



Technical and Legal aspects of CO2 transport by ship and implementation of the CO2 flow monitoring.

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Executive Summary

The CCS chain leads from the CO_2 source to the permanent CO_2 sink. The starting point and final destination are reasonably well defined, but the chain elements in between might vary. For practical purposes the capture or purification unit will be in close vicinity to the CO_2 -source, as is the compression or liquefaction unit. The distance to the sink however, can be considerable which creates the necessity for a transport system. For large scale, long term operations transport by a dedicated pipeline is the intuitive choice. However, in the initial stages of CCS development in Europe, the relative flexibility of shipping CO_2 both in terms of capacity and destination can offer a economically attractive solution. For example, the use of ships may be suitable for smaller amounts of CO_2 to be transported over long distances to multiple small storage sites which are to be used for a limited period of time. A network of transport pipes might become available at a later stage once the technology is proven at large scale and a large transport capacity is required to accommodate multiple sources.

The liquefaction, loading, transportation by CO_2 carrier, unloading and injection is clearly a complex chain of processes involving significant energy use and multiple transfer points. The CO_2 must be compressed for intermediate pipeline transportation from the capture unit, then potentially depressurized and re-compressed to between 60-80 bar at the liquefaction plant. After the CO_2 is condensed and depressurised to approximately 7 bar, it must be held at temperatures of -50°C. The liquid CO_2 must then be pumped onboard the vessel, transported and again pumped from the onboard storage tanks to the deck where it is heated to ambient temperatures. At the injection platform, the CO_2 is further heated to between 10°C to 20°C and injected at pressures of between 150 to 400 bar dependent on the in-situ reservoir pressure.

Since both the CCS-Directive and the EU ETS Monitoring and Reporting Guidelines for CCS were framed with only the transport through a network of pipes in mind, CO₂-transport by ship is not accommodated by the current regulation. This study examines the CCS chain including transport by ship with an emphasis on the regulatory aspects like permitting, liability and the ETS-monitoring. The capture unit can be operated within the ETS emission permit of the CO₂-source installation if the two units have the same owner/operator. In the case the two units are owned and operated by different legal entities both have their own ETS permits. Following the ETS Monitoring and Reporting Guidelines the transferred CO₂ stream has to be measured with high accuracy. The liquefaction plant and the on-shore transport can be arranged as an integral part of the (source and) capture operations under the same ETS-emission permit, or the transport operator can act as an independent ETS installation. The same holds for the temporary onshore CO₂ storage: it can be included as an integral part of the source, capture and/or transport operation, since there is nothing in the ETS guidelines that prevents an operator to 'juggle' with quantities of CO₂ on his site within his ETS-emission permits. The temporary storage will reduce the effect of possible variations in the CO₂ stream composition and quantity. Mixing CO₂ from different sources is likely to have the same effect. Several potential CCS parties have indicated that their preferred situation would be where the liability for the captured CO₂ would remain with its originator (or source). This preference still has to be negotiated for approval with the authorities.



In analogy with the temporary on-shore storage, the easiest way to include the shipping of CO_2 under an ETS permit would be to allow the CO_2 -transport by ship as part of the (pipe) transport permit. The ship is just considered as a flexible pipe section. The 'ship-as-flexible-pipe'-approach might however overstretch the willingness of the authorities to agree. An alternative option would be to enter CO_2 transport by ship as a new additional activity within the ETS, a so-called 'opt in'.

The consequence of including CO2-transport by ships as a new activity within the ETS is that both the quantities of CO2 physically transferred to and from the ship, as well as all the related CO2-emissions have to be measured. It would be quite ineffective to complicate the 'CO₂-transport by ship' ETS discussion with the inclusion of 'CO₂ transport only'-shipping emissions whereas all shipping emissions might be included shortly. For the European situation with storage on the North Sea basin the emissions from the ship engines are with less than1% small compared to the amount of CO₂ transported and small compared to the emissions resulting from the capture, compression and liquefaction processes. For ship owners it is quite unusual to accept the liability for the cargo they transport. With the formal addition of CO₂-transport by ship as activity in the ETS it becomes again questionable whether this approach can be maintained. The issue of liability for the transported CO₂ ship cargo is less complex and/or voluminous than the liability issues concerning the final CO₂ storage.

For off-shore monitoring the EU-CCS Directive focuses on the behavior of the CO_2 in the subsurface storage site, whereas the EU ETS Monitoring and Reporting Guidelines focus on the quantities of CO_2 . Literal interpretation of the available regulation results in a situation that is sub-optimal for measurement. For practical reasons it is recommended to determine the quantity of the injected CO2 once on the off-shore platform before pressure regulation. The chemical analysis for monitoring the composition is better performed on-shore. When the CO_2 stream passes the transfer point between the transport operator and the storage operator, the CO_2 stream leaves the EU emission trading system. The stored amount of CO_2 is not registered in the ETS other than transferred and not emitted.

Following the EU-ETS Monitoring and Reporting Guidelines the uncertainties in the measurement of CO₂ should satisfy strict requirements. These requirements place constraints on the monitoring techniques to accurately monitor carbon dioxide during transport and storage phase. Series of uncertainty calculation were performed to determine the critical parameters like temperatures, pressures, densities etc to establish an accurate measurement. The monitoring device chosen for this study is an orifice meter, as it is commonly used for measuring large streams of gasses and liquids. It is concluded that the uncertainties in the CO₂ flow measurement are minimum and meet the EU ETS requirements under 30 °C and at high pressures over 9 MPa. Moreover, an orifice is an adequate monitoring device to be installed at the transfer points from of capture to pipeline site and at the storage site. It is recommended that more monitoring equipment like venturi, magnetic and ultrasonic flow meters will also be evaluated before choosing a final option.



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Appendix I: Relevant texts from the MRG and CCS directive on monitoring42



Abbreviations

CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCTS	Carbon capture, transport and storage
CO ₂	Carbon dioxide
EC	European Commission
EIA	Environmental impact assessment
ETS	Emissions Trading Scheme
EU ETS	European Union Emissions Trading Scheme
EU	European Union
GHG	Greenhouse gas
IEA	International Energy Agency
LNG	Liquid natural gas
MRG	Monitoring & Reporting Guidelines
MW	Megawatt
OPEX	Operational expenditure
TPA	Third-party access
ZEP	Zero Emissions Platform



1 Introduction

The CCS (or CCTS, Carbon Capture Transport and Storage) chain leads from the CO_2 source to the permanent CO_2 sink. The starting point and final destination are reasonably well defined, but the chain elements in between might vary. For practical purposes the capture or purification unit will be in close vicinity to the CO_2 -source, as is the compression or liquefaction unit. The distance to the sink however, can be considerable which creates the necessity for a transport system. For large scale, long term operations transport by a dedicated pipeline is the intuitive choice. However, in the initial stages of CCS development in Europe, the relative flexibility of shipping CO_2 both in terms of capacity and destination can offer an economically attractive solution (Mikunda et al. 2011). For example, the use of ships may be suitable for smaller amounts of CO_2 to be transported over long distances to multiple small storage/enhanced oil recovery sites which are to be used for a limited period of time (i.e. 5 years or less). A network of transport pipes might become available at a later stage once the technology is proven at large scale and a large transport capacity is required to accommodate multiple sources.

1.1 Research objectives

Since both the CCS-Directive and the EU ETS Monitoring and Reporting Guidelines for CCS were framed with only the transport through a network of pipes in mind, CO₂-transport by ship is not accommodated by the current regulation. This study examines the CCS chain including transport by ship with an emphasis on the regulatory aspects like permitting, liability and the ETS-monitoring.

Starting with an overview of the current practices and available technology in liquefied gas transport, handling and storage to demonstrate the capabilities, the practical application of the current regulation is examined. The temporary CO_2 -storage and the CO_2 -transport by ship are new elements in the CCS-chain and several solutions for ETS-permitting and liabilities are discussed.

Also for off shore CO_2 -monitoring the current practices and existing technology on off-shore platforms are compared with the available regulation leading to a set of recommendations for measurement of the quantity of the injected CO2 and the chemical composition. In the final chapter the conditions are examined to minimize the uncertainties in the flow measurement of liquid carbon dioxide (CO_2) in a pipeline.



2 **CO**₂ transportation by ship: the concept

2.1 Introduction

Shipping CO_2 for the purpose of geological storage emerged as a feasible option for the transportation of CO_2 almost in parallel with the concept of CCS itself. Although industrial experience in the transportation of CO_2 by ship cannot be compared with the established practice of transporting CO_2 by pipeline (primarily in the US for enhanced oil recovery), a small number of CO_2 transporting vessels are in operation, delivering CO_2 for industrial purposes. Current CO_2 shipping operations involve small vessels with capacities of approximately 1,000 m³, whereas the sizes of vessels considered for large scale CO_2 transportation for geological storage are expected to require capacities of between 20-30,000 m³. Nevertheless, the design requirements for semi-refrigerated CO_2 vessels are understood to be very similar to those of liquid petroleum gas (LPG) carriers, of which 300 vessels are currently in operation (ZEP, 2011). Based on this experience, shipping operators and ship manufacturers alike regard the large-scale transportation of CO_2 by ship as a technically feasible alternative to pipelines.

From an economic point of view, in some cases shipping of CO_2 can offer a flexible and complimentary option to both onshore and offshore pipelines. In most circumstances, shipping is looked upon as an alternative to offshore CO_2 pipelines; however the use of CO_2 barges on large inland waterways has also been investigated (Tebodin, 2011). In the early phase of CCS demonstration, CO_2 shipping could play an important role where the length of a storage demonstration project is too short to allow investment in a pipeline. The CAPEX/OPEX ratio of an offshore pipeline is roughly 90:10, compared to a CO_2 carrier (and liquefaction unit) of 50:50 (ZEP, 2011). Therefore shipping offers a less capital intensive form of CO_2 transportation, given either a limited project lifetime, variable CO_2 storage/usage (in the case of enhanced oil recovery), or the possible delivery to multiple storage locations. Furthermore, the CO_2 carrier can have a residual value as an LPG carrier given the similar storage conditions required between CO_2 and LPG¹.

Mikunda et al. (2011) outline a number of foreseen benefits of transporting CO₂ through shipping:

- Volume flexibility: Transport by ship creates flexibility to changing CO₂ volumes over time. If more volume is offered for transport, an additional vessel can be introduced (as well as additional intermediate storage tanks). If volumes are reduced, ships and storage (designed for multi-purpose services), can be taken out of the CO₂ service and introduced to an alternative trade, or another CO₂ stream.
- Alternative use of assets: Ships represent a certain residual value (in time), especially combined carriers that can be employed in alternative trades. Residual value reduces the upfront investment risks. However the costs for the onshore CO₂ terminal, liquefaction and offshore conditioning do represent fixed investments.

¹ Onboard CO₂ storage conditions are around -50°C to -55°C and 6 to 7 bars, Liquid Petroleum Gases (LPG) is transported at -48°C and atmospheric pressure hence the re-use of the ship in this alternative trade



Source and sink flexibility: Offshore pipelines are significant assets, to build and to operate and therefore particularly suitable for long term high volume transport of CO₂. For smaller fields, or fields located out of the vicinity of a CO₂ trunk line, laying a pipeline may prove too expensive. A ship, however, can reach these fields, and in certain cases this could be performed at a lower cost.

The IPCC (2005) has undertaken a cost analysis of offshore and onshore pipelines, and the use of a CO_2 carrier, comparing costs against the transportation distance required.



The costs used in the analysis include intermediate storage facilities, harbor fees, fuel costs and loading/unloading activities. The costs also include additional costs for liquefaction compared to compression. There is a capital charge factor of 11% for all transport options. Over longer distances of approximately 1000km, shipping appears to be a lower cost option than offshore pipelines. One of the primary reasons for this is that over longer stretches of pipeline, a gradual pipeline pressure drop may lead to gas densities which are less efficient for pipeline transport. A significant pressure drop would warrant the requirement for offshore booster stations which add another level of technical complexity and cost.

Although shipping CO₂ has a number of foreseen advantages, there are also a number of disadvantages. The IEA GHG (2004) states that marine transport induces more associated CO₂ emissions than pipelines due to the additional energy use and fuel use in ships. These emissions were calculated as 2.5% extra CO₂ emissions for a distance of 200km, compared to the associated emissions of 1000km of pipeline understood to be between 1-2%. Another disadvantage of ship transport is the batch load nature of the transportation. For injection into a deep saline aquifer the discrete shipments do not present a problem, however most enhanced oil recovery operations require a continuous flow of CO₂ whereby a pipeline would be most suitable. This problem could be overcome via a logistical solution, and/or temporary CO₂ storage facilities on an offshore platform.

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The shipping of CO_2 also requires more gas handling steps in the whole CCS chain, which could add to the complexity and the length of time to plan and develop projects. In addition, the increased number of steps may have consequences for monitoring of associated or fugitive emissions from the additional liquefaction, intermediary transport and storage components of the chain. Figure 2.1 and 2.2 use simple CCS chain concepts to highlight the differences between a chain utilising an offshore pipeline and a chain involving a CO_2 carrier. The sub-sections below briefly explain the various steps in the CCS chain involving CO_2 transportation by ship. Further information on this topic is provided in Chapter 3.



Figure 2.1 CCTS chain utilising an offshore pipeline



Figure 2.2 CCTS chain involving a CO₂ carrier

2.2 Compression and intermediate transport

Once the CO_2 has been captured, the stream will most likely undergo additional purification and dehydration to ensure that the stream meets the required specifications for transportation and storage. The activities of the capture installation and the associated monitoring activities are not within the scope of this report, however the location of the capture installation may determine the transportation components. For example, if the capture installation has access to a waterway directly, then the liquefaction process, intermediate storage and loading can be completed onsite, with no requirements for an intermediate onshore pipeline. In most cases however, it can be expected that CO_2 will need to be transported onshore, or via inland waterways to a harbour facility (for example, a CO_2 terminal) with the ability to liquefy, store and load CO_2 carriers.

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To facilitate CO_2 transport from the capture location, the CO_2 will need to be compressed to a high pressure. The compressor requirements at the capture installation are dependent on a number of factors, such as the distance to the CO_2 terminal, any planning restrictions and the specifications of the liquefaction facility. In general, CO_2 is liquefied at ambient temperatures at absolute pressures of between 60 and 80 bar. The pressure drop for a 20 inch pipeline is approximately 0.3 bar per km (under constant ambient temperatures) (Yeddu and Gullen, 2008), and so this must be factored into the design to ensure that the CO_2 is kept within the desired phase flow. If there is a large distance between the emitter and the CO_2 terminal, transporting CO_2 in supercritical phase flow (achieved at pressures above 74 bar) is more efficient, however this will require higher operating pressures which may increase safety concerns if the pipeline is to run through densely populated areas. A concept of a liquid shipping supply chain involving three capture installations piping CO_2 to a CO_2 terminal in the Rotterdam harbour area, the Netherlands (Tebodin, 2011), chose to operate pipelines with a subcritical (vapour) phase at approximately 40 bar due to the short distances involved (>5 km) and the anticipated safety considerations of the port authority.

2.3 Liquefaction

The most efficient way to transport CO_2 by ship is in a liquid form. Liquid phase of CO_2 can be achieved by compressing it to pressures of between 60-80 bar, however this would require CO_2 carriers to have very thick-walled tanks which would be very expensive (Apselund et al., 2006). An alternative way to achieve the liquid phase without such high pressures is to cool the CO_2 to sub-ambient temperatures, between -45°C to -55°C. The diagram below provides the temperature-pressure diagram of CO_2 , including the phase distribution. With reference to the temperatures on the x-axis, it can be seen that by reducing the temperature to the range mentioned above, much lower pressures of between 5.5 and 7.5 bar are needed for the CO_2 to exist in a liquid phase.



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To liquefy CO_2 , it must be compressed, condensed and depressurized. There are a number of methods for CO_2 liquefaction, however these can be divided into two general process options. Dependent on the temperature of the available cooling water (such as sea-water), the system can be configured whereby the CO_2 acts as the cooling medium, without need for an additional refrigerant. The option is referred to as an open system, whereby a proportion of the compressed CO_2 is recirculated, expanded and thus cooled, and can then be used to cool another incoming CO_2 stream. For this option, the CO_2 has to be compressed to approximately 60 bar, at operating temperatures of 20°C and with cooling water between 10 and 15°C. The presence of non-condensable gases such as nitrogen and oxygen in the CO_2 stream will require higher pressures.

The second process option, involves the use of a single type of refrigerant, such as ammonia (NH_3). By using NH_3 at -30°C, the pressure requirements are reduced to approximately 25 bar at operating temperatures of 20°C (Hegerland et al., 2004). This process is a closed system, with the NH_3 recondensing at 40-50°C which can then be re-condensed, cooled and re-circulated. Both processes have potential advantages and disadvantages, both in terms of the energy requirements for compression and the toxicity of the refrigerant used.

2.4 Intermediate storage and pump system

The transportation of CO_2 by ship will be conducted in a batch wise fashion, whereby an intermediate storage facility will be needed as a 'buffer' between ship loadings. Once the CO_2 has been liquefied, it must be stored at pressures and temperatures above the triple point (see phase diagram above), pressures above 5.18 bar and temperatures lower than -56.6°C. Storage tanks will be made of high-tensile steel and can be in cylindrical form (often termed 'bullets') or spherical. Apselund et al., (2006), assume storage capacity will be available for 1.5 times the capacity of the CO_2 carrier.

Tebodin (2011) advises CO_2 storage tanks to have an operating pressure of 7.5 bar, with a margin of 1 bar either side of this figure for the control range. Above the control range, an additional 1.5 bar (a maximum at 10 bar), and below the range a margin of 0.7 bar (a minimum of 5.2 bar) should be provided for unintended events. A safety valve is needed on the tank, which can release the CO_2 if the pressure increases beyond the control range as a result of heating.

As the CO_2 within the storage vessel is at boiling point at -50°C and 7 bar, any heat-in leak will cause the liquid to boil creating boil-off-gas (BOG) (Tebodin, 2011). An increase in CO_2 in vapour phase will cause the pressure within the storage tank to increase. Heat in-leak can stem from the surrounding environment, and for example from electrical equipment associated with pumps. BOG can form in the intermediate storage vessel or in the CO_2 carrier. There are a number of ways identified by Tebodin (2011), for dealing with the BOG. For dealing with BOG that occurs during the intermediate storage or loading of the CO_2 carrier, the BOG can be removed and either

- a; recompressed upstream and re-liquefied, or
- b; injected into a downstream pipeline.

This choice depends on the proximity of the loading or storage facilities to the liquefaction unit, and/or the available infrastructure (i.e. a downstream pipeline).



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2.5 Loading equipment

The transfer of the liquefied CO_2 from the storage tanks to the CO_2 carrier is conducted at the quayside by using a loading arm. Cryogenic loading systems for many liquefied gases are available, so the availability of suitable equipment is not an issue. Both Tebodin (2011) and Apselund (2006) recommend a solution consisting of two parallel product pipes between the intermediate storage tanks and the CO_2 carrier, one for loading the liquid CO_2 and a return line for CO_2 vapour generated at the ship connected to the intermediate storage vessels. Tebodin (2011) states that the loading arms are high risk locations for leakage, and measures such as an emergency shutdown system must be incorporated.



http://gazprom-sh.nl/lng/technology/shipping/pic/4/

2.6 CO2 carrier

The market for LPG has grown considerably in recent years, and as a result the number of LPG carriers in service or under constructions has reached a global total of approximately 300 large² fully refrigerated vessels (Ship building history.com, 2012). A CO₂ carrying vessel will appear very similar to a LPG carrier, however the CO₂ must be transported at slightly lower temperatures (-50°C instead of -48°C) and higher pressures (7-9 bar instead of 5-7 bar). The required size of the CO₂ carrier is obviously dependent on the amount of CO₂ to be transported as part of the CCS chain. However, bearing in mind that the CO₂ carrier could at some point be re-commissioned to be used for LPG, a size between 10,000 and 30,000m³ may be appropriate. Mikunda et al., (2010) provide an estimate of the maximum amount of liquefied CO₂ that could be transported by the two different sizes of ships given different distances. The calculation are based on a maximum speed of 14 knots, loading and discharge rate 1000t/hr for the 10,000m³ ship, and 15 knots, loading and discharge rate 2000t/hr for the 30,000m³ ship.

² With a capacity of 10,000m³ and above.





Figure 2.3 Annual transport capacity (MtCO₂/year) for fully utilized ships at different distances

As with the transportation of either LPG or LNG, the liquid CO_2 will be held at its boiling point within the onboard tanks. Because no insulation is perfect, the heat from the environment will mean that a part of the CO_2 will boil off and the pressure of the CO_2 in vapour phase will increase during transportation. With LNG carriers, the associated boil off gas (methane) is warmed and fed into the boilers of the ships, which are often dual fuelled (heavy fuel oil and natural gas). Recent advances in technology mean that re-liquefaction units can be fitted onboard LNG carriers, meaning that more efficient diesel engines can be fitted (ChemEurope, 2007). Given that there is no use for the CO_2 onboard the ship, it is unclear whether it would be cost effective to fit re-liquefaction units to CO_2 carriers as a solution to the boil off gas.

2.7 Offshore terminal and unloading

This element of the chain could be considered the least technically mature, as industrial experience is primarily associated with the offshore loading of hydrocarbons onto vessels. The CO_2 must be transferred from the ship to an offshore platform for injection. There are a number of options for the unloading system, however a number of concepts (Apselund et al., 2006: Tebodin, 2011), involve the use of a separate offloading tower or buoy, connected to the injection platform via a fixed subsea pipeline.



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During the offloading, the CO_2 must be pumped from the storage tanks to the ship deck. The CO_2 leaving the storage tanks will be pumped to a pressure of 20 bar, after which it will be heated to ambient temperatures. The CO_2 must be heated in order to prevent damage to the steel equipment that could become brittle due to the very low temperatures, and later to approximately 10°C to 20°C to prevent hydrate formation at the wellhead. According to Apselund et al., (2006), the temperatures in the North Sea, as low as 5°C, are not technically suited to be used as heating media in a heat exchanger. Because of this, the heating of the CO_2 will require a heating system, adding to the capital and operational costs, and a significant increase in the CO_2 emissions due to fuel use.

The CO_2 is then transferred through the fixed sub-sea pipeline to the platform, where it is further heated to between 10°C to 20°C, potentially using waste heat from pump used for consequently injecting the CO_2 to pressures of between 150 to 400 bar. Both the temperature and the pressure requirement from the pumps are dependent on the reservoir pressure, which will increase as CO_2 is injected over time.

2.8 Summary

The liquefaction, loading, transportation by CO_2 carrier, unloading and injection is clearly a complex chain of processes involving significant energy use and multiple transfer points. The CO_2 must be compressed for intermediate pipeline transportation from the capture unit, then potentially depressurized and re-compressed to between 60-80 bar at the liquefaction plant. After the CO_2 is condensed and depressurised to approximately 7 bar, it must be held at temperatures of -50°C. The liquid CO_2 must then be pumped onboard the vessel, transported and again pumped from the onboard storage tanks to the deck where it is heated to ambient temperatures. At the injection platform, the CO_2 is further heated to between 10°C to 20°C and injected at pressures of between 150 to 400 bar dependent on the in-situ reservoir pressure.



3 Legal aspects in CO₂ transport by ship (as part of the CCS chain)

In the next paragraphs the different steps and elements in the CCTS (Carbon Capture Transport & Storage) chain including transport by ship will be discussed. Emphasis is given to legal aspects stemming from the CCS Directive or M&R-guidelines, and not so much on the technical aspects (as described in the preceding chapter). Several aspects are identified that will be elaborated in the following paragraphs.

3.1 Chain step 1 source

Starting point in the chain is the CO_2 -source. Depending on the nature of the CO_2 generating process more or less complicated capture processes are required to obtain concentrated or even pure CO₂streams. In previous CATO reports [CATO, 2010] it has been demonstrated that it can be a serious challenge to obtain the ETS-required accuracy in monitoring the small amount of CO₂ that is not captured but released to the atmosphere. The capture ratio or yield (as % of the original CO₂ stream) is determined by the capture process and its mode of operation. The captured CO₂ stream is prepared for transport by either purification, pressurization, liquefaction or a combination of these. Capacity variations in the source process will, in combination with performance variations in the capture and purification processes, generate fluctuations in the amount and purity of the CO₂ stream. For example, during periods with peak demand and thus top energy prices, it is well imaginable that a power plant will temporarily switch off the capture unit. After the peak period the capture unit will be put back in operation following the further load variations of the generating plant with changing capture yields. Measuring the resulting variable CO₂ stream for ETS monitoring can again be challenging as discussed in chapter 5. For simple logistical reasons it's highly likely that the capture unit is within a short distance from the source, making this first transport step probably a relatively simple one without major legal obstacles. The capture unit can be operated within the ETS emission permit of the CO₂-source installation if the two units have the same owner/operator. In the case the two units are owned and operated by different legal entities both have their own ETS permits and following the ETS Monitoring and Reporting Guidelines the transferred CO₂ stream has to be measured with high accuracy (as described in CATO [2010].

3.2 Chain step 2 Transport to temporary storage

The first major transport step is from the capture unit to the temporary on-shore storage buffer and this relatively short distance transport can take place through pipe, by barge or by train. The temporary storage will reduce the effect of the variations in the CO_2 stream composition and quantity. Mixing CO_2 from different sources is likely to have the same effect. If the CO_2 is compressed for the first on-shore transport step this compression energy can be utilized in the liquefaction process. The liquefaction process will generate some minor CO_2 emissions itself (from the necessary power generation and/or non-condensables separation), which have to be accounted for within the ETS.

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The on-shore transport can be arranged as an integral part of the (source and) capture operations under the same ETS-emission permit, or the transport operator can act as an independent ETS installation. The same holds for the temporary onshore CO₂ storage: it can be included as an integral part of the source, capture and/or transport operation, since there is nothing in the ETS guidelines that prevents an operator to 'juggle' with quantities of CO₂ on his site within his ETS-emission permits. It would also be possible to consider the temporary onshore storage facility, with its in- and outgoing CO₂ streams and possible own small CO₂-emission, as an independently operated CO₂-transport unit. For each of these possibilities the ETS monitoring plan for the site has to be adapted of course to include not only the formal transfer of the CO₂ stream to the transport or storage operator but also the (annual variation) in temporary storage quantity. Since it is highly likely that the amount stored in the temporary storage is quite modest compared to the annually transferred CO₂ quantities, the latter should not be too problematic. The environmental permits for such new elements like compressed CO2 transport or liquefied CO2 storage could be a different chapter however. In the case the liquefaction unit and temporary storage are included in the transport operator's ETS permit even the variations in the amount stored in the temporary storage can be larger than the annual CO₂ emission from the installation making the ETS CO₂ monitoring more critical.

To enable the formal transfer of CO_2 between two parties in the CCS-chain, both parties are required to have a valid CO_2 -emission permit which makes them legitimate ETS-participant. Annual CO_2 emissions have to be reported according to an approved monitoring plan which in turn has to be in line with the monitoring and reporting guidelines (MRGs) for transport by pipelines as described in the next paragraph. In the situation that CO_2 -streams from different sources are simultaneously stored in the temporary storage it has to be evident which party or operator holds the liability for that stored material. Several potential CCS parties have indicated that their preferred situation would be where the liability for the captured CO_2 would remain with its originator (or source). This preference, which still has to be negotiated for approval with the authorities, would complicate the situation with mixing in the temporary on-shore storage, transport and/or permanent storage.

3.2.1 **M&R Guidelines for transport by pipelines**

The transport of greenhouse gases by pipelines for geological storage in a storage site permitted under the EU CCS Directive, is applicable to the EU ETS Directive³, listed as an activity in Annex 1 of the latter. Therefore emissions associated with the transportation of CO_2 via pipeline must comply with the monitoring and reporting guidelines (MRGs) EU ETS. The most recent MRGs were released in 2007⁴, to be used during Phase II of the EU ETS (2008-2012). In June 2010, the European Commission released an amendment to the MRGs released in 2007. The amendment⁵, in addition to providing further guidance on the determination of emissions or amount of emissions transferred using continuous measurement systems (CEMS), also contains 'Activity-specific guidelines' for the determination of emissions from the capture process⁶, transport of CO_2 by pipelines⁷ and the

³ Decision 2009/29/EC as amending Directive 2003/87/EC

⁴ Decision 2007/589/EC

⁵ Decision 2010/345/EU

⁶ Annex XVI

⁷ Annex XVII



geological storage of CO_2^8 (including fugitive emissions from enhanced hydrocarbon recovery operations and leakage from the storage site.

In order to accurately report potential emissions from CO_2 transport pipelines, two approaches are permitted. In choosing which method to apply, the operator must demonstrate to the competent authority that the choice of method leads to more reliable results and a lower degree of uncertainty of overall emissions.

Method A is based on a mass-balance calculation by measuring the CO_2 entering and exiting the pipeline, using the formula:

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

With,

Emissions = Eown activity =	Total CO_2 emissions of the transport network Installation emissions from the transport networks own activity, such as fuel use in booster stations, not stemming from the CO_2 transported.
$T_{IN,i} =$	Amount of CO ₂ transferred to the network at entry point i,
$T_{OUT,i} =$	Amount of CO_2 transferred out of the network at exit point j,

In terms of accuracy, operators would be required to use continuous measurement systems capable of providing a level of uncertainty of CO_2 flow over the reporting period of less than $\pm 2,5\%^9$.

Method B is a calculation-based methodology, which would require the development and application of default emission factors for the various components of the CO_2 transport chain. These emission factors must be expressed in g CO_2 /unit time per piece of equipment, and be reviewed every five years. The activity-specific guidelines in the amendment to the EU ETS MRGs include four categories of potential emission sources from CO_2 transportation pipelines:

- Installation emissions; combustion and other processes at installations functionally connected to the transport network, e.g. fuel use in booster stations, heaters
- Fugitive emissions; from the pipeline seals, valves, measurement devices, intermediate compressor stations and intermediate storage facilities.
- Vented emissions; from the pipeline for maintenance or emergency reasons.
- Leakage events; emissions released due to the failure of one or more components of the transport network.

The calculation methodology is specified as:

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

⁸ Annex XVIII

⁹ Corresponding to Tier 4, as defined in Annex XII of Decision 2010/345/EU



Within the MRGs, no reference is made to accounting for emissions from any other forms of CO_2 transportation, such as maritime CO_2 carriers, transportation by railway or road. However, it can be said with confidence that the categories of emissions listed for CO_2 pipelines are also relevant for a CCS transportation chain including liquefaction and shipping, albeit that the emissions may be of a different order of magnitude.

3.3 Chain step 3 transport by ship

From the temporary on-shore storage the liquid CO_2 is physically transferred to the CO_2 -transport vessel. Since ship-owners have a broad experience in loading and unloading (valuable) compressed liquid gases, this transfer can be accomplished without significant CO_2 -emissions; high tech connectors equipped with vapor recovery equipment are available. Of course any CO_2 -emission has to be accounted for within the ETS.

Apart from any environmental, health and/or safety permits the shipping of CO_2 has to be included under an ETS permit. In analogy with the temporary on-shore storage, the easiest way would be to allow the CO_2 -transport by ship as part of the (pipe) transport permit. The ship is just considered as a flexible pipe section. The amount of CO_2 transferred from the capture operator to the transport operator and the amount of CO_2 transferred from the transport operator to the storage operator are both measured with high accuracy to calculate the 'leakage' contribution to the annual CO_2 emission from the transport operator. When performed with 'smart' timing there is no shipload included in this balance. Similar to the temporary storage the ETS guidelines do not prevent an operator to 'juggle' with quantities of CO_2 within his ETS-emission permit.

3.3.1 **CO₂ Shipping as opt-in activity**

However, the 'ship-as-flexible-pipe'-approach is far from elegant and, more important, might overstretch the willingness of the authorities to agree. An alternative option would be to enter CO_2 -tranport by ship as a new additional activity within the ETS. With Article 24 the ETS system provides an opportunity to include unforeseen CO_2 -related activities in the trading system. Article 24 of the EU ETS Directive, "Procedures for unilateral inclusion of additional activities", allows Member States to apply emission allowance trading to activities and gases that are not listed in Annex 1 of the Directive. A so-called 'opt in', as it is referred to outside of legislation, must take into account criteria such as the reliability of the planned monitoring and reporting system. Paragraph 3 of Article 24 states that (Directive 2009/29/EC p.L140/80),

"On the initiative of the Commission, or at the request of a Member State, a regulation may be adopted on the monitoring of, and reporting on, emissions concerning activities, installations and greenhouse gases which are not listed as a combination in Annex 1, if that monitoring and reporting can be carried out with sufficient accuracy".



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The European Commission has released no dedicated or detailed information regarding the possibility for a CO₂ transportation chain including liquefaction and shipping being adopted under the trading scheme. Two specific references have been made from the Commission however: In the "Minutes of the 3nd Sustainable Fossil Fuels Working Party for the 2009 Berlin Forum, 24 March 2009" as distributed by the EC DG Energy and Transport and available on the internet (http://ec.europa.eu/energy/oil/berlin forum/doc/working parties/sustainable fossil fuels/20090324 sff minutes.pdf), the answer to a question concerning the inclusion of CO₂-transportation by ship says "The Commission (Mr. Fallmann) replied that the commission only relates to pipeline transport because the legal framework (CCS directive and ETS review) only relates to pipeline transport. After initiative from a Member State or later on its own initiative, the Commission could work on such MRG. Other modes for CO₂ transport including shipping would require an opt-in of that transport activity under Article 24 of the ETS Directive." The second reference appears in 2011 in a frequently asked question (FAQ) document released as part of supporting material to the first round of applications for funding for CCS projects under the New Entrants Reserve 300 scheme. Question 266 asks "How would transport of CO₂ by ship be treated under the EU-ETS?". The response from the commission says that indeed the activity would have to be opted in under Article 24, and that the details including the corresponding monitoring and reporting obligations would be need to be specified in the opt-in decision.

3.3.2 Shipping and ETS monitoring

The consequence of including CO₂-transport by ships as a new activity within the ETS is that both the quantities of CO₂ physically transferred to and from the ship, as well as all the related CO₂-emissions have to be measured. CO₂ emissions during loading and unloading the ship certainly have to be included in the inventory. In these operations a balance has to be found between the reduction of CO₂-leakages and prevention of the ingression of contamination into the CO₂-stream. With the low temperatures (-50 °C) of the liquefied CO₂ condensation of water vapor will be hard to prevent, but as indicated before, the ship owners already have a broad experience and advanced equipment for performing such operations with minimal leakages or ingression. When the empty pressure tanks on the ship are filled with liquid CO₂ at the temporary storage location, the resulting vapors will be collected and condensed as a standard routine. The pressure tanks are well insulated and during the trip to the storage location the amount of heat conducted to the tanks will only result in a mild pressure build-up. The option to cool the contents by pressure blow down (as is current practice for liquid nitrogen tanks) is not considered necessary. During the unloading of the ship at the off-shore platform the conditions are likely to be more challenging than in harbor locations, but also here advanced technology is currently available in the offshore business. Since oil and gas transport by ships is a long existing commercial activity, seriously accurate measuring instruments have been developed to determine the transferred quantities.

The CO_2 -emissions related to transport by ship are all directly connected to the quantity of captured CO_2 , i.e. any leakage during transfer, liquefaction, cooling, venting, unloading etc. The emissions coming from the combustion engines on the ship to power the ship for propulsion are not included in the ETS, because mobile emission sources like cars, trucks and trains etc. are not included in the ETS (yet). The EU ETS has recently started a process to include aviation in the ETS, but these discussions have provoked such furious international political reactions from major countries like the US and China that it will likely take years before any agreement will evolve. Only when a working



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solution for the aviation industry has been established, it's anticipated that as the next step international shipping might become included in the emission trading system. It would be quite ineffective to complicate the 'CO₂-transport by ship' ETS discussion with the inclusion of 'CO₂ transport only'-shipping emissions whereas all shipping emissions might be included shortly. For instance, are only the emissions valid when the carrier is loaded with CO₂ and goes the empty ship 'free', and similar questions could be raised by situations involving a mixed cargo.

In a study within the IEA Greenhouse Gas R&D Programme performed by Mitsubishi Heavy Industries [Mitsubishi, 2004] the CO₂ emissions related to CO₂ maritime transportation were calculated and compared with the volumes of CO₂ transported. Although the results are largely dependent on a set of parameters like the distance between port and storage, the size and speed of the ship, it was demonstrated that for large volume ships (30,000 and 50,000 tonne) and distances up to 1,000 kilometer the ship fuel emissions are less than 1% from the amount of CO₂ transported. This 1% fraction is much lower than the 10% emission as calculated in the same study to result from the liquefaction of the CO₂-stream (with an atmospheric feed stream of CO₂, only 1.2% when delivered at the liquefaction plant at high pressure of 10 MPa). [From a 2004 article by Barrio & Aspelund "Shipbased transport of CO2" a 9% ratio can be calculated.] The IEA report further indicates a boil-off emission from the ship that is comparable in size with the ship emission from fuel consumption. The choice to cool the transported liquid CO₂ using boil-off evaporation instead of allowing a pressure build-up is probably related to the anticipated large shipping distances. In Chapter 4 "Transport of CO2" from the "IPCC Special Report on Carbon dioxide Capture and Storage" the CO2 emission due to both boil-off and exhaust from the ship's engine are estimated to be between 3 and 4% per 1,000 kilometer (without further references or clarification).

For the European situation with storage on the North Sea basin the distances are short enough to avoid the necessity of boil-off emissions. As a result the emissions from the ship engines are with less than 1% small compared to the amount of CO_2 transported and small compared to the emissions resulting from the capture, compression and liquefaction processes. With smaller ships (10,000 tonne) the relative fraction of the emission compared to the transported quantity increases to 2.5% for a 1,000 kilometer distance. This scale effect explains the use of supertankers for large distance oil transport; the shippers want to avoid that a ship requires a too significant fraction of its cargo volume for propulsion.

For ship owners it is quite unusual to accept the liability for the cargo they transport. They transport the cargo for the owner under an agreed set of conditions contract but as long as they don't make clear mistakes or culpable negligence, they will rarely become liable. With the formal addition of CO_2 -transport by ship as activity in the ETS it becomes questionable whether this approach can be maintained. The issue of liability for the transported CO_2 ship cargo is much less complex and/or voluminous than the liability issues concerning the final CO_2 storage, since:

- the quantity of the shipload is much smaller the cumulative quantity in the storage, and also
- the period of liability is limited to the duration of the transport and not potentially infinite as is the case for storage operators.



3.4 Chain step 4 Transfer to the storage location

After arrival at the storage site off shore platform the liquid CO_2 stream is transferred to the operator of the storage location. For injection into the underground reservoir the CO2 has to be heated up and pressurized. These process steps can be performed quite economically but still require energy input. Whether these steps are performed by the transport or the storage operator can be negotiated between these two parties. Whatever the outcome, the CO_2 emissions resulting from the energy consumption has to be accounted within the ETS. The transferred amount has to be measured with the ETS required accuracy.

4 **Off-shore monitoring methodology**

4.1 Introduction

In the 2011 CATO 2 report 4.1.5 a CCS transport network was discussed, which included off-shore storage. This chapter further explores the concept of monitoring in off-shore CO_2 storage. Measuring the CO_2 content in streams is not a common application of measuring equipment. Especially off-shore the measurement of CO_2 content with high accuracy requirements is a challenging task. In this chapter the technically feasible configurations are compared with the requirements.

In oil and gas production substances other then water or chemicals to assist the operation are injected into a well to enhance oil- and gas recovery. For these applications an accurate measurement of what is injected is of little importance. When injecting CO_2 for CCS-purposes the CO_2 represents value, and all streams have to be measured accurately before they are injected. In off-shore conditions this can be a challenge.

Currently there are guidelines on how a CO_2 stream should be measured and rules regulating the geological storage of CO_2 (CCS Directive) are well established in the EU. The Monitoring and Reporting guidelines (MRG) have been developed for his purpose. The MRG specifies that it should be known how much CO_2 enters and leaves an ETS-installation in 'Method A' which is discussed in chapter 3, paragraph 3.2.1. The regulation on CSS does however not contain any specifics on the measurement of CO_2 at sea yet, and this special situation is investigated in this chapter.

This chapter explores the above mentioned regulation in the off-shore situation. It takes the following approach:





- The off-shore situation is investigated. It is assumed that an off-shore sink receives CO2 at the end of a transport network.
- The rules that are applicable are investigated, the MRG requirements, CCS Directive. The definition of a wellhead is discussed and more information is obtained by interviewing experts in off-shore oil- and gas operations.
- Implementation discusses the practical aspects of off-shore CCS

4.2 Applicable rules

The CCS Directive and the MRG both mention 'monitoring' and by this they mean two different things. This can be confusing at first because the term monitoring is used from different viewpoints.

- In the CCS directive <u>monitoring is used to refer to the monitoring of the storage well itself for</u> operational and safety purposes. This means that the operator should be aware under which conditions the gas enters the well, what its composition is, how it migrates trough the well, what the conditions inside the well are and if leakage could be occurring. This can involve methods such as 3D geological models, surface detection devices, etc.
- The MRG refers to monitoring to determine the amount of the CO₂ that is transferred to a storage well. This has to be done with a set of requirements for measurement uncertainty.

The storage directive is meant to monitor the behavior of CO_2 gas that is stored underground, and the MRG is meant to be able to determine the amount of CO_2 transferred for emission trading purposes. They both apply in the situation of an off-shore well where CO_2 gas is injected into the well. When we talk about 'monitoring' we refer to the MRG definition of determining the amount of CO_2 transferred. Further details on the CCS directive and the MRG can be found in Appendix I: "Relevant texts from the MRG and CCS directive on monitoring".



4.3 Implementation

The regulation stated in the previous paragraph has practical consequences such as:

- Where the monitoring should be performed, according to the guidance and regulation.
- How the regulation has an effect on how injection stations should be laid out.

The two different types of monitoring mentioned in paragraph 4.2 have an overlap. For both types of monitoring the measurement of the volumetric flow and the composition of the gas is required. The CCS directive says the following about the monitoring of the stream (Annex II, 1.1):

- CO₂ volumetric flow at injection wellheads
- CO₂ pressure and temperature at injection wellheads (to determine mass flow)
- Chemical analysis of the injected material

4.3.1 Where should monitoring be performed?

What is the best location on an off-shore platform to perform the monitoring?

The MRG defines the point where measuring should be done as the system boundary of an EU Emission Trading System (ETS) installation. This definition suggests to use the 'wellhead' as the point where the monitoring for the CCS directive and MRG should be done. The practical consequences of this definition are considered in paragraph 4.3.3 of this chapter.

4.3.2 Industry practice

An industrial party has been consulted on their experience on injecting CO_2 off-shore. They operate a pilot CO_2 injection platform in the North Sea. The questioning focused on how they operate the platform and on the definition of the well-head' that is referred to in the CCS directive. In the off-shore industry a well-head is considered to be the end of the piping on an off-shore platform. This definition will be used in this deliverable.

4.3.3 **Schematic overview of typical installation**

We wish to measure a gas (with high accuracy) before it is injected into the well. That is not something that is done often. For reference we include the layout of a typical oil- and gas field here to make clear how the measurement of the quantity of streams is less important in normal oil- and gas field operations.

In figure 4.2 and figure 4.3 overviews of typical conventional oil- and gas field operations are given:



Figure 4.1 Upstream layout of a typical oil- and gas field

What can be seen in Figure 4.2 is that in such a set-up the metering to determine the amount of gas and oil is only done after processing (separation of oil, gas and water) has been done. In the case where a substance is injected as shown in Figure 4.3 (usually water in conventional fields to boost production) no metering is performed to determine the amount of injected substance.

The 'P' in Figure 4.2 and Figure 4.3 indicates the pressure measurement to ensure that the conditions under which the well is operated are correct.



Figure 4.2 Injection layout of a typical oil- and gas field

4.3.4 **Possible installation layout**

When reasoning with the monitoring and reporting guidelines (MRG) in mind, measuring should be done at the point where the ETS installation ends. That would be after the pressure has been regulated, and preferably at or otherwise just before the wellhead. After this point the CO_2 flows into the CCS reservoir and leaves the ETS trading system as such. The piping leading up to the wellhead can be considered as part of the storage site.

In Figure 4.4 below an illustration is made of where measurement would have to be situated when interpreting the CCS directive literally ('at the well-head') and the 'end' of an ETS installation. The 'G' indicates the gas meter which in this case would be integrated in the wellhead. It is assumed that the CO_2 is transferred to the platform using an underground pipeline that either comes from the shore or receives CO_2 from a ship at a nearby terminal as discussed in chapter 2 and 3 of this deliverable.





Figure 4.3 Example of the off-shore metering lay-out literally 'at the well-head'

However, integrating an accurate measurement device in the wellhead is not feasible, and is also not something that is done in a normal oil- and gas field (as can be seen in Figure 4.2). Figure 4.5 below illustrates the proposed situation in reality when the CO_2 is transferred from the shore using a pipeline. The gas meter before the well head can be considered as the last place where measurement can practically be done.



Figure 4.4 Example of the off-shore metering layout that is practically feasible

We see the gas meter on the platform ('G') before a pressure regulation device. Gas comes to the well at a different pressure (from a transport or distribution network or from a nearby terminal for a CO_2 carrier). Gas has to be measured before pressure regulation. In that way the problem of not having a lot of space on a platform is avoided, because measuring closely after a pressure regulation creates problems. This has to do with the flow being disturbed and possibly local phase changes that occur in the stream.



In other words: Measuring a gas stream accurately as is required by the MRG should happen in a stable stream, and on an off-shore platform with limited space that means the 'last point of measurement' should in practice be before pressure regulation – even though this differs from the literal text of the CCS directive and the MRG.

In the case of pressurized CO_2 being transferred to the off-shore injection platform the pressure regulation will typically be a pressure reduction. Because this pressure reduction results in a temperature drop a need for temperature control to reach the required injection temperature will exist.

As explained in chapter 2 liquefied CO_2 will have to be heated and pressured again for injection. This can happen on the ship and/or on the platform. Because the gas was cold it will have to be heated even when it is pressurised as described in chapter 2.

So in all cases the CO_2 stream will have to be heated to a moderate temperature and pressure regulated. Because seawater does not have a high enough temperature, the required energy is likely to involve some fuel input. The emissions associated with these operations are to be counted in the ETS. The same is true for any leakage from the system pipes, valves or pumps. The situation thus becomes as pictured in figure 4.6:





4.3.5 **Composition monitoring and chemical analysis**

The following was already discussed briefly in deliverable 4.1.5 of CATO2: To determine composition of the injected material it should be sufficient to know what goes into the transport network. Deliverable 4.1.5 states that measuring at the entrance of the network (at the source) would in theory be sufficient: If we know what goes in then we know what goes out. When this is done there should be no concern about substances threatening the integrity of the network, and discussions about the transport of chemical substances are avoided.



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However, the requirements in the storage directive (see paragraph 4.3.1) call for chemical analysis and monitoring of the composition at the wellhead. The CCS directive requires certainty about what's going into the well. If the rules are again interpreted literally that would call for a chemical analysis to monitor the composition on the off-shore platform where a wellhead is located. We reckon that this is not practical – having complex equipment such as a gas chromatograph to measure CO_2 composition off-shore is not practical in our opinion.

We therefore propose that, with the CCS directive's requirements in mind, the chemical analysis and monitoring of the composition of the CO_2 flow is done at the last point where any external party could have an influence on the gas being transported to the storage site can be ruled out.



Figure 4.6 An example of a situation where the chemical analysis and monitoring of the composition are performed on-shore

Considering that the gas is transported under high pressure and that a chemical analysis checks whether concentrations of certain substances in the gas fall within a certain bandwidth we assume that it can be ruled out that the transport to the off-shore storage site has any significant effect.

Figure 4.8 shows the same situation when CO_2 is transported by ship. Composition can then be determined on-shore.



Figure 7 An example of a situation where the chemical analysis and monitoring of the composition are performed on-shore at a harbour

The only foreseeable difficulty with determining the composition of the injected CO_2 on a storage site is when a storage site receives CO_2 from two or more different locations on-shore trough separate pipelines. If these pipelines connect and form a network it may be difficult to determine composition and especially a possible biomass fraction on-site. This was discussed in deliverable 4.1.5 of CATO2. So, when we continuously want to know the composition of the injected gas that comes from two or more different pipelines, assumptions about gas flows trough the network would have to be made through modeling, or monitoring of the composition would have to be done off-shore.



4.3.6 **Monitoring of pressure, temperature and fugitive emissions**

The measurement of pressure, temperature and fugitive emission such as stated in the CCS directive is rather straightforward (compared to the chemical composition):

- Measuring of pressure and temperature should be done at the wellhead. It is not for the purpose of establishing the amount of CO₂ that is injected but happens for operational and safety reasons and is specified by the CCS directive.
- The fugitive emissions on the platform will be small and can be estimated or taken as default values on a case-per-case base. These emissions do not include the fuel input for heating / pressurization mentioned in the previous paragraph

Taken together this results in a realistic and practical layout for off-shore injection of CO_2 . The complete layout is shown in Figure 4.9. The P and T sign mean pressure and temperature measurement.



Figure 4.8 Example of a monitoring set-up including pressure and temperature measurement, fugitive emissions and chemical analysis / monitoring of the composition

4.4 Conclusions on off-shore monitoring

In this chapter the monitoring on an off-shore platform is explored into more detail. The conclusions:

• Literal interpretation of the available regulation results in a situation that is impractical for measurement. Our proposal is to only determine the quantity of the flow of CO₂ injected once, on an off-shore platform before pressure regulation.



- The chemical analysis and monitoring of the composition is better performed on-shore and that this should not influence in a significant way the outcome of that analysis or composition monitoring.
- In a typical off-shore situation the 'well-head' or multiple well-heads are situated on a offshore platform and the distance between the last point where monitoring of the flow is performed can be kept minimal. Nothing should influence the amount transferred between the small 'no-mans-land' between the last point of measurement and the wellhead.
- And finally, one noticeable observation: when the CO₂ stream passes the transfer point between the transport operator and the storage operator, the CO₂ stream leaves the EU emission trading system. The stored amount of CO₂ is not registered in the ETS other than transferred and not emitted.



5 Identifying critical measurement conditions for orifice CO₂ flow measurement by means of uncertainty calculations

5.1 Introduction

Measurement of CO₂ should satisfy the requirements in the EU-ETS "Monitoring Reporting and Verification (MRV)" guidelines (EU, 2012). The MRV guidelines state that the uncertainties at transfer of carbon dioxide (MRV page 86) should fulfill the minimum requirement. That is it should remain under 2.5 % uncertainty (Tier 4 of EU ETS, page 98). This places constraint on the monitoring techniques to accurately monitor carbon dioxide during transport and storage phase. In a previous CATO2 deliverable the general requirements and implications of the measurements uncertainty are assessed. (CATO2, F.T. Blank, H. Spoelstra (2010). WP4.1-D03)

The objective of this research on uncertainty calculation is to assist in determining the critical parameters like temperatures, pressures, densities etc which should be avoided / carefully addressed to establish an accurate measurement. The monitoring device chosen for this study is an orifice meter. The basis to choose an orifice is that being a small device it can be easily fitted on offshore and onshore well sites without taking much space. It is commonly used for measuring large streams of gasses and liquids. In a previous CATO2 deliverable the applicability of measuring principles and techniques is assessed (CATO2, F.T. Blank, H. Spoelstra (2010). WP4.1-D02)

The primary places to monitor CO_2 streams are at the transfer points (see figure 5.1). At this transfer points the most common conditions of the CO_2 are:

- From Capture plant to the Network; At this point CO₂ can be present at relatively high temperatures >30 °C and high pressures >80 bar. At this pressure CO₂ will exist in a dense supercritical state. When cooling further in the pipeline this pressure will prevent the occurrence of a multiphase flow (gaseous and liquid).
- From the Network to the storage site (off shore or onshore). At this point CO₂ will commonly be
 present at lower temperatures 0-20 °C and high enough pressure to keep the CO₂ in liquid state.
 The measurement most probably take place before any further pressurization or de-pressurization
 for injection.





The range of pressures and temperatures at which CO_2 behaves as a liquid can be seen in Figure 2. It can also be seen that CO_2 behaves as a supercritical fluid at temperatures above 304.25 K (31 ^oC). The Density of liquid carbon dioxide varies with temperature and pressure changes. The temperature and pressure range selected are:



- Temperature range: 20-40 °C
- Pressure range: 8-15 MPa or 80-150 atm

The reason for selecting the particular temperature range is that it can help in studying carbon dioxide in both liquid and supercritical phases. Moreover it can be observed from figure 5.2 and the findings in this report that the change in physical properties of CO_2 under 20 $^{\circ}C$ are much smaller. This implies that below 20 $^{\circ}C$ uncertainties will also be met.

Carbon dioxide is pumped at high temperature (compression to a liquid raises temperature) after capture but gradually cools down during transport to the selected range. The reason to select the pressure range is that CO_2 is liquid or supercritical at these pressures within the selected temperature range. Moreover, carbon dioxide is captured as a gas and compressed to a dense liquid/gas, to be transported via pipelines. The compression and transport pressures can reach the selected pressures too. (*McCollum & Ogden, 2006, page 2*). Figure 2 gives the CO_2 phase changes at various temperatures and pressures.

Flow meters are used in the industry to measure the volumetric or mass flow rate of fluids. Differential pressure type flow meters measure flow rate by introducing a constriction in the flow. The pressure difference caused by the constriction is derived to the flow rate using Bernoulli's theorem. An orifice meter is a differential pressure flow meter which reduces or restricts the flow creating a pressure drop. (*Flow lab Orifice tutorial, 2007, page 1*)





5.2 Methods used to Establish / Calculate Uncertainty in CO₂ flow:

The research and the calculations are based on gas/liquid CO_2 flow and a requirement to meet a mass flow rate of 1-3 million ton/year. The selected mass flow is a logical transport quantity for a CCS project. Moreover, it is assumed that the carbon dioxide flow is pure.

For this research/case study the pipe and orifice dimensions are selected according to the selected mass flow rate. Moreover a CO_2 property calculator (*by McCollum of University of California, Davis*) is used for calculating the density of CO_2 at different temperatures. The calculator's data is used to set up an uncertainty spread sheet / calculator in excel to aid in the research.

The basis for the calculations is ISO 5167 named "Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 1: General principles and requirements standard approach". This ISO standard also gives an equation to directly calculate the uncertainty, used in this investigation.

The equation to calculate the mass flow rate q_m is taken from the ISO 5167-1 standard. It is:

$$qm = C * \varepsilon * \frac{\pi}{4} * d^2 * \frac{\sqrt{2\Delta P\rho}}{\sqrt{1 - \beta^4}} \qquad (1)$$

qm	Mass flow rate (kg/s)
С	Orifice coefficient (Unit less)
3	Expansibility [expansion] factor (Unit less)
d	Orifice throat diameter (m)
ΔP	Differential pressure or pressure difference (Pa)
ρ	density (kg/m3)
β	Beta / Diameter ratio = d/D (Unit less)
D	Pipe Diameter (m)

Some values of the variables in equation 1 are taken from the ISO standard (*ISO 5167-1, 2003, pages 15-18*) and the provided CO₂ property calculator. In this research CO₂ is considered liquid so ε is taken as unity (*ISO 5167-1, 2003, page5*). However, the pressure difference (ΔP) needs to be calculated and can only be calculated once the velocity is known. Moreover, Diameter ratio (β) is calculated too. The reason to calculate the diameter ratio is because of its dependence to the diameters which are chosen according to the pipe dimensions and the flow rate.

The calculated values for β should range between 0.3-0.7. A beta ratio lower then 0.3 means the orifice plate has a small hole i.e. pressure loss will be high. A higher beta ratio increases the discharge coefficient (**C**) uncertainty. Moreover, higher beta ratio means low differential pressure across orifice and difficulty to measure it. The orifice and pipe diameters are chosen as to keep the Beta ratio within range (<u>http://www.control.com/thread/1026239315</u>).

Secondly, the value of discharge coefficient (C) depends on the type of orifice being used. For the sake of calculations it is assumed that the orifice is a square edged one and thus C value is 0.61. (http://www.tasonline.co.za/toolbox/pipe/velorif.htm)



The mass flow rate is assumed between 1 and 3 million tons per year. To calculate the velocity the following equations taken from ISO 5167-1 are used:

$$qv = qm \div \rho$$
 (2)
 $V = qv \div A$ (3)

qv Volumetric flow rate (m3/s)

qm Mass flow rate (kg/s)

ρ density (kg/m3)

V Velocity (m/s)

A Area (m²)

First β or Diameter ratio is calculated using the following equation:

$$\beta = \frac{d}{D}$$
 (4)

After calculating the diameter ratio (β) and velocity (V), the pressure difference (ΔP) is calculated by using a rearranged form of equation 1 containing velocity instead of q_m . The reason to calculate (ΔP) is that it is dependent on the diameters of the pipe and orifice so it has to be calculated according to the diameters taken. Moreover, (ΔP) is a variable in equation 1 so it has to be calculated to see its effect on the uncertainty of q_m . The rearranged equation with velocity is as follows:

$$\Delta P = \left(\frac{v}{c}\right)^2 * \frac{\sqrt{1-\beta^4}}{2} * \rho \qquad (5)$$

 ΔP Differential pressure or pressure difference (Pa)

V Velocity (m/s)

 ρ density (kg/m³)

C Orifice coefficient (Unit less)

B Beta / Diameter ratio = d/D (Unit less)

After the calculation of variables, equation 1 is used to calculate the q_m . This is done so that qm contains all the influences caused by the input variables. Finally, the following equation from ISO 5167-1 (*ISO 5167-1, 2003 page 18*) is used to calculate the uncertainty. However, it must be noted that this equation is multiplied by 2 to get (95% CI / expanded uncertainty) in mass flow rate.

$$\frac{\delta q_m}{q_m} = \sqrt{\left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta \varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\beta^4}{1-\beta^4}\right)^2 \left(\frac{\delta D}{D}\right)^2 + \left(\frac{2}{1-\beta^4}\right)^2 \left(\frac{\delta d}{d}\right)^2 + \frac{1}{4} \left(\frac{\delta \Delta p}{\Delta p}\right)^2 + \frac{1}{4} \left(\frac{\delta \rho_1}{\rho_1}\right)^2} \quad * 2$$
(6)

The $\delta C / C$ and all other variables / sensitivities are represented as percentages in equation 6. The value of $\delta \Delta P / \Delta P$ is user defined. For this case study calculation it is assumed 1%. The basis for this assumption is that the diameter ratio is chosen between 0.3-0.7 which is ideal for many reasons as described here. Moreover, having an ideal beta ratio will also decrease the pressure loss or difference thus keeping the uncertainties or variations low.

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The value of the standard uncertainties (for example $\delta D / D$) are taken from the ISO 5167-1 standard (ISO 5167-1, 2003, page 15-18)

- a) The value of $\delta D / D$ cannot exceed 0.4%
- b) The value of δd / d has a maximum value of 0.1%.
- c) The value of $\delta C / C$ is taken as values below 0.23%.
- d) The value of $\delta\epsilon / \epsilon$ is varied to judge its effect.

The uncertainty of the density is dependent of the method to calculate or measure the density. The density of pure CO_2 can easily be derived from the measured temperature of the CO_2 . Therefore the sensitivity of the density (ρ) towards the different temperatures needs to be established.

The default uncertainty in temperature here is taken as ± 1 °C. At this temperature steps the calculated densities are used to establish the sensitivity towards temperature changes.

Sensitivity of
$$b = \frac{a-c}{b}$$
 (7)

Where a and c represent two values of density at different temperature.

This is clarified by an example given in figure 5.3, using the density figures which are also given in figure 5.7.

	Temperature ℃	Density kg/m ³
А	34	702.6
В	35	679.9
С	36	657.3

Figure 5.3: Sensitivity Analysis Variables

The uncertainty of b is then calculated using normal distribution method for a CI of 95%. That is:

Ub (%) =
$$\frac{\text{Sensitivity}}{2} * 100$$
 (8)

A sample calculation for equations 7 & 8 is as follows:

Sensitivity of b (35 °C) = (702.6 - 657.3) / 679.9 = 0.067

Which results in: Ub = 0.067 / 2 * 100 = 3.4 %



5.3 Results / Discussions / Sample Calculations:

After the calculation a calculator is set up in MS-Excel. The reason to set up a calculator is to aid in monitoring the changes in the uncertainty with the changes in temperature, pressure and densities, etc. The screenshot of the calculator is given in figure 5.4.

Input Parameters:	Units	Temperatu re (°C)	Density (Kg/m^3)	q _v (m³/s)	Orifice Velocity (m/s)	∆ P (Pa)	q _m (kg/s)	% δC/C	% δε/ε	% δd/d	% δD/D	δΔ Ρ /ΔΡ	% δρ/ρ	% u qm (95% Cl)
		20	848.9	0.037	0.528	277	31.69							
Orifice Coefficient (C)		21	841.7	0.038	0.533	279	31.69	0.23	0.2	0.1	0.2	1	0.9	1.57
0.61	-	22	833.3	0.038	0.538	282	31.69	0.23	0.2	0.1	0.2	1	1.0	1.62
Expanisbility Factor (e)		23	824.8	0.038	0.543	285	31.69	0.23	0.2	0.1	0.2	1	1.0	1.63
1		24	816.3	0.039	0.549	288	31.69	0.23	0.2	0.1	0.2	1	1.0	1.64
Beta (β)		25	807.8	0.039	0.555	291	31.69	0.23	0.2	0.1	0.2	1	1.1	1.64
0.600	-	26	799.3	0.040	0.561	294	31.69	0.23	0.2	0.1	0.2	1	1.1	1.66
Orifice Diameter (d)		27	790.6	0.040	0.567	297	31.69	0.23	0.2	0.1	0.2	1	1.1	1.69
0.3	m	28	781.5	0.041	0.574	301	31.69	0.23	0.2	0.1	0.2	1	1.2	1.72
Pipe Diameter (D)		29	772.4	0.041	0.580	304	31.69	0.23	0.2	0.1	0.2	1	1.2	1.73
0.5	m	30	763.3	0.042	0.587	308	31.69	0.23	0.2	0.1	0.2	1	1.2	1.74
Orifice Area		31	754.2	0.042	0.594	312	31.69	0.23	0.2	0.1	0.2	1	1.2	1.75
0.070695	m²	32	745.1	0.043	0.602	315	31.69	0.23	0.2	0.1	0.2	1	1.9	2.32
Mass Flow rate q _m		33	725.2	0.044	0.618	324	31.69	0.23	0.2	0.1	0.2	1	2.9	3.20
31.68808781	. kg/s	34	702.6	0.045	0.638	334	31.69	0.23	0.2	0.1	0.2	1	3.2	3.46
Mass Flow Rate q _m		35	679.9	0.047	0.659	346	31.69	0.23	0.2	0.1	0.2	1	3.3	3.56
1	miilion ton / yr	36	657.3	0.048	0.682	358	31.69	0.23	0.2	0.1	0.2	1	3.4	3.67
Pressure Used		37	634.7	0.050	0.706	370	31.69	0.23	0.2	0.1	0.2	1	3.7	3.87
9.5	Mpa	38	610.9	0.052	0.734	385	31.69	0.23	0.2	0.1	0.2	1	4.3	4.46
		39	582.4	0.054	0.770	404	31.69	0.23	0.2	0.1	0.2	1	4.9	5.05
		40	553.9	0.057	0.809	424	31.69							

Figure 5.4: Calculator

The input parameters can be changed as desired under the limits described in this report. The pressure used has a range from 8 to 15. The calculator takes up the density values for each pressure from the reference table developed by using the CO_2 property calculator (*by McCollum of University of California, Davis*). Moreover, the standard uncertainty can also be changed as desired under the limits described in section 4.

Sample calculations done to create the calculator at 9.5 MPa, 21° C and 1 million ton CO₂ /yr are as follows:

Using equation 2 volumetric flow (q_v): 31.69 / 841.7 = 0.038 m³/s

Using equation 3 Velocity (v): 0.038 / 0.070695 = 0.533 m/s

Using equation 5 ΔP : 0.533 * $\left(\frac{\sqrt{(1-0.6)}}{2*0.61}\right)^2$ * 841.7 = 279 Pa

Using equation 1 q_m: $0.61 * 1 * \frac{pi}{4} * 0.3 * (\frac{\sqrt{2*279*841.7}}{\sqrt{1-0.6^4}}) = 31.69$ kg/s

Using equation 6 the expanded uncertainty is:

$$(\delta q_m / q_m): \ (\sqrt{0.23^2 + 0.2^2 + \left(\frac{2*0.6^4}{1 - 0.6^4}\right)*0.4^2 + \left(\frac{2}{1 - 0.6^4}\right)*0.1^2 + \frac{1}{4}*1^2 + \frac{1}{4}*0.9^2} * 2 = 1.62 \%$$



Using the calculator at different pressures and flow rates it is concluded that the uncertainty in the mass flow rate (q_m) is mainly dependent on the density and the operating pressure.

It is also observed that $\delta \Delta P / \Delta P$ has relative large effect on the uncertainty in the mass flow rate (q_m) after density. So for the sake of calculation the value of $\delta \Delta P / \Delta P$ is selected as better than 1%, being the maximum of commonly used pressure difference transmitters in their optimum measurement range. However, $\delta \Delta P / \Delta P$ value is specified by the manufacturer in specific measurement ranges and these values should be used when performing specific uncertainty calculations. The results are shown in figure 5.5 and explained here.

Tempera	ature (°C)					10.5	11	11.5	12	12.0	15	15.5	14	14.5	15
						, i	u q _m (%)								
2	.0					-									
2	1 1	.73 1.	66 1.61	1.57	1.54	1.51	1.49	1.47	1.46	1.45	1.43	1.42	1.42	1.41	1.40
2	2 1	.86 1.	76 1.68	1.62	1.58	1.54	1.52	1.50	1.48	1.46	1.45	1.44	1.43	1.42	1.41
2	3 1	.89 1.	78 1.69	1.63	1.59	1.55	1.52	1.50	1.48	1.47	1.45	1.44	1.43	1.42	1.41
2	4 1	.90 1.	79 1.70	1.64	1.59	1.55	1.53	1.50	1.49	1.47	1.46	1.44	1.43	1.42	1.41
2	5 1	.92 1.	80 1.71	1.64	1.60	1.56	1.53	1.51	1.49	1.47	1.46	1.45	1.43	1.42	1.41
2	.6 2	2.24 1.	95 1.77	1.66	1.60	1.56	1.54	1.52	1.51	1.50	1.48	1.47	1.45	1.44	1.42
2	.7 3	3.46 2.4	48 1.95	1.69	1.58	1.54	1.54	1.55	1.56	1.57	1.56	1.55	1.52	1.49	1.45
2	8 4	1.50 2.	93 2.10	1.72	1.57	1.53	1.54	1.57	1.61	1.63	1.63	1.61	1.57	1.53	1.48
2	9 4	1.69 3.	00 2.13	1.73	1.57	1.53	1.55	1.58	1.61	1.63	1.64	1.61	1.58	1.53	1.48
3	0 4	1.89 3.	07 2.15	1.74	1.58	1.54	1.55	1.59	1.62	1.64	1.64	1.62	1.58	1.54	1.49
3	1 5	5.12 3.	14 2.18	1.75	1.58	1.54	1.56	1.59	1.63	1.65	1.65	1.63	1.59	1.54	1.49
3	2 6	5.02 4.	04 2.94	2.32	1.98	1.79	1.69	1.64	1.61	1.59	1.58	1.56	1.54	1.52	1.49
3	3 7	7.30 5.	32 4.06	3.20	2.59	2.17	1.88	1.69	1.58	1.52	1.49	1.48	1.48	1.49	1.50
- 3	4 8	3.06 5.	84 4.43	3.46	2.77	2.27	1.93	1.71	1.58	1.51	1.48	1.47	1.47	1.49	1.50
- 3	5 8	3.73 6.	17 4.61	3.56	2.82	2.30	1.95	1.72	1.59	1.51	1.48	1.47	1.48	1.49	1.51
3	6 9	9.54 6.	55 4.81	3.67	2.88	2.33	1.97	1.73	1.59	1.52	1.48	1.47	1.48	1.49	1.51
- 3	9	9.95 6.	83 5.04	3.87	3.05	2.47	2.07	1.80	1.63	1.54	1.50	1.48	1.48	1.49	1.51
3	8 /	.76 6.	43 5.37	4.46	3.69	3.04	2.52	2.12	1.84	1.66	1.55	1.50	1.48	1.49	1.50
3	9 5	0.50 6.	00 5.71	5.05	4.31	3.59	2.95	2.43	2.03	1.//	1.00	1.52	1.48	1.48	1.50

Figure 5.5: Uncertainties at Different Pressures and Temperatures

Figure 5.5 shows that:

- The uncertainties vary greatly with the increase in temperature at low pressures. The reason
 is that at low pressures and high temperatures the CO₂ changes phase to become super
 critical with densities close to a vapor.
- Moreover as pressure increases the uncertainty vary less at high temperatures. The reason is that at high pressures and temperature the CO₂ changes into a more dense critical fluid. The densities are close to the liquid.

These results prove that the main variable affecting the uncertainty is the change in density and the uncertainty associated to that phenomenon.

A graph (Figure 5.6) is made to visualize the effects of figure 5.5 in a better way:



Figure 5.6: Change in Uncertainty with Increase in Temperature and Pressure

From figure 5.6 it can be concluded that to keep uncertainties low and satisfy the EU ETS requirement the ideal temperature are below 30 °C and above 9 MPa.

The calculations performed and results shown above satisfy the requirements of EU but it must be noted that the uncertainty calculated here is of pure CO_2 . In real flows the stream of CO_2 has some impurities in it, for example N_2 . The presence of gasses has a substantial influence on the density of the CO_2 mixture. The change in density is calculated in reference (DLR, 2011) for a 100 mol% CO_2 mixture at 792 kg/m³ at 110 bar, 30 °C as 792 kg/m³ and for a 95 mol% CO_2 / 5 mol% N_2 mixture; 681 kg/m³. The change per mol% then is 2.7% change in density.

In CATO2 deliverable 4.1.01 chapter five (CATO2 2010) the expected concentrations for three capture processes is given. For Post combustion Capture (amine absorption) the expected concentration is 99.5%, Pre combustion Capture (IGCC & physical absorption) 99.9% and for Oxyfuel (coal) 99.2% of CO_2 . If assuming a general purity of the capture processes of 99 - 100 %, the change in density is 97.3-100%.

The associated uncertainty in the density can be found out by using the rectangular distribution method (QUAM, 2000, page 102).

A sample calculation is: $(\frac{100-97.3}{2})/\sqrt{3}$ = 0.78%



Within this purity range stated above the change in density is relatively small in comparison with the required measurement uncertainty (2.5%). A limited number of analysis per year (4) will suffice to establish the CO_2 concentration and calculated density. With higher concentration of impurities an increased number of analysis or continuous analysis of CO_2 concentration and other main components would be required. This information could also be supplied by the network operator by calculation of the input streams in the network.

The values from the calculator were also used to set up a density vs pressure graph of CO_2 (Fig. 5.7). The figure clearly shows and illustrates the findings on uncertainty of CO_2 flow measurements and the density.

- At high pressures and low temperatures the density fluctuations are low.
- At low pressure 8-12 MPa the density drops at high temperatures. This means that the liquid CO₂ becomes a gas.
- It can also be seen that the below 30 ^oC the density fluctuate less along the temperature range meaning the CO₂ remains as a liquid. This observation also proves and supports the conclusions from figure 5.5 and 5.6.
- The red circle shown shows the area that should be avoided to have lower uncertainties and good monitoring values.



Figure 5.7: Density versus Pressure



5.4 Conclusion:

It can be concluded from the calculations and results that using an orifice for CO₂ flow measurements is well feasible under 30 °C and relatively high pressures.

Moreover, it is also concluded that the biggest effect on the uncertainties is caused by variations in density. The density is sensitive to the increase in temperature and pressure changes. So it must be made sure that optimum conditions are present during the transport of CO₂. Optimum conditions can be temperatures below 30 °C and pressures in the ranges above 9 MPa.

These conditions can be easily met at the end of the pipeline in countries with colder climate, for example the Netherlands. However after the capture process it is well possible that CO_2 is at temperatures and/or pressures giving too large uncertainties in the CO_2 measurement using an orifice. At these conditions the uncertainty of the flow measurement could be improved by better temperature measurement or online density measurement.

In regions with hot and arid climate such as the Middle East CO_2 will more or less exist around the super critical stage at the storage side also. Other measurement techniques could then better provide the monitor of supercritical CO_2 at high temperatures.

If the CO_2 has purity over 99% the associated density change is of minor influence on the total measurement uncertainty. Under this range density needs to be measured at increased intervals or continuously measured direct or from composition.

The uncertainty conclusions on orifice flowmeters will also typically apply for a Venturi meter, as the measurement principle and calculations are similar. The uncertainty calculation method therefore is described in ISO standard 5167-3.

The results of this study do not exclude the applicability of other types of flow meters. Magnetic or ultrasonic flow meters are small and can be easily used on shore or off shore. Coriolis meters directly measuring the stream in ton/hour would be a good alternative, but are not available for the magnitude of flow within CCS.



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Appendix I: Relevant texts from the MRG and CCS directive on monitoring

Explicit requirements from relevant documents

EU 2007

Establishing Guidelines for the Monitoring and Reporting of Greenhouse Gas Emissions Pursuant to Directive 2003/87/EC of the European Parliament (2007).

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:229:0001:0085:EN:PDF

EU 2007 Annex I, Section 10.1: Data Acquisition and Handling

The operator shall establish, document, implement and maintain **effective data acquisition and handling activities** (hereinafter referred to as data flow activities) for the monitoring and reporting of greenhouse gas emissions in accordance with the approved monitoring plan, the permit and these guidelines. These data flow activities include **measuring, monitoring, analyzing, recording, processing and calculating parameters** in order to be able to report on the greenhouse gas emissions.

This section refers to a quality assurance system that has to be in place for the data acquisition and handling activities.

EU 2007 Annex 1, Section 16: Requirements for installations with low emissions

To Sections 4.3, 5.2, 7.1, 10 and 13 the following exemptions from the requirements of this Annex shall apply for installations with average verified reported emissions of less than 25 000 tonnes of CO_2 per year during the previous trading period. If the reported emission data are no longer applicable because of changes to the operating conditions or the installation itself or if a history of verified emissions is missing, the exemptions apply if the competent authority has approved a conservative projection of emissions for the next five years with less than 25 000 tonnes of fossil CO_2 for each year. Member States may waive the mandatory need for annual site visits by the verifier in the verification process and let the verifier take the decision based on the results of his risk

analysis:

— Where necessary, the operator may use information as specified by the supplier of relevant measurement instruments irrespective of specific use conditions to estimate the uncertainty of activity data,

— Member States may waive the need of proof of compliance with the requirements regarding calibration in Section 10.3.2 of this Annex,

— Member States may permit the use of lower tier approaches (with Tier 1 as minimum level) for all source streams and relevant variables,

— Member States may permit the use of simplified monitoring plans which contain at least the elements listed under items (a), (b), (c), (e), (f), (k) and (l) as listed in Section 4.3 of this Annex,

- Member States may waive requirements regarding the accreditation against EN ISO 17025:2005 if the laboratory in question:

- provides conclusive evidence that it is technically competent and is able to generate technically valid results using the relevant analytical procedures, and

- participates annually in inter-laboratory comparisons and subsequently undertakes corrective measures if necessary,

— the uses of fuels or materials can be determined based on purchasing records and estimated stock changes without further consideration of uncertainties.



When the emissions of transport infrastructure are the result of operating them and leakage, they will qualify as installations with low emissions. This reduces the requirements following from EU2007 and EU 2010.

EU 2009a

DIRECTIVE 2009/29/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009

amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0063:0087:en:PDF

EU 2009a Article 14.4, Monitoring and reporting of emissions

4. The regulation referred to in paragraph 1 may include requirements on **the use of automated systems and data exchange formats** to harmonise communication on the monitoring plan, the annual emission report and the verification activities between the operator, the verifier and competent authorities.';

Automated data acquisition methods are discussed here. This is relevant for off-shore applications.

EU 2009b

Directive of the European Parliament and of the Council on the Geological Storage of Carbon Dioxide and Amending Council Directives 85/337/EEC, 96/61/EC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No 1013/2006.

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

EU 2009b Page 10-11/123-124, Article 7.4, Application of storage permits

Applications to the competent authority for storage permits shall include at least the following information:

•••

4. the total quantity of CO_2 to be injected and stored, as well as the prospective sources and **transport methods**, the composition of CO_2 streams, the injection rates and pressures, and the location of injection facilities;

The is relevant in relation to EU2010:

- Transport method (source), composition and injection rates will in part overlap with EU2010, the CCS MRG
- The location will describe the interface, possible the 'wellhead' as mentioned in EU2009b, the Storage directive

EU 2009b Article 9.4, Content of storage permits

The permit shall contain at least the following:



•••

4. the requirements for the **composition** of the CO_2 stream and the CO_2 stream acceptance procedure pursuant to **Article 12**, and, if necessary, further requirements for injection and storage in particular to prevent significant irregularities;

EU 2009b Article 12 refers to the 'composition' of the CO₂ stream:

EU 2009b Article 12.1, 12.3, CO2 stream acceptance criteria and procedure

1. A CO₂ stream shall consist overwhelmingly of carbon dioxide. To this end, no waste or other matter may be **added** for the purpose of disposing of that waste or other matter. However, a CO₂ stream **may contain incidental associated substances from the source**, capture or injection process and trace substances added to assist in monitoring and verifying CO₂ migration. Concentrations of all incidental and added substances shall be below levels that would:

(a) adversely affect the integrity of the storage site or the relevant transport infrastructure;

(b) pose a significant risk to the environment or human health; or

(c) breach the requirements of applicable Community legislation.

3. Member States shall ensure that the operator:

(a) accepts and injects CO₂ streams only if an analysis of the **composition**, **including corrosive substances**, of the streams and a risk assessment have been carried out, and if the risk assessment (**Annex 1**) has shown that the contamination levels are inline with the conditions referred to in paragraph 1;

(b) keeps a register of the quantities and properties of the CO_2 streams delivered and injected, including the composition of those streams.

The analysis of the composition of CO₂ streams is clearly meant to identify

- Possible waste related issues
- Posible side effects with non-CO₂ substances in the reservoir

The 'composition' as mentioned here is not meant to determine the amount of CO_2 and in that sense does not relate to the CCS MRG (EU2010).

EU 2009b Article13.2, Monitoring

Page 11/124, Article14, Reporting by the operator

At a frequency to be determined by the competent authority, and in any event at least once a year, the operator shall submit to the competent authority:

1. all results of the monitoring pursuant to Article 13 in the reporting period, including information on the monitoring technology employed;

2. the quantities and properties of the CO_2 streams delivered and injected, including composition of those streams, in the reporting period, registered pursuant to Article 12(3)(b);



3. proof of the putting in place and maintenance of the financial security pursuant to Article 19 and Article 9(9);

4. any other information the competent authority considers relevant for the purposes of assessing compliance with storage permit conditions and increasing the knowledge of CO_2 behaviour in the storage site.

So, following from the requirements of EU2009b at least once a year a report on the <u>geological</u> <u>aspects</u> of CCS has to be made. This is unrelated to the requirements for EU2007 and EU2010.

EU 2009b Article15, Inspections

1. Member States shall ensure that the competent authorities organise a system of routine and nonroutine inspections of all storage complexes within the scope of this Directive for the purposes of checking and promoting compliance with the requirements of the Directive and of monitoring the effects on the environment and on human health.

2. Inspections should include activities such as visits of the <u>surface installations</u>, including the injection facilities, assessing the injection and monitoring operations carried out by the operator, and checking all relevant records kept by the operator.

3. Routine inspections shall be carried out at least once a year until three years after closure and every five years until transfer of responsibility to the competent authority has occurred. They shall examine the relevant injection and monitoring facilities as well as the full range of relevant effects from the storage complex on the environment and on human health.

4. Non-routine inspections shall be carried out:

(a) if the competent authority has been notified or made aware of leakages or significant irregularities pursuant to Article 16(1);

(b) if the reports pursuant to Article 14 have shown insufficient compliance with the permit conditions;

(c) to investigate serious complaints related to the environment or human health;

(d) in other situations where the competent authority considers this appropriate.

5. Following each inspection, the competent authority shall prepare a report on the results of the inspection. The report shall evaluate compliance with the requirements of this Directive and indicate whether or not further action is necessary. The report shall be communicated to the operator concerned and shall be publicly available in accordance with relevant Community legislation within two months of the inspection.

There is a reference to 'surface installations'. This means that in case the wellhead is not located on the surface this does not apply.



Annex I, Step 3.1, Criteria for the characterisation and assessment of the potential storage complex and surrounding area referred to in article 4(3) - Characterisation of the storage dynamic behavior

At least the following factors shall be considered:

(a) possible injection rates and CO₂ stream properties;

(b) the efficacy of coupled process modelling (that is, the way various single effects in the simulator(s) interact);

(c) reactive processes (that is, the way reactions of the injected CO_2 with in situ minerals feedback in the model);

(d) the reservoir simulator used (multiple simulations may be required in order to validate certain findings);

(e) short and long-term simulations (to establish CO_2 fate and behaviour over decades and millennia, including the rate of dissolution of CO_2 in water).

The dynamic modelling shall provide insight into:

(f) pressure and temperature of the storage formation as a function of injection rate and accumulative injection amount over time;

- (g) areal and vertical extent of CO_2 vs time;
- (h) the nature of CO_2 flow in the reservoir, including phase behaviour;
- (i) CO₂ trapping mechanisms and rates (including spill points and lateral and vertical seals);
- (j) secondary containment systems in the overall storage complex;
- (k) storage capacity and pressure gradients in the storage site;
- (l) the risk of fracturing the storage formation(s) and caprock;
- (m) the risk of CO_2 entry into the caprock;

(n) the risk of leakage from the storage site (for example, through abandoned or inadequately sealed wells);

- (o) the rate of migration (in open-ended reservoirs);
- (p) fracture sealing rates;

(q) changes in formation(s) fluid chemistry and subsequent reactions (for example, pH change, mineral formation) and inclusion of reactive modelling to assess affects;

(r) displacement of formation fluids;



(s) increased seismicity and elevation at surface level.

The reference to the composition made in Article 11 and Article 12, and the accompanying risk analysis, is related to the geological impact of injected streams.

Annex II 1.1, Criteria for establishing and updating the monitoring plan referred to in article 13(2) and for post-closure monitoring

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 CO₂ at the injection facility;

(f) CO₂ volumetric flow at injection wellheads;

(g) CO₂ 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 CO₂-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 CO₂ out of the storage complex.

Annex II defines what a monitoring plan for a geological storage should contain. Under point (f) and (g) the measurement of flow, pressure and temperature is defined. This has to happen 'at the wellheads'. In oil and gas exploration a wellhead is the construction that forms the end of a bore hole. Usually on top of such a wellhead a blow out preventer construction will be mounted. This construction is used to seal the well in emergencies. On top of this a so called 'Christmas Three' is placed. This is equipment to control the pressure and flow of the stream coming out or being injected into the well. Other functionality is provided by modern Christmas Three equipment as well: This includes monitoring of the flow, temperature and pressure measurements. Christmas Three equipment is distinguished in two categories, surface equipment and submerged for off-shore wells. These categories are referred to as 'Surface Three' and 'Subsea Three'. A Surface Tree may be places on land, or on a platform at sea. A Subsea Tree will be submerged. It will have a different design as a Surface Three. It will consist of fewer separate parts and be constructed of corrosion resistant material. Control of a Subsea tree will happen via a so called umbilical cable. Such a cable contains electronic and hydraulic connections.

In the case of subsea storage the monitoring that is mentioned will be located at a Surface Tree on a platform or on a Subsea Tree. This is what is meant by 'at the wellhead' in the text.

EU 2010

<u>Commission Decision of 8 June 2010 amending Decision 2007/589/EC as regards the</u> inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide.

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:155:0034:0047:EN:PDF

EU2010, the CSS Monitoring and Reporting Guidelines (CCS MRG) amend and replace sections of EU2007.

Annex I Section 2 (b):

'(j) 'measurement point' means the emission source for which continuous emission measurement systems (CEMS) are used for emission measurement, or the cross-section of a pipeline system for which the CO_2 flow is determined using continuous measurement systems.'

The inclusion of pipeline systems is clearly defined here:

EU 2010 Annex I Section 5.7 adds the following cases of transferred CO₂ out of and installation:

- $-CO_2$ transferred to capture installations,
- CO₂ from capture installations transferred to transport networks,
- $-CO_2$ from transport networks transferred to storage sites.

This does not mention a transport method using shipping of CO₂.

Annex XVII Section 2: Quantification of CO₂ Emissions

EU 2010 Emissions of a transport network are defined as follows:

During the transport of CO_2 by pipeline, potential emission sources for CO_2 emissions include:



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- combustion and other processes at installations functionally connected to the transport network,

- e.g. booster stations,
- fugitive emissions from the transport network,
- vented emissions from the transport network,
- emissions from leakage incidents in the transport network.

It can be assumed that these are below 25000 tons in all foreseeable situations.