value. Note that the de-minimis source streams are no longer part of the minor source streams.

All other source streams are classified as **major source streams**.

Figure 7: Source Stream classification as given in EU ETS MRGs.
(ETS Directive’s MRR Guidance document No. 1, 2017 (MRGs))

4. Identify the tier requirements based on the installation category. Note that the system of required tiers has been significantly changed from the MRG 2007 to the MRR.

The MRGs state the that “CCS installations are monitored using a form of mass balance approach, where some of the CO_2 entering or leaving the installation (i.e. at the transfer points) is monitored using continuous emission measurement systems (CEMS)”.

The tiers define the uncertainty requirements of the monitoring undertaken and for the continuous emission monitoring systems required (CEMS) the highest tier 4 has to be used (MRGs, 2017). (Section 5.2)

	Tier 1	Tier 2	Tier 3	Tier 4
CO_2 emission sources	± 10%	± 7.5%	± 5%	± 2.5%
N_2O emission sources	± 10%	± 7.5%	± 5%	N.A.
CO_2 transfer	± 10%	± 7.5%	± 5%	± 2.5%

Table 4: Uncertainty requirements stated in MRGs.
(MRR Guidance document No. 1, 2017 (MRGs))

5. List and assess potential sources of data:

a. For activity data:

i. How can the amount of fuel or material be determined?

• Are there instruments for continual metering, such as flow meters, weighing belts etc. which give direct results for the amount of material entering or leaving the process over time?

• Or must the fuel or material quantity be based on batches purchased? In this case, how can the quantity on stock piles or in tanks at the end of the year be determined?

For the proposed continuous monitoring techniques flow meters will be the predominant source of data, i.e. to calculate injected and produced CO_2. To calculate the emissions from the gas separation process and compressor units separate monitoring techniques will be required to calculate fuel usage.

The amount of fuel used at the site for surface facility activities will also need to be included.

ii. Are measuring instruments owned/controlled by the operator available?

• If yes: What is their uncertainty level? Are they difficult to calibrate? Are they subject to legal metrological control?

• If no: Can measuring instruments be used, which are under the control of the fuel supplier? (This is often the case for gas meters, and for many cases where quantities are determined based on invoices.)

As discussed above in Section 4, the Coriolis flow meter is expected to be the most appropriate monitoring instrument currently available and would be incorporated as shown in Figure 6 above.

iii. Estimate uncertainty associated with those instruments and deter-mine the achievable tier associated. Note: For uncertainty assessment several simplifications are applicable, in particular if the measuring instrument is subject to national legal metrological control. For details see guidance document No. 4.

Uncertainty assessments of flow metering for CO_2 streams are still being undertaken. As no CO_2 injection has been undertaken in the EU under the ETS Directive (either for EHR or permanent storage) there is limited information regarding uncertainty assessments.

b. Calculation factors (NCV, emission factor or carbon content, oxidation or conversion factor, biomass fraction): Depending on the required tiers (which are determined based on installation category and source stream category):

i. Are default values applicable? If yes, are values available? (Annex VI of the MRR, publications of the competent authority, national inventory values)?

ii. If the highest tiers are to be applied, or if no default values are applicable, chemical analyses have to be carried out for determining the missing calculation factors. In this case the operator must

• Decide on the laboratory to be used;

• Select the appropriate analytical method (and applicable standard);

• Design a sampling plan.

Calculation factors will be required for any combustion activities occurring at surface facilities such as those for injection, production and separation technologies. Further details of how to calculate combustion based emissions are give in detail in Section 4.3.1 of the MRGs.

6. Can all required tiers be met? If not, can a lower tier be met, if allowed in accordance with technical feasibility and unreasonable costs?

For calculation based approaches the following tiers are required: (Category B is highlighted as the likely category for the Q-16 Maas case study)

Source stream	Category A	Category B	Category C
Major	Annex V	Highest	Highest
Major, but technically not feasible or unreasonable costs	up to 2 tiers lower with a minimum of tier 1	up to 2 tiers lower with a minimum of tier 1	1 tier lower with a minimum of tier 1
Major, but still technically not feasible or unreasonable costs; improvement plan (max. 3 year transition)	Minimum tier 1	Minimum tier 1	Minimum tier 1
Minor	highest tier technically feasible and without unreasonable costs (minimum tier 1)		
De-minimis	Conservative estimation, unless a defined tier is achievable without additional effort		

Table 5: Summary of tier requirements for different category installations.
(ETS Directive's MRR Guidance document No. 1, 2017 (MRGs))

The required tier and attributed uncertainty requirements regarding leakage emission quantification (+/-7.5%) may be difficult to reach given current monitoring techniques although work is currently being undertaken in this area. A literature review of current flow metering techniques demonstrate these techniques should meet current regulatory requirements for quantifying injected and produced CO_2.

7. Will measurement based approaches (CEMS, see sections 4.3.3 and 8) be used? Can the relevant tiers and other requirements be complied with? (Note that the requirements for using CEMS have been significantly changed compared to the MRG 2007.)

Yes measurement based approaches used for CEMS will be required.

8. If answers for points 6 and 7 are negative: Is there a way of using a fallback methodology (see section 4.3.4)? A full uncertainty assessment for the installation is required in this case.

If the flow meters cannot meet the uncertainties required fallback methodologies can also be utilised. For the buffer case the fallback methodologies would have be defined in a next study.

9. Next the operator should define all data flows (who takes which data from where, does what with the data, hands over the results to whom, etc.) from the measuring instruments or invoices to the final annual report. The design of a flow diagram will be helpful. More details on data flow activities are found in section 5.5.

This element of a monitoring plan will be very site specific and depend on the operators usual workflow to carry out storage operations. This would be part of the implementation stage during the FEED (Front End Engineering Design) study.

10. With this overview of the data sources and data flows, the operator can carry out a risk analysis (see section 5.5). Thereby he will determine where in the system errors might occur most easily.

The risk assessment will also be highly site specific but similar risks are likely to be present across storage site monitoring e.g. human error, instrument errors such as failure or calibration errors.

11. Using the risk analysis, the operator should: a. If applicable, decide whether CEMS or calculation based approaches are more suitable;

b. Assess which measuring instruments and data sources to use for activity data (see point 5.a above).

In case of several possibilities, the one with the lowest uncertainty and lowest risk should be used;

c. In all other cases which need decisions, decide based on the lowest associated risk; and

d. Define control activities for mitigating the identified risks (see section 5.5).

CEMS will be most applicable to CCS sites and a buffer concept as highlighted above.

12. It may be necessary to repeat some of the steps 5 to 11, before finally writing down the monitoring plan and the related procedures. In particular, the risk analysis will need update after having the control activities defined.

13. Then the operator will write the monitoring plan (using the templates provided by the Commission, an equivalent template by a Member State or a dedicated IT system provided by a Member State), and the supporting documents required :

a. Evidence that all the tiers noted in the monitoring plan are complied with (this requires an uncertainty assessment, which can be very simple in most cases);

b. The result of the final risk analysis, showing that the defined control system is appropriately mitigating the identified risks;

c. Further documents (such as installation description and diagram) may need to be attached;

d. The written procedures referenced by the MP need to be developed, but do not need to be attached to the MP when submitting it to the CA.

The operator should make sure that all versions of the monitoring plan, the related documents and procedures are clearly identifiable, and that the most re-cent versions are always used by all staff involved. A good document management system is advisable from the beginning.

8.2 Monitoring of CO_2 composition

The monitoring of CO_2 composition is required under the CCS Directive. Three sampling locations are recommended for the Q-16 Maas site as shown in Figure 6 (above), two are for accounting purposes (as knowing the stream composition can improve metering accuracy) and one sampling point is used to provide quality specifications for the CO_2 to be re-used in greenhouses.

8.2.1 CO_2 composition monitoring for accounting purposes

Sampling is required prior to injection and after to back-production. This is required to quantify the amount of CO_2 entering and leaving the CO_2 storage reservoir and can be used to improve the accuracy of flow metering, as outlined in Section 4.2 of this report.

8.2.2 CO_2 composition monitoring for conformance with quality specifications

For CO_2 to be fed into the greenhouses it has to meet strict quality specifications in order not to damage the crops and the people working in the greenhouses (Table 6). In ENOS deliverable D4.4 (Koenen et al., 2018) the composition of the back-produced CO_2 during various buffer cycles was reported on, based on reservoir simulations predicting the interaction between the injected CO_2 and remaining hydrocarbons in the Q16-Maas reservoir. Figure 8 (below) shows the molar fraction of methane and ethane present in the back-produced CO_2 for various buffer cycles. At the start of each cycle the fractions are low, and they increase towards a maximum at the end of the cycle. With each next cycle, the maximum decreases. Heavier hydrocarbons are also present, but in lower amounts. They follow the same patterns as methane and ethane over the cycles. Depending on the scenario, the total hydrocarbons in the CO_2 goes up to 20-40 % which is 200,000 to 400,000 ppm, whereas the specs give a limit of 1200 ppm. Other components than hydrocarbons have not been measured in the gas from Q16-Maas. An analysis of the chemical reactions between the gas, formation water and rock mineralogy did not lead to high risks of any additional gas components. The formation of H_2S due to chemical reactions is unlikely since it requires microorganisms which are most likely not present. An additional uncertainty is the presence of metals in the back-produced stream. Very few articles have been published that investigated the extraction of metals from the formation water by supercritical CO_2. No public information is found on field evidence. Yet, if metals can be transported to the surface dissolved in the CO_2, they will precipitate as soon as the CO_2 changes to gaseous or liquid state.

Component(s)	Limit value (ppm)
H_2O	40
NO	2.5
NO_2	2.5
Total hydrocarbons (including methanol)	1200
Total aromatic hydrocarbons	0.1
Ethanol	1
Acetaldehyde and ethylacetate (together)	0.2
H_2S	5
Carbonyl sulphide (COS)	0.1
Dimethyl sulphide (C_2H_6S)	1.1
CO	750
Ethylene	1
HCN	20

Table 6: Limit values for impurities in the CO_2 as provided by OCAP. Higher values of these impurities are potentially harmful to the greenhouse products.

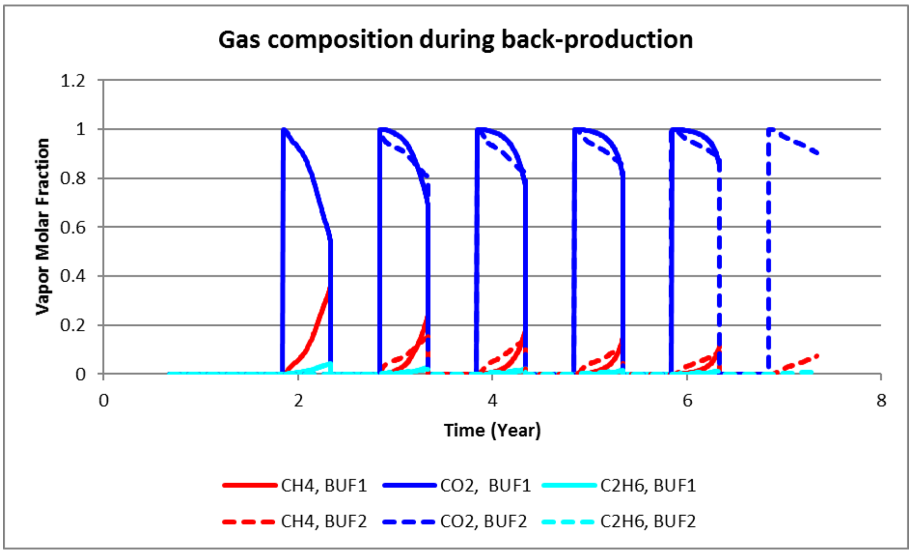

Figure 8: CH_4, CO_2 and C_2H_6 fraction in the back-produced gas streams for several buffer cycles. BUF1: scenario with first back-production starting immediately after the first injection cycle. BUF2: scenario with two injection cycles before the start of back-production (Koenen et al., 2018)

Figure 6 (page 25) shows that sampling of the CO_2 stream for chemical analysis should be done after the stream is purified. At this point in the chain, the CO_2 stream should conform with the quality specification and therefore needs to be checked. In ENOS deliverable D4.9 (to be finalized) the required separation technologies to purify the gas stream to OCAP specs will be reported. These are solely focused on the separation of hydrocarbons. The final gas stream should be sampled frequently, and the composition should be measured using a gas chromatograph.

9 Summary

As studied in ENOS deliverable D4.7 (Rycroft and Mikunda, 2019) regarding EHR and current regulations, a buffering project where CO_2 is temporarily stored, alongside permanent storage, is possible within the current regulatory framework of the CCS and ETS Directives. This report has therefore reviewed the monitoring plan that would be required should an integrated buffering and permanent CO_2 storage project be undertaken within an EU Member State. This report has concluded that current requirements regarding quantification of injection and production of CO_2 can be met although the quantification of leakage at the low uncertainties required (+/- 7.5%) may currently be difficult to achieve. This is not specific to a buffering scenario but will also apply to permanent storage.

The design of the monitoring, reporting and verification plan will follow a site and project specific risk assessment. The risks and therefore monitoring plan will be site specific and no fundamental differences regarding monitoring technologies were identified between CO_2 storage and CO_2-EHR projects. Current best practices in monitoring appear to also cover every aspect required for the buffering scenario with regards to CCS Directive requirements.

The main challenge for a CO_2 buffer regarding the monitoring plan and current European legislation is to meet ETS Directive quantification requirements. A complex mass balance is required to calculate the amount of CO_2 injected and produced, the amount emitted at surface facilities and any potential leakage to allow a final assessment of the proportion of CO2 permanently stored. This will require additional metering for production as well as calculating extra surface facility emissions associated with buffering e.g. CO_2 separation technology and artificial lift for production.

As part of the monitoring program a buffering project where CO_2 is utilized after back-production would also require extra chemical analysis, post-separation and pre-sale, to make sure it meets the specifications for re-use. The required quality of CO_2 after back-production will depend on the intended end-use. For re-use in greenhouses the CO_2 stream will have to be high quality pure CO_2 to meet food standard requirements.

To develop this study further and provide a detailed project specific monitoring plan, a feasibility study for the buffer concept, including a full risk assessment for a specific project site would be required. The monitoring system concept should be designed based on the risk assessment and a detailed monitoring plan should be based on a subsequent implementation study which includes an operational injection and back-production plan.

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