CLEEN
Cluster for Energy and Environment

Helsinki 2012

Reetta Sorsa

Transportation of CO_2 by ship: Monitoring of greenhouse gas emissions

ccsp
Carbon Capture and Storage Program

CLEEN LTD
ETELÄRANTA 10
P.O. BOX 10
FI-00130 HELSINKI
FINLAND
www.cleen.fi

Cleen Ltd.

Reetta Sorsa

Transportation of CO_2 by ship: Monitoring of greenhouse gas emissions

ccsp
Carbon Capture and Storage Program

Cleen Ltd
Helsinki 2012

Report Title: Transportation of CO_2 by ship: Monitoring of greenhouse gas emissions

Key words: ship transportation, carbon dioxide (CO_2), carbon capture and storage (CCS), monitoring, greenhouse gas emissions.

Abstract

According to the directive of European Union on emission trading scheme, the only permitted transportation method of CO_2 is transportation by pipeline (EC, 2009). Finland has prohibited geological storage of CO_2 in its territory (L416/2012). This is one reason why transportation of CO_2 by ship could be important in the future.

The emission trading directive includes an opportunity to extend the emission trading scheme by adding new sectors. The way to include new sectors is the so-called comitology process. This way the CO_2 transportation by ship could be covered by the emission trading directive. If covered, captured CO_2 that is transported by ship to a storage location and stored in a geological formation could be accounted as an avoided emission of a particular plant and the emission reduction could be taken into account in the emission trading scheme. However, guidelines for monitoring, reporting and verification for CO_2 transportation by ship needs to be established first in order for CO_2 transportation by ship to be included in the emission trading scheme as a new sector (HE 36/2012vp).

The ability to measure, report, and verify CO_2 emission reduction activities is a key requirement of any greenhouse gas mitigation approach. In this report the transportation of CO_2 by ship and monitoring of this action is being studied. Outline of monitoring procedure for ship transportation is introduced.

Helsinki, December 2012

Table of contents

1 Introduction

According to the directive of European Union on emission trading scheme, the only permitted transportation method of CO_2 is transportation by pipeline (EC, 2009). This can be a legislative barrier to carbon capture and storage activities in Finland. The possibility of transporting CO_2 by ship is important. First of all, Finland has prohibited geological storage of CO_2 in its territory (L416/2012). Second, the nearest potential storage sites are located far away and are, to a large extent, offshore. Third, the largest potential power plants and industrial sites to implement carbon capture and storage in Finland are located on the coast. In addition, ship transportation can be economically more viable than pipeline transportation when the transportation distance is long, about 1000 km (IPCC, 2005). However the distance where ship transportation becomes cheaper than pipeline transportation is not only a matter of distance. It involves many other factors, such as transport capacity of the route, fuel cost, loading terminals etc. (IPCC, 2005).

The emission trading directive includes an opportunity to extend the emission trading scheme by adding new sectors. The way to include new sectors is the so-called comitology process. This way the CO_2 transportation by ship could be covered by the emission trading directive. If covered, captured CO_2 that is transported by ship to a storage location and stored in a geological formation could be accounted as an avoided emission of a particular plant and the emission reduction could be taken into account in the emission trading scheme. However, guidelines for monitoring, reporting and verification for CO_2 transportation by ship needs to be established first in order for CO_2 transportation by ship to be included in the emission trading scheme as a new sector (HE 36/2012vp).

The ability to measure, report, and verify CO_2 emission reduction activities is a key requirement of any greenhouse gas mitigation approach. In this report the transportation of CO_2 by ship and monitoring of this action is being studied. Outline of monitoring procedure for ship transportation is being introduced.

2 Transportation of CO_2 by ship

The cycle of ship transport is discrete; it includes all processes receiving CO_2 from the capture process to its injection into a reservoir (see fig. 1). A marine transportation system includes temporary storage on land and a loading facility. If the delivery point is onshore, the CO_2 is unloaded from the ship into temporary storage tanks. If the delivery point is offshore, ship might unload (IPCC, 2005):

- to a platform
- to a floating storage facility
- to a single-buoy mooring, or
- directly to a storage system

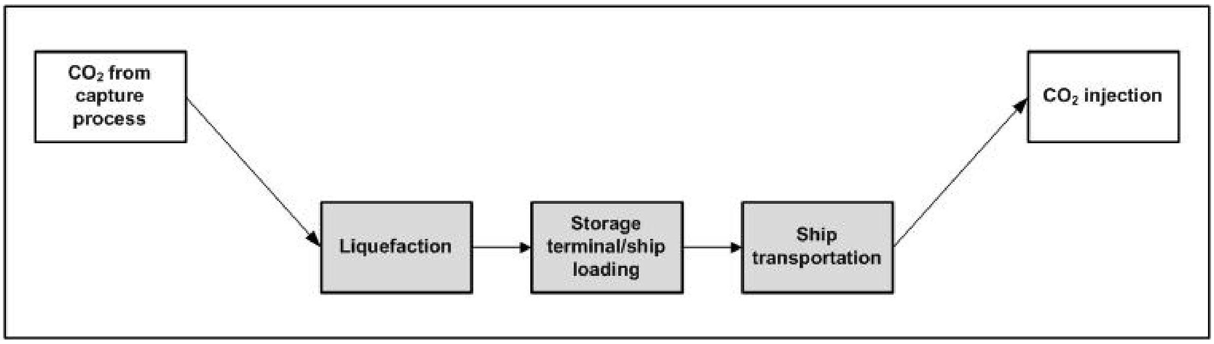

Figure 1. Carbon capture and storage chain. The boxes in grey indicate the phases that belong to the ship transportation and are included in this report.

2.1 Liquefaction

Lee et al. (2012) studied multistage liquefaction cycles. CO_2 itself can be used as a coolant as well as an external cooling media. Contaminants from the carbon dioxide stream are removed before liquefaction process. Water is usually removed before and during CO_2 liquefaction process in order to avoid gas hydrates, the freezing of water and corrosion. The liquid CO_2 resulting from the liquefaction process is sent to a CO_2 intermediate storage terminal.

2.2 Storage terminal and ship loading

Lee et al. (2012) modelled an intermediate CO_2 storage system for long-distance ship transportation (see fig 2.) It was composed of four processes:

- CO_2 input process
- storage tank and loading process
- recirculation process, and
- boiled-off gas (BOG) reliquefaction process

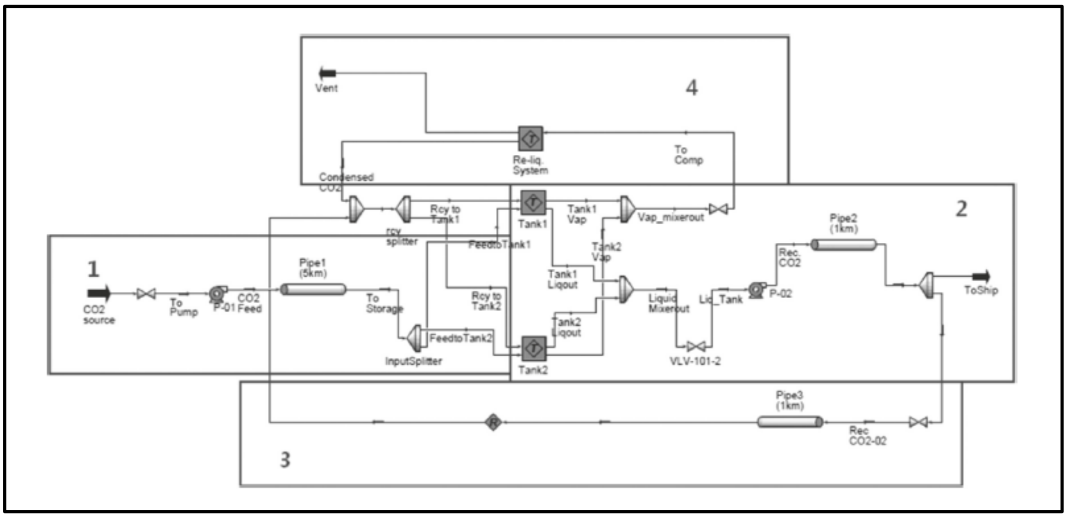

Figure 2. Flow diagram of intermediate CO_2 storage terminal system (Lee et al., 2012).

Intermediate storage terminal serves as a port for CO_2 carriers and storage tank. The liquid CO_2 accumulates inside the storage tank due to the continuous CO_2 feed, and a small part of the liquid CO_2 is recirculated to maintain cryogenic conditions inside the loading pipeline. Other option is to feed liquid CO_2 continuously into tanks, while the stored CO_2 is sent to the transportation ship. The storage terminal performs as a buffer between the continuous CO_2 liquefaction process and discrete marine ship transportation (Lee et al., 2012).

2.2.1 Recirculation process

In order to maintain the CO_2 in the liquid phase during the whole process, both the pipeline and the tank temperature should be kept within the operating limits using the recirculation process. If the pipe is kept empty while the ship loading does not take place, the temperature inside of the pipe can increase near the ambient temperature. In such circumstances, liquid CO_2 can be vaporized rapidly on introduction to the loading pipe. Boil-of-gas (BOG) generation can lead to operation energy increments as well as to safety problems. The recirculation process, which pumps a small fraction of cryogenic liquid to the loading pipe, is required to keep the pipe temperature within the operation limits. Also the ship loading scenario requires recirculation process.

2.2.2 BOG reliquefaction process

The storage terminal requires a BOG reliquefaction system to control the amount of gaseous CO_2 generated from the storage tank. For example insulation failure or sudden increases in the atmospheric temperature can cause larger heat fluxes that eventually generate BOG in the storage tank. BOG can be captured at the top of the tank and sent to compressors. Using multistage compressors, the CO_2 gas is compressed to near the critical pressure and cooled to room temperature using an ambient or seawater cooling cycle. The product stream is, then, sent to the Joule-Thomson valve and expended to the pressure inside of the tank. A flash column can be used for phase separation. The liquid stream from the flash is recycled to the storage tank, and the gas stream is recycled back to the compressor until the flow rate of the stream reaches 0.1% of the CO_2 input stream (Lee et al., 2012).

2.3 Ship transportation

Transport of CO_2 by ship already takes place in small scale. Usually CO_2 is transported as refrigerated liquefied gas in insulated containers at temperatures below ambient and low pressures. Worldwide there are few ships used for this purpose. Most of these ships transport liquefied foodgrade CO_2 from large point sources to distribution terminals on coastal area.

The method of discharging the ship will depend on the type of ship, cargo specification and terminal storage. Three basic methods may be used (McGuire & White, 2000):

- Discharge by pressurising the vapour space

- Discharge with or without booster pumps
- Discharge via booster pump and cargo heater

Depending upon cargo tank design, residual liquid can be removed by pressurisation, normal stripping or, in the case of fully refrigerated ships by using the puddle heating coils fitted for this purpose. The first operation to be carried out is the removal of all cargo liquid remaining in the tanks or in any other part of the cargo system. When all cargo tank liquid has been removed, the tanks can be inerted as required by the next cargo (McGuire & White, 2000).

Liquid CO_2 is charged from the temporary storage tank to the cargo tank with pumps adapted for high pressure and low temperature. Liquid CO_2 is unloaded at the destination site. The volume occupied by liquid CO_2 in the cargo tanks is replaced with dry gaseous CO_2, so that humid air does not contaminate the tanks. This CO_2 can be recycled and reliquefied when the tank is refilled (IPCC, 2005).

The properties of liquefied CO_2 have similarities with those of liquefied petroleum gas (LPG). LPG is transported on a large commercial scale by marine tankers. CO_2 can be transported by ship in much the same way. The latest LNG carriers reach more than 200,000 m^3 capacity. This kind of carrier could carry some 230 kt of liquid CO_2 (IPCC, 2005).

There are three types of tank structure for liquid gas transport ships (IPCC, 2005):

- pressure type
- low temperature type
- semi-refrigerated type

The pressure type is designed to prevent the cargo gas from boiling under ambient air conditions. On the other hand, the low temperature type is designed to operate at a sufficiently low temperature to keep cargo gas as a liquid under the atmospheric pressure. Most small gas carriers are pressure type, and large LPG and LNG carriers are of the low temperature type. The low temperature type is suitable for mass transport. The semi-refrigerated type, including the existing CO_2 carriers, is designed taking into consideration the combined conditions of temperature and pressure necessary for cargo gas to be kept as a liquid (IPCC, 2005). For all refrigerated and semi-pressurised gas carriers, it is necessary to maintain strict control of cargo temperature and pressure throughout the loaded voyage. This is achieved by reliquefying cargo boil-off and returning it to the tanks. During these operations, incondensibles must be vented as necessary to minimise compressor discharge pressures and temperatures (McGuire & White, 2000).

3 International regulation related to transportation of CO_2 by ship

International laws are particularly important in cases, where the physical project boundary crosses national borders and enters international waters, as transportation of CO_2 by ship. Transport of CO_2 would have to comply with international transport regulations. There are numerous specific agreements, some of which are conventions and others protocols of other conventions. There are also a variety of regional agreements dealing with transport of goods. Examples of international conventions affecting CO_2 transportation are:

- The Basel convention
- The Espoo Convention
- The London Convention
- The UN Law of the Sea Convention

1996 protocol to the London convention on the prevention of marine pollution by dumping of wastes and other material was amended to allow for export of CO_2 for CCS purposes. The Espoo convention covers environmental assessment. The most significant aspect of the Espoo Convention is that it lays down the general obligation of states to notify and consult each other if a project under consideration is likely to have a significant environmental impact across boundaries. In some cases the acceptability of CO_2 storage under these conventions could depend on the method of transportation to the storage site (UCL, 2012).

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal aims to protect humans and the environment from risks caused by international trade in hazardous waste. The convention controls transboundary movements of dangerous waste. Currently CO_2 is not classified as a dangerous waste. Therefore Basel Convention does not restrict transportation of CO_2 by ship. In case the carbon dioxide stream includes impurities such as heavy metals, the interpretation of the convention could be different (UCL, 2012).

International transport codes and agreements adhere to the UN Recommendations on the Transport of Dangerous Goods: Model Regulations published by the United Nations (2001). CO_2 in gaseous and refrigerated liquid forms is classified as a non-flammable, non-toxic gas; while solid CO_2 (dry ice) is classified under the heading of miscellaneous dangerous substances and articles. Transportation of CO_2 adhering to the Recommendations on the Transport of Dangerous Goods: Model Regulations can be expected to meet all relevant agreements and conventions covering transportation by whatever means. Nothing in these recommendations implies that transportation of CO_2 would be prevented by international transport agreements and conventions (IPCC, 2005).

4 Current monitoring regulations for transportation of gases by ship

4.1 Amount of fuel bunkered

Total amount fuel bunkered is monitored due to the existing legislative requirements. According to the regulation 18 of MARPOL Annex VI a bunker delivery note (BDN) is to be kept on board for a period of three years. A BDN contains information of the total quantity of fuel bunkered in metric tonnes and density at 15 °C [kg/m^3], as well as sulphur content [%m/m] (Faber et al., 2009).

4.2 International gas code

International code for the construction and equipment of ships carrying liquefied gases in bulk 1983, is to provide an international standard for the safe carriage by sea in bulk of liquefied gases and certain other substances by prescribing the design and construction standards of ships involved in such carriage and the equipment they should carry so as to minimize risk to the environment (IMO, 1983). The code gives details for example on pressure gauges and temperature indicators to be installed in the liquid and vapour piping systems, in cargo refrigerating installations, and in the inert gas systems. Accordingly each cargo tank should be provided with means for indicating level, pressure and temperature of the cargo (IMO, 1983).

4.2.1 Monitoring of liquid level in cargo tank

Each cargo tank should have at least one liquid level gauging device, designed to operate at pressures not less than the MARVS (maximum allowable relief valve setting) of the cargo tanks and at temperatures within the cargo operating temperature range (IMO, 1983).

Cargo tank liquid level gauges may be of the following types for carbon dioxide transport (IMO, 1983):

- Indirect devices, which determine the amount of cargo by means such as weighting or pipe flow meters
- Closed devices, which do not penetrate the cargo tanks, such as devices using radioisotopes or ultrasonic devices
- Closed devices, which penetrate the cargo tank, but which form part of a closed system and keep the cargo from being released, such as float type systems, electronic probes, magnetic probes and bubble tube indicators. If a closed gauging device is not mounted directly on the tank it should be provided with a shut-off valve located as close as possible to the tank

4.2.2 Overflow control of cargo tank

Each cargo tank should be fitted with a high liquid level alarm operating independently of other liquid level indicators. The alarm should give an audible and visual warning when activated. Another sensor operating independently of the high liquid level alarm should automatically actuate a shut-off valve in a manner which will both avoid excessive liquid pressure in the loading line and prevent the tank from becoming liquid full. These rules are applicable to all cargo tanks except if the cargo tank is (IMO, 1983):

- a pressure tank with a volume not more than 200 m^3; or
- designed to withstand the maximum possible pressure during the loading operation and such pressure is below that of the start-to-discharge pressure of the cargo tank relief valve.

4.2.3 Monitoring of pressure

The vapour space of each cargo tank should be provided with a pressure gauge which should incorporate an indicator in the control position. In addition, a high-pressure alarm and, if vacuum protection is required, a low-pressure alarm, should be provided on the navigating bridge. Maximum and minimum allowable pressures should be marked on the indicators. The alarms should be activated before the set pressures are reached. Each cargo pump discharge line and each liquid and vapour manifold should be provided with at least one pressure gauge. Local-reading manifold pressure gauges should be provided to indicate the pressure between stop valves and hose connections to the shore. Hold spaces and interbarrier spaces without open connection to the atmosphere should be provided with pressure gauges (IMO, 1983).

4.2.4 Monitoring of temperature

At least two devices for indicating cargo temperatures should be provided in each cargo tank, one placed at the bottom of the cargo tank and the second near the top of the tank, below the highest allowable liquid level. The temperature indicating devices should be marked to show the lowest temperature for which the cargo tank has been approved by the administration. When a cargo is carried in a cargo containment system with a secondary barrier at a temperature lower than -55 °C, temperature indicating devices should be provided within the insulation or on the hull structure adjacent to cargo containment systems.

The devices should give readings at regular intervals and, where applicable, audible warning of temperatures approaching the lowest for which the hull steel is suitable. If cargo is to be carried at temperatures lower than -55 °C, the cargo tank boundaries, if appropriate for the design of the cargo containment system, should be fitted with temperature indicating devices as follows (IMO, 1983):

- A sufficient number of devices to establish that an unsatisfactory temperature gradient does not occur.
- On one tank a number of devices in excess of those required in order to verify that the initial cool down procedure is satisfactory. These devices may be either temporary or permanent. The number and position of temperature indicating devices should be to the satisfaction of the administration.

4.2.5 Cargo documentation

Bill of lading

The transport of liquefied gas is subject to similar commercial documentation as in oil cargoes. The Bill of Lading is the most important one. It is the basis against which the cargo receiver can assess if the proper quantity has been discharged. The shipmaster, before departure from the loading terminal, should ensure that the Bill of Lading quantities accurately represent the cargo loaded. The shipmaster should also be sure that cargo calculation records made at loading and discharge are properly prepared (McGuire & White, 2000).

A Bill of Lading is a document signed by the shipmaster at the port of loading. It details (McGuire & White, 2000):

- the type and quantity of cargo loaded
- the name of the ship, and
- the name of the cargo receiver.

The cargo quantity written on the Bill of Lading can be either the shore tank figure or the quantity as given by shore-based custody transfer meters. It is common to use the ship's figure, which is calculated after completion of loading, usually with verification from an independent cargo surveyor. The Bill of Lading has three functions (McGuire & White, 2000):

- The shipmaster's receipt for cargo loaded
- A document of title for the cargo described in it
- Evidence that a Contract of Carriage (such as a voyage charter party) exists

The Bill of Lading is a vital document in the trade. By signing the Bill of Lading, the shipmaster agrees to the quantity of cargo loaded and any subsequent claim for cargo loss will hinge on the quantity stated on the document. In some circumstances, where the Bill of Lading quantities do not match the ship's figure, the shipmaster may be expected to issue a Letter of Protest at the loading port (McGuire & White, 2000).

The one, who possesses the Bill of Lading, rightfully owns the cargo and can demand a shipmaster to discharge that cargo to him. Therefore, it is important that the Bill of Lading does not fall into the wrong hands. The common practise is to issue only one Bill of Lading. On completion of loading, the original Bill is mailed from the loading port to the rightful cargo receiver (McGuire & White, 2000).

Certificate of Quantity

A Certificate of Quantity is issued by the loading terminal as, or on behalf of, the shipper and the cargo quantities declared as loaded may be verified by an independent cargo surveyor. The certificate is to help the shipmaster in determining the quantities to be inserted in the Bill of Lading. However, the quantities as stated on the Bill of Lading remain the official record of the cargo as loaded (McGuire & White, 2000).

Certificate of quality

A Certificate of Quality provides the product specification and quality in terms of physical characteristics (such as vapour pressure and density) and component constituents. It is issued by the loading terminal as, or on behalf of, the shipper, or by an independent cargo inspection service. The data contained in the document helps the shipmaster in signing the Bill of Lading (McGuire & White, 2000).

Cargo manifest

A Cargo Manifest is usually prepared by the ship's agent at the loading port or by the shipmaster and lists all cargoes according to the Bills of Lading. Its purpose is to provide data for customs authorities and ships' agents in the discharge port. The appropriate preparation of the Cargo Manifest is controlled by the SOLAS convention (McGuire & White, 2000).

5 Greenhouse gas emission from ship transportation of CO_2

In CO_2 transport chain some CO_2 will be lost during gas treatment and conditioning (Aspelund et al. 2006). In addition, ships engines emit greenhouse gas emissions. Some of these emissions can be avoided by technical arrangements. Indirect emissions occur from auxiliary energy used in liquefaction unit, in storage terminal, in loading, and in ship. The ship uses diesel oil in engines and to maintain the temperature and the pressure of the cargo tank to keep CO_2 in liquid form. The intermediate storage terminal system includes several pumps and compressor, which uses electricity or for example gas turbines to provide the auxiliary energy. Direct emissions occur from boil-off gas, which can be generated both in storage tanks and cargo tanks, and during loading. In addition, direct emissions might occur through accidental release of CO_2 to the atmosphere.

In the liquefaction plant, volatiles need to be removed from the feed gas. The molar loss of CO_2 through removing of volatiles is approximately equal to the amount of removed volatiles unless the volatile purge stream is pretreated or recycled to the industrial or capture process. Minor losses of CO_2 occur, when some CO_2 is solved in the waste water in the liquefaction plant (Aspelund et al., 2006).

When loading, the cargo tanks are usually filled and pressurized with gaseous CO_2 to prevent contamination by humid air and the formation of dry ice. This CO_2 can be recycled and reliquefied to minimize CO_2 emissions to the atmosphere.

CO_2 can leak into the atmosphere during transportation. Heat transfer from the environment through the wall of the cargo tank will boil CO_2 and raise the pressure in the tank. It is not dangerous to discharge the CO_2 boil-off gas together with the exhaust gas from the ship's engines, but doing so does, of course, release CO_2 to the air. The objective of zero CO_2 emissions during the process of capture and storage can be achieved by using a refrigeration unit to capture and liquefy boil-off and exhaust CO_2 during the whole transport chain (IPCC, 2005).

The approximated total loss to the atmosphere from ships is 3-4% per 1000 km, counting both boil-off and exhaust from the ship's engines. These leakages could be reduced by capture and liquefaction, and recapture onshore would reduce the loss to 1-2% per 1000 km (IPCC, 2005). According to Aspelund et al. (2006) the total relative CO_2 loss from CO_2 transport chain is 1.4% (see Table 1.).

Table 1. Relative CO_2 emissions from CO_2 transport concept (Aspelund et al., 2006).

Phase	[%]
Liquefaction	0.3
Storage	0
Loading	0
Ship	0.65
Unloading	0.45
Total	1.4

6 Current monitoring methods for transport chain of liquefied gases

The techniques for monitoring ship transportation already exist. There is no obstacle from that perspective to monitor CO_2 emissions (IPCC, 2005). For example, the injected volume can be monitored using flow meter and the injection pressure using pressure meter. In addition, composition of CO_2 stream can be detected by chemical analysis of injectate (Forbes & Siegler, 2010).

6.1 Measuring quantity of liquefied gas

The quantity of liquefied gas cargoes loaded to, or discharged from, ships is measured and calculated by finding cargo volume and cargo density and, after correcting both to the same temperature, by multiplying the two to obtain the cargo quantity.

Cargo loaded in a ship's tank may vary in temperature over the loading period. Either by boil-off or by condensation, a tank's liquid and vapour content will adjust to saturated equilibrium. However, this equilibrium may not be achieved immediately after loading. It is, therefore, desirable to delay cargo measurement and sampling for as long as possible, subject to the constraints of the ship's departure time (McGuire & White, 2000).

The cargo is quantified indirectly by taking a small sample of the cargo and determining its density. If this density is multiplied by the cargo volume, then the quantity of the whole cargo can be obtained (McGuire & White, 2000).

It is obvious that the volume of the cargo is very important, and this is in turn dependent on its temperature. So, it is necessary to specify the conditions of the cargo at which it is to be quantified. The condition most commonly chosen is to evaluate the cargo as though it was at 15°C; it is further assumed that the entire cargo is a liquid at its boiling point (McGuire & White, 2000).

The derivation of cargo weight may be carried out in practice by two methods. The mass may be calculated and this converted to weight by use of a conversion factor, with the liquid density at 15°C. The second practical method of determining the weight of a cargo is from its volume at 15°C using a volume to weight conversion factor. This weight conversion factor is the weight per unit volume of the saturated liquid at 15°C (McGuire & White, 2000).

The volume of liquefied gas loaded onto a gas carrier can be determined by conventional tank gauging. Alternatively, the volumes transferred can be monitored by flow meter. There are several types of metering systems in regular use at liquefied gas terminals (McGuire & White, 2000):

- Positive displacement meters, in which the number of revolutions of the meter are proportional to the volume of fluid passed.
- Turbine meters where the rotation of the blades is proportional to the flow.
- Coriolis metering where the fluid is passed through a vibrating U-tube, the mass gas flow being determined from the twisting of the U-tube caused by the Coriolis Effect.
- Ultrasonic metering whereby the volumetric flow rate can be determined
- Vortex meter, which may be thought as an obstruction within the pipe which causes vortices to be generated on each side of the obstruction.

6.2 Monitoring during cargo handling

At the start of and during cargo handling, frequent checks should be made by the responsible officer to confirm that cargo is only entering or leaving the designated cargo tanks and that there is no escape of cargo. Independent cargo surveyors are often employed by cargo buyers or sellers and the survey companies provide personnel to check cargo operations and cargo quantities (McGuire & White, 2000).

Automatic gas detection systems for monitoring possible leakage of flammable and toxic vapours are installed in terminals and at jetties. The number and location of detector heads depends on the prevailing wind velocity and direction, on the density of the gas being monitored, and on the more likely sources of release (McGuire & White, 2000).

A close watch should be kept on the ship's cargo tank pressures, temperatures, liquid levels and interbarrier space pressures, throughout the loading operation (McGuire & White, 2000).

6.3 Storage tank measuring

Terminals usually require storage tanks to be measured for day-to-day internal accounting. Shore tank measurements for cargo loaded or received are not always as accurate as ship measurements. Shore storage tanks usually have greater cross-sections than the ship's tanks. This can lead to greater inaccuracies associated with on-shore liquid level measurement. When loading a ship, vapour flow may be from other shore storage tanks, from liquid vaporisers or from the ship-to-shore vapour return line in order to maintain shore tank pressure within pressure limits. Similarly, during ship discharge, vapour flow may be from the shore tank to other shore tanks, to the shore reliquefaction plant or to the ship by the shore-to-ship vapour return line. If there is only one shore tank, the liquid input to the tank from production run-down must also be taken into account. These factors increase uncertainty in shore tank measurement. Often the ship's figures are used to determine cargo volumes for custody transfer at both loading and receiving terminals. Some customs authorities require the ship's tank calibration tables to be certified by an approved classification society or by suitable independent cargo surveyors. It is usual for cargo interests to appoint an independent cargo surveyor as an unbiased third party to verify the ship and shore volume measurements, the use of appropriate density values and the cargo calculations (McGuire & White, 2000).

All ships are provided with a calibration table for each cargo tank. The calibration table enables liquid and vapour volumes to be found from a measurement of the liquid level. A calibration table is obtained from careful measurements taken at ambient temperature and pressure after the ship is built. The volumes given in the tables normally assume the ship to be upright and with no trim. The calibration tables, therefore, contain correction factors with which to adjust the liquid level measurements in accordance with the actual conditions of the ship's list and trim and with the cargo tank temperatures at the time of cargo measurement. Since liquefied gases are boiling liquids, the measurement of density requires laboratory equipment not available on ships. Cargo liquid density is measured on shore and the results are provided to the ship for its cargo calculations.

6.3.1 Liquid density measurements

There are four principal methods of liquid density measurement. Liquid composition analysis is the most accurate method of density measurement. It is increasingly used in modern terminals. The liquid composition is usually obtained by a gas liquid chromatograph. The density is calculated from this analysis by means the Francis Formula or the Costald Equation. The Costald Equation is more suitable for calculating the density of LNG, chemical gas and mixed gas cargoes. This method provides density at any desired temperature without introducing the inaccuracy of generalized conversion tables. Shore tank density can be measured by density meters. The differing types are listed below (McGuire & White, 2000):

- Differential pressure across the height of a known vertical liquid column
- Resonant frequency of a vibrating element immersed in the liquid
- Buoyancy of a body immersed in the liquid
- Variation of electrical capacitance of an immersed probe, or
- The variation of the speed of ultrasonic signals within the liquid

The use of a densitometer involves diverting a portion of the product flow in a pipeline through the instrument. The instrument contains a vibrating element and the resonant frequency of the vibrating element is related to the density of the liquid. Each densitometer requires careful calibration. Corrections need to be applied to its correlations between frequency and density for pressures, temperatures and for products differing from the calibration values. The overall accuracy is approximately ±0.2 % which is similar to that achieved from compositional analysis. The corrected output of the densitometer can be combined with the output of the volume flow measurement to give mass flow. This can be integrated over the transfer period to give the total liquid mass transferred (McGuire & White, 2000).

6.4 Monitoring of maritime transport

Faber et al. (2009) outlined monitoring methods for maritime transport. The monitoring could be based on measuring fuel use or alternatively, emissions can be approximated by using data on tonne-miles travelled, average fuel use per tonne-mile for a given ship and type of fuel used.

CO_2 emissions are proportional to fuel consumption. The amount of CO_2 emissions from the combustion of an amount of fuel depends on the mass fraction of carbon in the fuel which depends on the chemical composition, content of water, sulphur etc. Instead of analysing numerous bunker samples and defining accurate mass fractions of carbon for each sample, the carbon content could be based on a set of default values. CO_2 emission factors according to the IPCC Guidelines are documented in Table 1. Distinction between residual and distillate fuels is done by density. Fuels with density < 890 kg/m^3 are classified as distillate (Faber et al., 2009).

Table 2. Fuel based CO_2 emission factors [t/t_{fuel}].

Fuel	Low	Default	High
Marine diesel and marine gas oils (distillate)	3.01	3.19	3.24
Residual fuel oils	3.00	3.13	3.29

In order to find out CO_2 emissions from ships, the easiest way is to establish the fuel consumption. Two main ways to track fuel consumption on board is fuel inventory management, and measuring and recording fuel consumption as it happens. This can be done by utilising four main data sources that are (Faber et al., 2009):

- Total amount of fuel purchased by the ship
- Total amount of fuel bunkered
- Measuring fuel tank levels or pressure
- Measuring flow to engines, day tanks or settling tanks

Record of total amount of fuel purchased is normally kept at a ship operator. This is a simple monitoring method in case the ship only transports for one company (Faber et al., 2009). Measuring of fuel tank levels is an existing procedure on board ship. In modern ships, tank soundings are automatized. Automatic systems, using for example pitot tubes, need to be regularly calibrated. Tank soundings can be manually taken via sounding pipes. Alternatively, fuel mass in the tank can be measured by way of measuring the pressure in the bottom of the tank (Faber et al., 2009).

Fuel flow can be measured using various type fuel flow meters. The most accurate and reliable method of measuring fuel consumption is to use monitoring systems incorporating electronic fuel flow meters. Flow meters of turbine type are common, too. Turbine flow meters measure rotational speed of a turbine in a pipe which can be converted to volumetric flow (Faber et al., 2009).

There are two principal options for documenting fuel consumption in the regulatory perspective. One is inventory control that involves monitoring of fuel consumption by documenting all fuel on board the ship at start and end of the period as well as all supply and possible de-bunkering. The other option is direct fuel consumption measurement that involves installation and maintaining an approved system for documenting fuel consumption (Faber et al., 2009).

According to Faber et al. (2009) the following elements should be included in the monitoring, reporting and verification scheme for maritime transport:

- The responsible entity submits an emissions monitoring and verification plan to the competent authority, based on the most accurate fuel measurements possible on his ship(s).
- The responsible entity establishes the amount of CO_2 emissions from his or her activities that are subject to the regulation in a manner that facilitates verification at a later time.
- The documentation necessary for verification is kept by the responsible entity for a specified period of time.
- The verifier verifies the accuracy of the monitoring report.
- The responsible entity report verifies emissions to the responsible entity.

7 Outline of monitoring procedure for ship transportation of CO_2

The EU's monitoring and reporting regulation for transport of CO_2 by pipeline (EC, 2012) was used as a model for this outline.

7.1 Scope

Each transport network shall have a minimum of one start point and one end point, each connected to other installations carrying out one or more of the activities: capture, transport or geological storage of CO_2. Start and end points may include bifurcations of the transport network and cross national borders (EC, 2012).

The start point for the monitoring and reporting emissions from CO_2 transport by ship is the liquefaction unit and the end point is at the storage facility where CO_2 is unloaded from the ship's cargo tanks. The main phases included in the monitoring are liquefaction unit, intermediate storage, loading, transportation, and unloading.

Each operator shall consider at least the following potential emission sources for CO_2 emissions: combustion and other processes at installations functionally connected to the transport network including booster stations; fugitive emissions from the transport network; vented emissions from the transport network; and emissions from leakage incidents in the transport network (EC, 2012).

The possible emission sources from the ship transportation chain were described in Chapter 5. If the storage terminal and the ship does not have reliquefaction process for boiled-off gas, these emissions has to be monitored. In case the CO_2 liquefaction unit is included in the monitoring plan of the CO_2 capture plant, emissions from liquefaction does not need to be monitored twice. If the intermediate storage terminal does not have a recirculation process for the liquefied CO_2, the BOG emissions need to be monitored, too.

7.2 Quantification methodologies for CO_2

The operator of transport networks shall determine emissions using one of the following methods (EC, 2012):

- overall mass balance of all input and output streams, or
- monitoring of emission sources individually

Best available technology should be used. If emission sources are monitored individually, the operator has to prove that the overall uncertainty for the annual level of greenhouse gas emissions does not exceed 7.5% (EC, 2012).

The operator of a transport network who monitors emissions sources individually shall not add CO_2 received from another installation permitted in accordance with Directive 2003/87/EC to its calculated level of emissions, and shall not subtract from its calculated level of emissions any CO_2 transferred to another installation permitted in accordance with Directive 2003/87/EC (EC, 2012).

At least once a year, each operator should use overall mass balance method to validate the results of individual monitoring of emission sources (EC, 2012).

7.2.1 Overall mass balance of all input and output streams

Each operator shall determine total CO_2 emissions of the transport network in accordance with the following formula (EC, 2012):

$$Emissions[tCO_2] = E_{own\ activity} + \sum_i \boldsymbol{T}_{IN,i} - \sum_j T_{OUT,j} \quad (1)$$

$E_{own\ activity}$= Emissions from the transport network's own activity, meaning not emissions stemming from the CO_2 transported, but including emissions from fuel used in booster stations

$\sum_i \boldsymbol{T}_{IN,i}$= Amount of CO_2 transferred to the transport network at entry point i

$\sum_j T_{OUT,j}$= Amount of CO_2 transferred out of the transport network at exit point j

In case of ship transportation chain, emissions from own activity includes emissions from auxiliary energy used in the liquefaction unit, intermediate storage, recirculation process, boiled-off gas process, loading, transportation, and unloading.

Monitoring of most of the phases from ship transport chain is familiar from other processes monitored under EU's emission trading scheme. The new part that has not yet been monitored is the fuel use in the ship and the monitoring of the liquid CO_2 transferred to and out of the ship cargo tanks.

Monitoring of the fuel used in the ship can be done either per voyage or per annum. The simplest way to monitor the amount of fuel used is to utilize existing data. Ships have on board a bunker delivery note (BDN) that contains information of the total quantity of fuel bunkered. To guarantee accurate data, the BDN should be verified by independent surveyor. In case the ship has other purposes than transportation of CO_2, the BDN is not suitable data source for determining the amount of fuel used. The BDN does not state fuel used per voyage, only the whole amount bunkered at certain time. When the fuel used per voyage has to be monitored, it should be done by measuring fuel tank levels or pressure, or by measuring flow to engines/day tanks/settling tanks. Modern ships already have the technical ability to execute these measurements. The emissions from fuel used are then calculated using emission factors presented in Table 2.

The bill of lading contains information on the type and quantity of cargo loaded. This information can be utilized when the amount of liquid CO_2 transferred to and out of the cargo tanks are monitored. Independent cargo surveyor should verify this data. To make sure the amount of CO_2 transferred to the cargo tank is the same that is unloaded at the destination, the volume flow as well as the temperature and pressure of the CO_2 flow should be measured. International gas code gives instructions on how to monitor liquid level, temperature and pressure of cargo tank. These existing procedures should be utilized in this context.

7.2.2 Monitoring of emission sources individually

Each operator shall determine emissions considering all processes relevant to emissions at the installation as well as the amount of CO_2 captured and transferred to the transport facility using the following equation (EC, 2012):

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

$CO_{2\,fugitive}$= Amount of fugitive emissions [t CO_2] from CO_2 transported in the transport network, including from seals, valves, intermediate compressor stations and intermediate storage facilities;

$CO_{2\,vented}$= Amount of vented emissions [t CO_2] from CO_2 transported in the transport network;

$CO_{2\,leakage\ events}$= Amount of CO_2 [t CO_2] transported in the transport network, which is emitted as the result of the failure of one or more components of the transport network;

$CO_{2\,installations}$= Amount of CO_2 [t CO_2] being emitted from combustion or other processes functionally connected to the pipeline transport in the transport network.

Fugitive emissions from the transport network

According to 2006 IPCC guidelines for national greenhouse gas inventories guidelines, no emission factors for fugitive emission from CO_2 transportation by ship is available. The amount of gas should be metered during loading and discharge using flow metering (IPCC, 2006).

Emissions from leakage events

The operator of a transport network shall provide evidence of the network integrity by using representative (spatial and time-related) temperature and pressure data. Where the data indicates that a leakage has occurred, the operator shall calculate the amount of CO_2 leaked with a suitable methodology documented in the monitoring plan, based on industry best practice guidelines, including by use of the differences in temperature and pressure data compared to integrity related average pressure and temperature values (EC, 2012).

In CO_2 transportation by ship, possible leakage is detected when cargo is unloaded and the amount unloaded does not match the amount loaded to the cargo tanks. The amount of CO_2 leaked is easily calculated from the data of loaded and unloaded liquid CO_2.

Vented emissions

Each operator shall provide in the monitoring plan an analysis regarding potential situations of venting emissions, including for maintenance or emergency reasons, and provide a suitable documented methodology for calculating the amount of CO_2 vented, based on industry best practice guidelines (EC, 2012).

8 Conclusions

According to the directive of European Union on emission trading scheme, the only permitted transportation method of CO_2 is transportation by pipeline (EC, 2009). Fortunately, the emission trading directive includes an opportunity to extend the emission trading scheme by adding new sectors. The way to include new sectors is the so-called comitology process. However, guidelines for monitoring, reporting and verification for CO_2 transportation by ship needs to be established first in order for CO_2 transportation by ship to be included in the emission trading scheme as a new sector (HE 36/2012vp). In this report outline of monitoring procedure for ship transportation was introduced.

The cycle of ship transport is discrete; it includes all processes receiving CO_2 from the capture process to its injection into a reservoir. Intermediate storage system for long-distance ship transportation is composed of four processes: CO_2 input process, storage tank and loading process, recirculation process, and boiled-off gas (BOG) reliquefaction process. Intermediate storage terminal serves as a port for CO_2 carriers and storage tank (Lee et al., 2012). Transport of CO_2 by ship already takes place in small scale. Worldwide there are a few ships used for this purpose. Most of these ships transport liquefied foodgrade CO_2.

The properties of liquefied CO_2 have similarities with those of liquefied petroleum gas (LPG). LPG is transported on a large commercial scale by marine tankers. CO_2 can be transported by ship in much the same way (IPCC, 2005).

International laws are particularly important in cases, where the physical project boundary crosses national borders and enters international waters, as transportation of CO_2 by ship. There are numerous specific agreements, some of which are conventions and others protocols of other conventions. There are also a variety of regional agreements dealing with transport of goods. As a conclusion from literature review, there seems not to be any severe obstacles for transporting CO_2 by ship.

International gas codes provides an international standard for the safe carriage by sea in bulk of liquefied gases and certain other substances by prescribing the design and construction standards of ships involved in such carriage and the equipment they should carry so as to minimize risk to the environment (IMO, 1983). The code gives details for example on pressure gauges and temperature indicators to be installed in the liquid and vapour piping systems, in cargo refrigerating installations, and in the inert gas systems. Currently transportation of gases by ship is monitored according to these requirements. In addition, bunker delivery note and bill of lading includes data on fuel and cargo loaded to the ship. These can be utilized in monitoring of ship transportation chain.

In CO_2 transport chain some CO_2 will be lost during gas treatment and conditioning (Aspelund et al. 2006). In addition, ships engines emit greenhouse gas emissions. Some of these emissions can be avoided by technical arrangements. Indirect emissions occur from auxiliary energy used in liquefaction unit, in storage terminal, in loading, and in ship. The ship uses diesel oil in engines and to maintain the temperature and the pressure of the cargo tank to keep CO_2 in liquid form. The intermediate storage terminal system includes several pumps and compressor, which uses electricity or for example gas turbines to provide the auxiliary energy. Direct emissions occur from boil-off gas, which can be generated both in storage tanks and cargo tanks, and during loading. In addition, direct emissions might occur through accidental release of CO_2 to the atmosphere. According to Aspelund et al. (2006) the total relative CO_2 loss from CO_2 ship transport chain is 1.4%.

The techniques for monitoring ship transportation already exist. There is no obstacle for that perspective to monitor CO_2 emissions (IPCC, 2005). For example the injected volume can be monitored using flow meter and the injection pressure using pressure meter. In addition, composition of CO_2 stream can be detected by chemical analysis of injectate (Forbes & Siegler, 2010).

The EU's monitoring and reporting regulation for transport of CO_2 by pipeline (EC, 2012) was used as a model for the outline of monitoring procedure. The start point for the monitoring and reporting emissions from CO_2 transport by ship is the liquefaction unit and the end point is at the storage facility where CO_2 is unloaded from the ship's cargo tanks. The main phases included in the monitoring are liquefaction unit, intermediate storage, loading, transportation, and unloading.

Monitoring of most of the phases from ship transport chain is familiar from other processes monitored under EU's emission trading scheme. The new part that has not yet been monitored is the fuel use in the ship and the monitoring of the liquid CO_2 transferred to and out of the ship cargo tanks.

Monitoring of the fuel used in the ship can be done either per voyage or per annum. The simplest way to monitor the amount of fuel used is to utilize existing data. Ships have on board a bunker delivery note (BDN) that contains information of the total quantity of fuel bunkered. To guarantee accurate data, the BDN should be verified by independent surveyor. In case the ship has other purposes than transportation of CO_2, the BDN is not suitable data source for determining the amount of fuel used. The BDN does not state fuel used per voyage, only the whole amount bunkered at certain time. When the fuel used per voyage has to be monitored, it should be done by measuring fuel tank levels or pressure, or by measuring flow to engines/day tanks/settling tanks. Modern ships already have the technical ability to execute these measurements. The emissions from fuel used are then calculated using emission factors.

The bill of lading contains information on the type and quantity of cargo loaded. This information can be utilized when the amount of liquid CO_2 transferred to and out of the cargo tanks are monitored. Independent cargo surveyor should verify this data. To make sure the amount of CO_2 transferred to the cargo tank is the same that is unloaded at the destination, the volume flow as well as the temperature and pressure of the CO_2 flow should be measured. International gas code gives instructions on how to monitor liquid level, temperature and pressure of cargo tank. These existing procedures should be utilized in this context.

9 References

Aspelund et al. 2006. Ship transport of CO_2. Technical solutions and analysis of costs, energy utilization, exergy efficiency and CO_2 emissions. Chemical Engineering Research and Design, 84(A9), 847-855.

EC, 2009. 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. Official Journal of the European Union, L140/63, 5.6.2009.

EC, 2012. Commission regulation No 601/2012 of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council. Official Journal of the European Union L 181, 12.7.2012.

Faber et al., 2009. Technical support for European action to reducing greenhouse gas emissions from international maritime transport. Tender DG ENV.C3/ATA/2008/0016, Delft, December 2009. Available: http://ec.europa.eu/clima/policies/transport/shipping/docs/ghg_ships_report_en.pdf

Forbes, M. & Ziegler, M. 2010. WRI issue brief. Carbon dioxide capture and the UNFCCC recommendations for addressing technical issues. World Resource Institute. November 2010.

HE36/2012vp. Hallituksen esitys eduskunnalle laeiksi hiilidioksidin talteenottamisesta ja varastoinnista, ympäristönsuojelulain muuttamisesta ja merensuojelulain 7 §:n muuttamisesta sekä Koillis-Atlantin merellisen ympäristön suojelusta tehdyn yleissopimuksen II ja III liitteeseen tehdyn muutoksen hyväksymisestä ja laiksi muutoksen lainsäädännön alaan kuuluvien määräysten voimaansaattamisesta. Available:http://217.71.145.20/TRIPviewer/show.asp?tunniste=HE+36/2012&base=erhe&palvelin=www.eduskunta.fi&f=WORD

IMO, 1983. International code for the construction and equipment of ships carrying liqufed gases in bulk, 1983. International Maritime Organisation.

IMO, 1996. 1996 London protocol to the convention on the prevention of marine pollution by dumping of wastes and other matter, 1972. International Maritime Organisation.

IMO, 1993. International gas carrier code. International Maritime Organisation.

IPCC, 2006. 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan. Available:http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_5_Ch5_CCS.pdf

IPCC, 2005. Carbon capture and storage. Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer (Eds.). Cambridge University Press,

UK. 431 p.
Available: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

L416/2012. Laki hiilidioksidin talteenottamisesta ja varastoinnista.
Available: http://www.finlex.fi/fi/laki/alkup/2012/20120416

Lee et al., 2012. CO_2 storage terminal for ship transportation. Industrial & Engineering Chemistry Research 2012, 51, 389-397.

McGuire & White, 2000. Liquefied gas handling principles on ships ans in terminals. Third edition. Witherby Publishers, London, England. ISBN 1 856091643.

UCL, 2012. CO_2 transport for storage: Regulatory regimes [www-document]. University College London. Cited 30.10.2012.
Available: http://www.ucl.ac.uk/cclp/ccstransport-int-waste-basel.php