Network Technology
Guidance for CO_2 transport by ship

ZEP/CCSA Report

March 2022

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2 Executive Summary

2.1 Overview

Transporting CO_2 by ship and by inland waterway will be crucial for large-scale CCS deployment in Europe by enabling emitters across Europe to connect to safe and permanent storage. CCS projects, including both cross border CO_2 infrastructure projects of common interest and domestic projects, have identified the need for both inland waterway and maritime shipping solutions.

Transport of CO_2 by ship has been recognised as essential both at EU level – in the European Taxonomy for Sustainable Activities as well as within the EU ETS Directive – and at a national level – e.g. in the Dutch SDE++ subsidy scheme and the UK CCUS programme.

For CCS projects aiming at transporting CO_2 by ship, interoperability could be important in order to optimise the development of CO_2 infrastructure, although it is likely that initial transport projects and contracts will be between a given emitter and a specific storage location. There is a need for some degree of standardisation on CO_2 specifications (composition, pressures, temperatures, etc.), ship design and specifications (e.g. referring to loading and off-loading). As many CCS projects will become operational in the mid-2020s, many new ships for CO_2 transportation will be needed within five years, making this guidance urgent and needed.

This report documents the findings and the conclusions of an industry workgroup convened by ZEP and the CCSA to address this requirement.

2.2 Significant findings and recommendations

The key findings of this workgroup are that

- The CCS value chain is complex, and decisions taken at one point in the value chain can have significant technical and economic impact elsewhere along the value chain. For example, a decision to ship CO_2 liquefied at -50˚C requires the emitter to purify the CO_2 to a more rigorous standard than might otherwise be required.
  At this early stage of the development of the liquified CO_2 shipping market, it appears likely that two or more "standards" of temperature and pressure and composition will be appropriate – most likely at a "low pressure" of 5.5-7barg and -50 ˚C or at a "medium pressure" of 15-18barg and -30˚C. Note that some projects are considering transport at closer to ambient temperatures linked to direct ship-to-offshore offloading.
- Some elements of CO_2 phase behaviour are similar to liquified petroleum gas (LPG) which is already widely transported by ship, although LPG does not solidify close to the transport conditions. Existing standards for the transport of LPG and other

liquified gases are largely fit-for-purpose for the transport of liquified CO_2 – indeed many standards specific to the transport of liquefied CO_2 already exist. It is recommended that the relevant standards and guidelines issuing organisations be requested to review their specific standards and guidelines with a view to adapting them for the high-volume transportation of liquified CO_2 associated with CCS.

- To support early CCS projects that need to use shipping to transport CO_2 to the storage site, this report was used as the basis for a new "Guidance for CO2 transport by ship – Guidance Note" which the Workgroup developed.

3 Abbreviations used

The following abbreviations are used in this report

CCSA	Carbon Capture and Storage Association – a trade association promoting the commercial deployment of Carbon Capture, Utilisation and Storage
CCS and CCUS	Carbon Capture (Utilisation) and Storage – a concept involving the capture, transport, possible usage and the geological storage of CO_2 for the purpose of climate change mitigation.
GIIGNL	The International Group of Liquefied Natural Gas Importers - a non-profit organisation whose objective is to promote the development of activities related to LNG: purchasing, importing, processing, transportation, handling, re-gasification and its various uses
IMO	International Maritime Organisation – a United Nations Agency
LCOC	Liquified CO_2 carrier (ship)
OCIMF	Oil Companies International Marine Forum
SIGTTO	Society of International Gas Tanker and Terminal Operators – a not-for-profit non-governmental organisation that represents owners of gas carriers and terminals, including LNG terminals. SIGTTO publish numerous guidelines relevant to the transport of liquefied gases including CO_2.
ZEP	Zero Emissions Platform - a European Technology and Innovation Platform (ETIP) under the Commission's Strategic Energy Technologies Plan (SET-Plan). ZEP is the technical adviser to the EU Commission on the deployment of CCS and CCU.

4 Introduction

4.1 Climate change – European Green Deal – a gamechanger

On 11 December 2019 the European Commission presented the European Green Deal, a set of proposals to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Achieving these emission reductions in the next decade is crucial to Europe becoming the world's first climate-neutral continent by 2050 and making the European Green Deal a reality.

Specific objectives include

- Making the EU climate neutral by 2050
- Decarbonising the energy sector – which accounts for more than 75% of the EU's greenhouse gas emissions
- Renovating buildings to help reduce their energy use – 40% of EU energy consumption is from buildings
- Support industry to innovate and to become global leaders in the green economy

This work group seeks to contribute to these goals by facilitating the rapid adoption of the shipping of CO_2. This report seeks to provide advice and guidance on the process of ship transport of CO_2, ensuring awareness of existing standards and guidelines, and identifying where existing standards and guidelines need to be adapted to facilitate the transport of CO_2 by ship.

4.2 The role of CCS in meeting net-zero targets,

Carbon Capture and Storage (CCS) is crucial if Europe is to meet its 30-year target of bringing greenhouse gas emissions to net zero. In order to cut emissions CCS is essential – to decarbonise existing emission sources, particularly in those hard to abate industries where fuel switching is not a credible alternative and to enable the manufacture of early "blue" hydrogen to support the creation of a hydrogen economy.

Although we are incorporating more and more renewable energy in our power system, we cannot decarbonise our economies unless we also tackle CO_2 emissions from using fossil fuels in power and other sectors.

The geographical location of emitters in Europe, and the location of the potential geological storage sites in the North Sea, demands the long-distance transport of CO_2. As emitters are in a wide range of locations and have volumes that do not justify the construction of a dedicated pipeline, the shipping of CO_2 from source to store is critical to the development of the CO_2 storage market.

4.3 Scope and objectives of the work

The overarching aim of this work group is to develop consensus on international guidance and standards for key elements of CO_2 transport by ship – maritime and inland – that are needed to facilitate the development of a safe and efficient European CO_2 infrastructure. Such infrastructure would support cost-efficient CCUS deployment in multiple regions and countries in Europe by ensuring that liquified CO_2 carrier (LCOC) ships can load at any port and discharge at any port or storage site with suitable facilities.

This work aims to:

- Identify the expected scale and geographical distribution of European requirements for CO_2 ship transport, and to consider how these may evolve over time.
- Deliver a “ZEP technical guidance” document for CO_2 ship transport.
- Identify elements that require standardisation action by others, building on existing experience, e.g. from LNG and LPG shipping, ISO TC265, etc.
- Assess which existing standardisation organisation would be best placed to adopt and advance standards for CO_2 transport by ship and river barge (standards bodies, IMO, shipping classification societies, etc.), as well as identify and agree on next steps.

5 CO_2 shipping in the European landscape

Shipping provides a versatile, scalable transport solution for bulk CO_2 which can be implemented at dispersed sites which are far from potential geological storage locations. Shipping provides the potential to develop projects earlier and at lower cost than equivalent pipeline options (provided suitable storage and support mechanisms are available). Large industrial installations in Europe emit over 1,300 million tonnes of CO_2 per year[1] of which a significant proportion could be captured and transported.

5.1 Overview

The first shipping projects in a region will likely be centred on large emitters close to coastal sites – possibly to co-located with other emitter sites in a cluster. Within Europe there are a significant number of low-cost capture opportunities in areas that could be accessed via ship for transport.

In the longer term it may also be possible to aggregate, and transport captured CO_2 from cluster sites using an onshore pipeline gathering system and further expand terminal infrastructure to service the growing demand. In addition, it may be possible to use other non-pipeline transport methods such as river barges, rail, and trucks to transfer CO_2 from less accessible areas, particularly for smaller installations. Specific opportunities will need to be considered through techno-economic analyses on a case-by-case basis at individual sites in the context of supporting business models.

Shipping also offers a flexible opportunity for transboundary transport of CO_2 between emitter and storage projects. Where there are suitable support regimes in place and sufficiently low costs of capture and storage a mechanism could be developed to encourage a transport market. There are currently potentially low-cost capture opportunities in Europe without stores, as well as several initial projects developing stores with import potential. The majority of storage is around the UK and in the North Sea, and whilst there are other storage options across Europe their long distances from CO_2 sources makes a pipeline network uneconomic.

[1] Verified emissions reported in the EU ETS for 2020 from stationary installations emitting >25,000tCO_2/year.

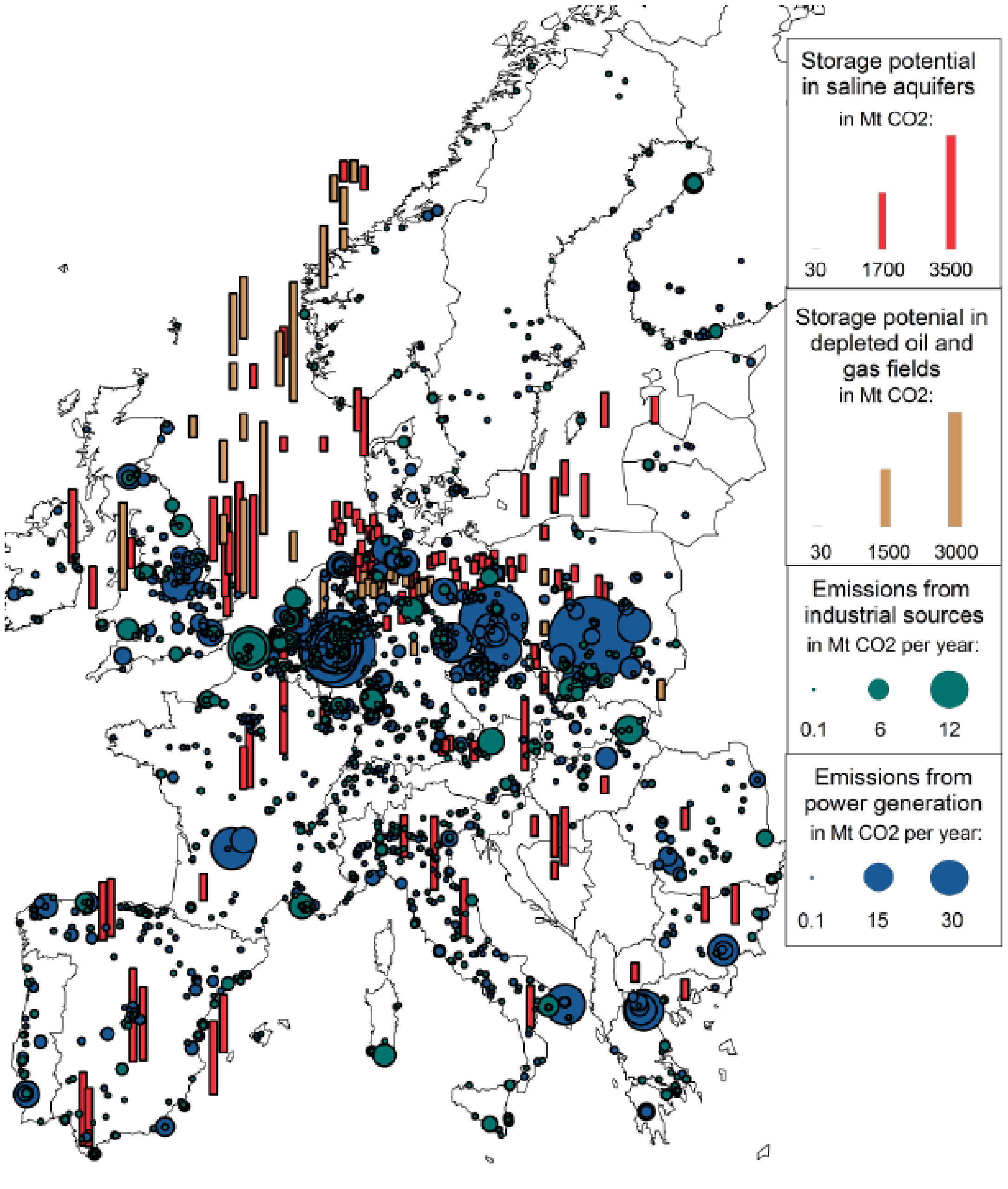


Figure 1: Map of major European emission sites and potential storage sites

Source "Development Scenarios for a CO_2 Infrastructure" published February 2014 and available from https://www.researchgate.net/publication/259998544_Development_Scenarios_for_a_CO_2_Infrastructure_Network_in_Europe/download

The map above shows major emitters in Europe. Blue circles show electricity generation source, green circles show industrial sources. The red bars show potential aquifer stores, and the orange bars show depleted oil and gas field stores.

5.2 Requirement for shipping of CO_2.

Several factors are evident from this map

- Whilst many of the emitters are at coastal locations, including clusters around major ports, the major emitters are inland, away from the coast
- Many of these inland emitters are located near to the major inland waterways of the Danube, the Volga, the Loire, the Rhine and the Elbe.
- Onshore storage sites are generally smaller than those offshore. In addition some EU states have effectively banned onshore underground storage of CO_2, making the transport of CO_2 to remote storage site imperative.
- Therefore, a CO_2 shipping market must be developed, with support for emerging CO_2-ship import locations with associated storage (or for direct injection).

5.3 Maritime and inland (rivers and canals) possibilities.

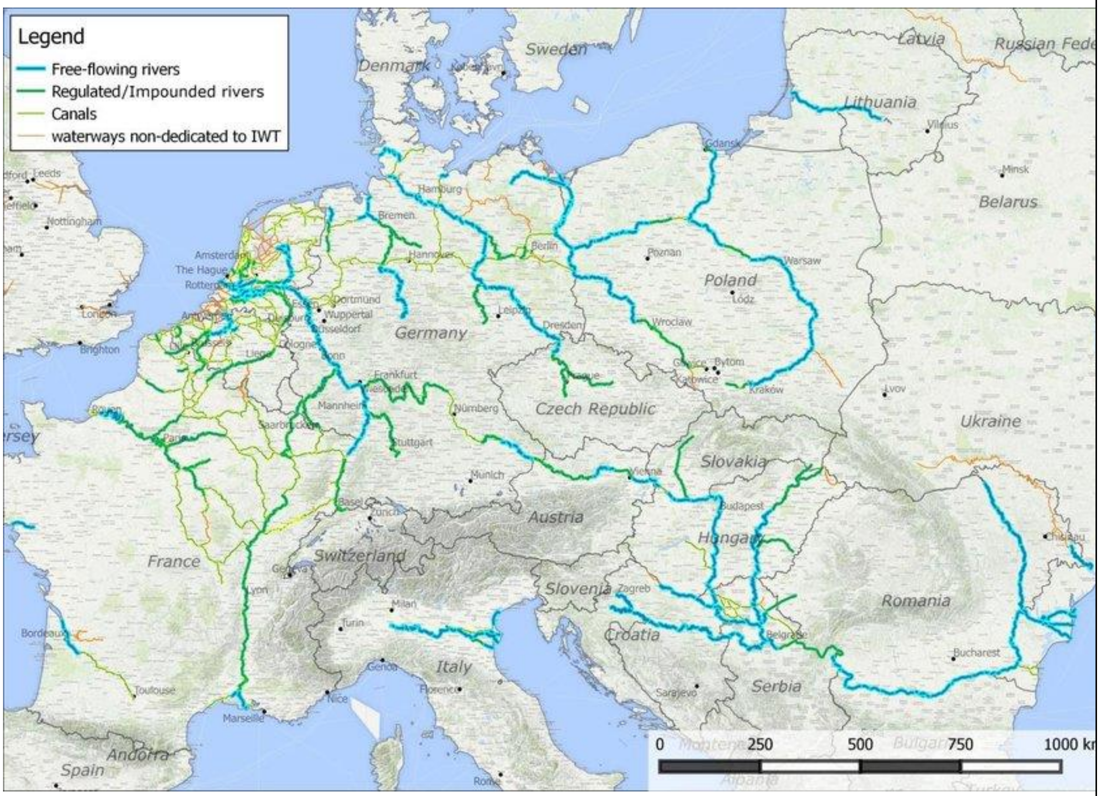


Figure 2: Map of major European waterways

Source "Identification of the fleet, typical fleet families & operational profiles on European inland waterways" published by PROMINENT (funded under the Horizon 2020 Programme) and accessible here https://www.researchgate.net/publication/320347490_PROMINENT_-_D11_List_of_operational_profiles_and_fleet_families/download

It may be possible to transport large volumes of CO_2 by barge to seaports where the CO_2 can be sent by pipeline for storage, or trans-shipped for transport by ship to the store. The specification of the barge transportation was originally outside the scope of this study, but has been included due to the large number of major inland emitters who will need to transport their CO_2 to the coast for trans-shipment (see section 7.4).

6 CO_2 Shipping standardisation requirements

In this section we identify all the areas where the ship transportation of CO_2 requires some form of standard or guidance. In many cases existing standards or guidance are available and can be used unaltered or could be adapted with very minor change.

6.1 CO_2 specific hazards

CO_2 is not flammable or combustible, so many of the hazards normally associated with the transportation of liquified gases are not present. However, the transport of liquified CO_2 does introduce different hazards which need to be taken into account in ship, barge and port storage system.

6.1.1 Asphyxia

CO_2 poses a threat to life through asphyxiation when it displaces the oxygen in air down to dangerously low levels. For CO_2 to reduce the oxygen concentration in air down to a level that is immediately dangerous to life, the CO_2 concentration would need to be in the order of 50% v/v.

Evidence shows, however, that CO_2 does create an immediate threat to life at a concentration of only 15% in air due to the toxicological impact it has on the body when inhaled.

This hazard is described in greater detail in the UK Health & Safety Executive publication "Assessment of the major hazard potential of carbon dioxide (CO_2)".

6.1.2 Toxicity

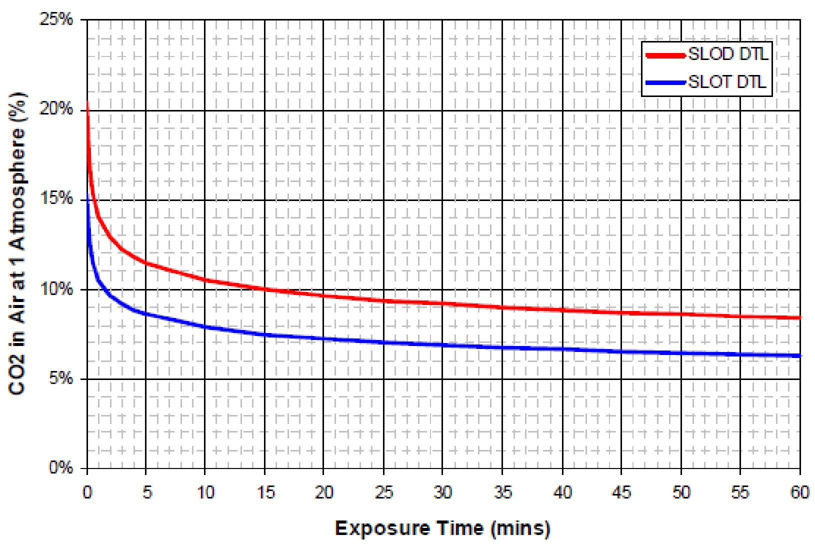
CO_2 poses a threat to life through toxicity, at levels summarised on the following table: -

Carbon Dioxide Concentration	Time	Effects
17 – 30%	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death
>10 – 15%	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
7 – 10%	1.5 minutes to 1 hour	Unconsciousness, near unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing

6%	1 – 2 minutes #16 minutes Several hours	Hearing and visual disturbances Headache, dyspnoea Tremors
4 – 5%	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnoea
3%	1 hour	Mild headache, sweating, and dyspnoea at rest
2%	Several hours	Headache, dyspnoea upon mild exertion

Figure **3**: Acute Health effects of high concentrations of CO_2

Source – www.epa.gov "APPENDIX B – Overview of Acute Health Effects of Carbon Dioxide"



SLOT DTL = Specified Level Of Toxicity Dangerous Toxic Load
SLOD DTL = Significant Likelihood Of Death Dangerous Toxic Load

Figure 4: Dangerous Toxic Load Limits for CO_2

Source – DNV GL Recommended practice DNVGLK-RP-F104

Relevant document - https://www.hse.gov.uk/foi/internalops/hid_circs/technical_osd/spc_tech_osd_30/spctecosd30.pdf

6.1.3 CO_2 density

CO_2 at atmospheric pressure has a density of 1.98 kg/m3 – approximately 1.5 times that of air.

As a result any CO_2 that leaks from a pipeline, process vessel, ship or barge will tend to accumulate at low points such as depressions in the ground, manholes, drains and in other confined spaces. Large volumes of CO_2 will tend to roll down hill, displacing air and creating an asphyxia hazard (see section 6.1.1). CO_2 will tend to disperse rapidly, making asphyxia a real but transitory hazard.

The paper "PHAST Validation of Discharge and Atmospheric Dispersion for Pressurised Carbon Dioxide Releases" published by IChemE in 2012 presents the results of modelling using the PHAST software validated against CO_2 emission and dispersion tests conducted by BP at the UK Spadeadam test site as part of the CO2PIPETRANS JIP. This paper shows rapid dispersion of leaked CO_2 into the atmosphere (less than 3 minutes to <1mol% CO_2)

6.1.4 Localise sub-zero temperatures

CO_2 will generally be stored and transported in pipelines in a liquid or dense phase fluid – typically at temperatures above 0˚C and in excess of the critical pressure of 73.82 bar. CO_2 maybe also be stored and transported in ships and the associated port storage as a liquid – typically refrigerated to -30˚C to -50˚C and at 7-20 bar although other temperature / pressure combinations are being considered.

If the storage vessel or pipeline should leak the pressure drops to atmospheric pressure of 1 bar, a two-stage process occurs:

- The liquid in the pipeline leaks and immediately flashes to a gas.
- Due to the rapid expansion the Joule Thomson effect creates the potential for the sub-zero temperature. The risk is of a jet of extremely cold gas jet that is hazardous to human health (asphyxia and freezing risk) and able to cause structural failure due to embrittlement of steels due to low temperature. Additionally small crystals of solid CO_2.can form, creating a risk of cold burns in the lungs if inhaled.

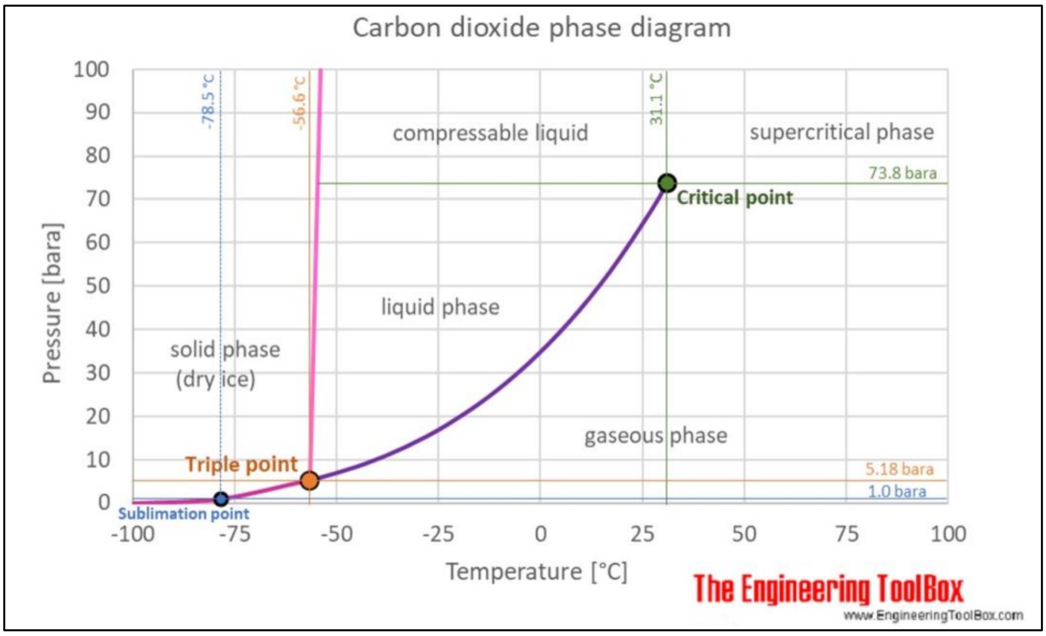


Figure 5: Carbon Dioxide Phase diagram

Source https://www.engineeringtoolbox.com/CO2-carbon-dioxide-properties-d_2017.html

Figure 6: Aerial photograph of a CO_2 leakage from the rupture of a Denbury Resources CO_2 pipeline in Yazoo County Mississippi, USA on 22 February 2020

Figure 7: Close up photograph of a CO_2 leakage from the rupture of a Denbury Resources CO_2 pipeline in Yazoo County Mississippi, USA 22 February 2020 showing localised freezing caused by the Joule Thompson effect

Source Mississippi Emergency Management Agency and https://eu.clarionledger.com/story/news/local/2020/02/27/yazoo-county-pipe-rupture-co-2-gas-leak-first-responders-rescues/4871726002/

This hazard is described in greater detail in the UK Health & Safety Executive publication "Assessment of the major hazard potential of carbon dioxide (CO_2)" https://www.scribd.com/document/82879884/Major-Hazard-Potential-Carbon-Dioxide

6.2 Ship Transport conditions

6.2.1 Cryogenic transport conditions

6.2.1.1 Analogy with LPG shipping

Based on discussions with multiple ship owners and designers there are, for liquified gasses, two primary cryogenic transport conditions that appear relevant to liquified CO_2 transport:

- Smaller vessels (<10,000 m^3) can readily be operated at medium pressure (~15 barg) and at -30°C). These are the conditions under which the current small food grade CO_2 transport vessels operate at.
- Larger vessels (>10,000m3) are more likely to be operated at low medium pressure (~7 barg) and at -50°C).

These cryogenic conditions and the size thresholds are the conditions under which Liquified Petroleum Gas (LPG) is currently transported. It is informative to note that no LPG carrier operating at 15barg / -30°C exceeds ~10,000 m3 cargo capacity.

These size thresholds were originally linked to LCO2 in a June 2016 paper by researchers at the Korea Advanced Institute of Science and Technology, the Korea Maritime and Ocean University, and the Korean Register entitled “Comparison of CO_2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain” which concluded that “the optimal liquefaction pressure was 15 bar (−27 ◦C), which had an appropriate pressure, temperature, and density. As the liquefaction pressure increased, the costs of the liquefaction and pumping system decreased, and the costs of the storage tanks and CO_2 carrier increased. The cost of the liquefaction system was the largest contributor to the LCC”. Source: https://www.sciencedirect.com/science/article/pii/S1750583616303012

Two other papers have repeated this data, acknowledging the source as the above June 2016 paper: -

- A July 2021 SINTEF paper entitled “At what pressure shall CO_2 be transported by ship? An in-depth cost comparison of 7 and 15 Barg Shipping” concludes that 7barg / -46C is the optimal condition for large volume shipping due to the lower vessel cost (~30%) Source: https://www.mdpi.com/1996-1073/14/18/5635/pdf
- Element Energy Limited ‘Shipping CO_2—UK Cost Estimation Study” Source https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf

6.2.1.2 Recent Northern Lights projections

The Northern Lights project has provided information advising that that their full chain economic evaluation using market-based ship CAPEX costs indicates that

Vessel cargo size	Lowest end-to-end costs
Up to 15,000m^3	Medium pressure ((~15 barg) and at -30°C) gives lowest cost
15,000-20,000 m^3	Evaluation inconclusive. Either medium or low pressure may be lower cost depending on finer details of the project
Above 20,000 m^3	Low pressure ((~7 barg) and at -50°C). gives lowest cost

Figure 8: Cryogenic ship cargo size at different pressure and temperature

The reason for the two cryogenic operating conditions relates to the mass of steel required. In the smaller vessels the steel required to contain a pressure of 15 barg is acceptable. In a larger vessel the mass of steel required to contain 15 barg becomes uneconomic despite the greater energy requirement to cool the liquified gas to -50°C.

6.2.2 Non-cryogenic transport conditions

The justification for the above cryogenic conditions focuses largely on the shipping elements of the value chain.

A number of published papers note that the economics of the full CCS value chain which includes shipping as part of the transport scheme can be dominated by the OPEX of the liquefaction and refrigeration process and the shipping operation.

The economically optimum transport condition does not just depend on the 3 parameters normally used to compare shipping transport scheme against pipeline options, i.e.:

- The annual volumes to be transported
- The distance over which the CO_2 needs to be shipped
- The length of contract duration

Instead, the economically optimum transport condition needs to consider how shipping is incorporated into the full CCS chain.

Some companies are considering the option of transporting liquified CO_2 at "ambient" conditions - smaller vessels (<10,000 m^3) that operate at higher pressures (40–50 barg) and "ambient" temperatures (i.e. above 0°C). These schemes are often linked to the idea of direct injection of CO_2 from ship into the storage reservoir.

Some specific projects have opted for these different shipping conditions, driven by their project specific requirements:

- Carbon Collectors of the Netherlands propose ship transportation of CO_2 as a liquid at 40bar / 5C and will deploy point-of-injection pumping to reach the CO_2 injection pressure requirements, without the need for additional heating.
- Cape Omega and Knutsen Shipping of Norway propose ship transportation of CO_2 as a liquid at 44bar / 10C and will also deploy point-of-injection pumping to reach the CO_2 injection pressure requirements.

6.2.3 Whole system perspective

The ship transportation temperature and pressure have to meet a number of different criteria that requires the decision on shipping conditions to be based on an integrated technical and economic assessment: -

- Liquefying CO_2 to -30˚C to -50˚C requires the use of cryogenic technology. This is both costly and energy intensive. Such a process requires cryogenic equipment at the port of origin and requires additional processing at the port of destination to prepare the CO_2 for injection.

- Liquifying CO_2 at higher temperatures requires higher pressure containment tanks on a ship. This allows the use of lower grade steel, adds weight and may add capital cost to the vessel, both due to the increased wall thickness of the pressure containment tank and due to the structural requirements of the hull required to carry the heavier tank. This greater weight also increases fuel consumption on the vessel.

Progressive Energy conducted an unpublished study that analysed a source-to-store CCS chain considering ship transport of CO_2 at operating pressures of between 5 and 70barg. A technoeconomic assessment into the processing requirements and cost of the whole value chain was made and the system optimised.

At low pressure, the high refrigeration (and subsequent regasification) loads dominated the system energy demand due to the low temperatures required to reach the fluid dew point. At high pressure, compression and cooling carried the highest load. Due to the advantage of needing a less cold temperature to achieve liquefaction conditions at high pressure, up to 40% less energy (thermal equivalent) was needed (depending on storage assumptions).

A levelised cost of shipping was calculated for a range of scenarios which discounted CAPEX, OPEX and transported CO_2 over the lifetime of a project. The relative contributions of capital and operating costs were found to vary with transport pressure where higher pressure systems carried a lower OPEX due to reduced overall processing loads, but where this was offset by the higher CAPEX requirements of equipment, onshore storage, and fleet purchase costs.

When optimised, the system model predicted a minimum cost at pressures between 10-25barg, however, the costs of every system pressure were close enough to be within the bounds of uncertainty of the model. This indicates that, in the case of this study and until better data is available, there is little evidence of a significant economic driver to selecting the operating pressure of ships on a levelised system cost basis, and that other metrics or factors should be used to inform choice of ship conditions.

6.2.4 Relevant references

- https://doi.org/10.1016/j.ijggc.2016.07.025:

  "Techno-economic evaluation of the effects of impurities on conditioning and transport of CO_2 by pipeline" by Geir Skaugen, Simon Roussanaly, Jana Jakobsen, Amy Brunsvold of SINTEF Energy Research, Norway (2016)

  International Journal of Greenhouse Gas Control, 54, 627-639, 2016.

- https://doi.org/10.1016/j.ijggc.2016.07.003

  "Key findings and recommendations from the IMPACTS project" by Amy Brunsvold, Jana P. Jakobsen, Marit J. Mazzetti, Geir Skaugen, Morten Hammer of SINTEF Energy

Research, Norway, Charles Eickhoff of Progressive Energy UK and Filip Neele of TNO The Netherlands – published in the International Journal of Greenhouse Gas Control, 54, 588-598, 2016.

- "Comparison of CO_2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain" by Youngkyun Seo a, Cheol Huh b, Sangick Lee c, Daejun Chang of Korea Advanced Institute of Science and Technology and Korea Maritime and Ocean University – published in International Journal of Greenhouse Gas Control 52 (2016) 1–12
- ISO 27913, Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems, 2016.

6.3 Composition

6.3.1 General considerations

The primary objective of shipping of CO_2 is to transport CO_2 from an emitter to a storage site. As a result, the cargo will be predominantly CO_2 – generally >98% CO_2.

Depending on the source of the CO_2 or the method of capture, there may be contaminants in the CO_2 which create several areas of concern:

- Health. Minor components in the CO_2 cargo may be toxic (e.g. hydrogen sulphide or carbon monoxide)
- Safety. Minor components may be corrosive (e.g. hydrogen can cause embrittlement of steels, and CO_2 with free water creates carbonic acid which is highly corrosive)
- Phase behaviour. Some contaminants materially change the phase envelope of CO_2, potentially creating issues with keeping the CO_2 in a liquid phase. This is illustrated in the diagram below.

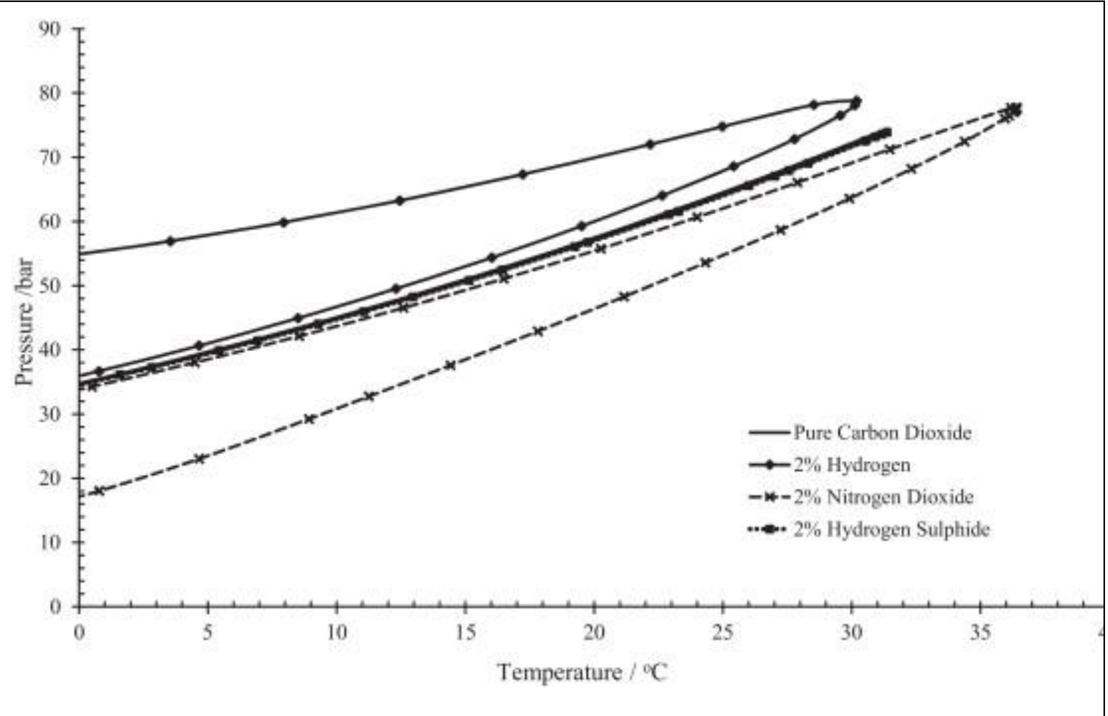


Figure 9: Phase diagram for binary combinations of CO_2 and 2mol% H2, H2S and NO2 (calculated using the Peng Robinson equation of state)

Source The Effect of CO2 Purity on the Development of Pipeline Networks for Carbon Capture and Storage Schemes published in International Journal of Greenhouse Gas Control, 2014.and available here

6.3.2 Techno-economic considerations

The acceptable composition of CO_2 to be carried by ship is influenced by a number of factors:

- **The CO_2 sources and CO_2 capture technology.** CO_2 from different sources will contain different impurities, which may be reduced by the CO_2 capture technology deployed. For example, the exhaust from a natural gas turbine contains fewer impurities than the exhaust from a coal fired steam boiler.
  Power generation remains the largest GHG-emitting sector, as illustrated in Figure 10 below.

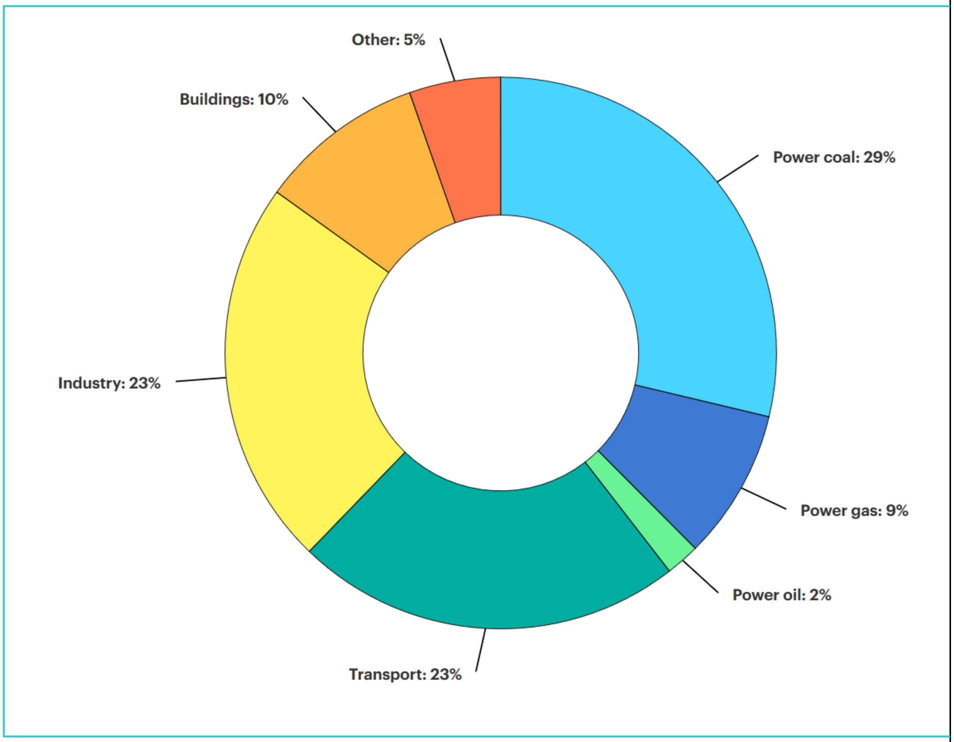


Figure 10: Global energy related CO_2 emission by sector dated March 2021

Source - https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector

- **The temperature and pressure of ship transportation.** Transporting CO_2 at very low temperatures (-30˚C or -50˚C) may be attractive as density increase as temperature drops, increasing the cargo capacity of a ship. However, the energy required to operate the cryogenic facilities is considerable.
  Due to the impact of impurities on the CO_2 phase envelope, the lower the pressure and temperature the greater the impact, as defined by the bubble point line. Hence higher pressure and temperature transport conditions can be more impurity tolerant.
- **The impact of the temperature and pressure of ship transportation.** Some impurities that present no issue at temperatures above 0˚C may create metallurgical issues at -30˚C or -50˚C.
- **The destination store.** Some impurities may react unfavourably with the storage reservoir rock or the original fluid in the storage reservoir or the (low) pressure of the store impact, for example the level of water in the CO_2.
- **Boil off rates.** The "boil off rate" is the amount of liquid that is evaporating from a cargo due to heat ingress and is expressed as a percentage of the total liquid volume per unit time. Typical LNG boil off rates are 0.15% / day and below, although some recent projected LNG carriers are offered with a BOR close to 0.1% (source Wartsila).

These variables mean that the optimal CO_2 temperature / pressure / composition may vary between projects. This could lead to the construction of project-specific ships.

The aim of this workgroup is to seek to achieve some degree of standardisation so that a CO_2 shipping market can emerge.

6.3.3 Requirement for CO_2 specifications

The following table lists all the components identified in various published CO_2 specifications (for shipping and for pipelines) and seeks to identify why the component may be relevant to be considered

Component	Reason for considering this component
Carbon Dioxide (CO_2)	The primary fluid to be transported – so content >98% normally required
Acetaldehyde	Toxic to aquatic life at 1-100mg/litre Corrosion impact minimal
Amine	Potential for carry over from amine capture plant. If the heat-stable salt content of any amine liquid exceeds 500ppm it can be corrosive. Reference "Amine system problems arising from heat stable salts and solutions to improve system performance" published in Fuel Processing Technology April 2009.
Ammonia (NH_3)	Highly toxic – physical effects at 1700 ppm, fatal at 2500-4500ppm. Potential stress corrosion issues.
Argon (Ar)	Potential asphyxiant if high concentrations (displaces oxygen) – but unlikely to be significant with >98% CO_2 present. A non-condensable so significant impact on phase envelope. Inert gas so not a metallurgical concern.
Cadmium (Cd)	Highly toxic (WHO provisional tolerable weekly intake for cadmium at 7 µg/kg of body weight).
Carbon monoxide (CO)	Toxic at concentrations above 100ppm.

Component	Reason for considering this component
	In the presence of carbon monoxide (CO) and water, stress corrosion cracking (SCC) is a risk in susceptible metals.
Formaldehyde	Fatal at concentrations above 100ppm.
Glycol	Toxic at very high concentrations (1.4ml / kg of body weight). In high concentrations causes steel to become harder and tensile strength increases.
Hydrocarbons	Potentially toxic. Corrosion impact minimal.
Hydrogen (H_2)	Potential asphyxiant at high concentrations due to displacement of oxygen – but unlikely to be significant with >98% CO_2 present. Hydrogen embrittlement risk increases as steel strength increases and as temperature is reduced.
Hydrogen sulphide (H_2S)	Fatal at concentrations over 500-1000 ppm. Flammable gas. Corrosive to steels.
Mercury (Hg)	Toxic at concentrations of 200-800 mg/kg of body weight – fatal at concentrations above 2400 mg/kg of body weight Corrosive when combined with other elements to produce corrosive compounds.
Methane (CH_4)	Potential asphyxiant at high concentrations due to displacement of oxygen – but unlikely to be significant with >98% CO_2 present. Corrosion impact minimal.
Nitric oxide (NO_x)	Toxic at concentrations of 100-150 ppm over 1 hour.

Component	Reason for considering this component
	Corrosion impact minimal – but nitrous oxides can contribute to corrosion when combined with SO_x and O_2 without free water.
Nitrogen dioxide (NO_2)	Irritant at concentrations of 20 ppm over 1 hour. Corrosion impact minimal – but nitrous oxides can contribute to corrosion when combined with SO_x and O_2 without free water.
Nitrogen (N_2)	Makes up 78% of the air. Potential asphyxiant at higher concentrations due to displacement of oxygen – but unlikely to be significant with >98% CO_2 present. Corrosion impact minimal – but nitrous oxides can contribute to corrosion when combined with SO_x and O_2 without free water.
Oxygen (O_2)	Toxic at concentrations above 50% (air concentration is ~21%) Corrosive in the presence of water.
Sulphur oxides (SO_x)	Toxic effects detected at 10ppm – fatal at concentrations of ~150 ppm over a few minutes. Corrosive in the presence of water – and nitrous oxides can contribute to corrosion when combined with SO_x and O_2 without free water
Temperature	Relevant as • Some impurities are more of a problem at low temperatures -30˚C or -50˚C. • Some metallurgical properties deteriorate as temperature falls.
Titanium (Ti)	Titanium – low toxicity and no known environmental effects.

Component	Reason for considering this component
	Added to steel to enhance properties (strength and corrosion resistance).
Water (H_2O)	Corrosive when combined with CO_2 to form carbonic acid

Figure 11: List of components which feature in various CO_2 transport specifications

6.3.4 Published Shipping CO_2 specification

The following table shows two published CO_2 compositions for shipping: -

Component	Northern Lights [1] Concentration (ppm mol)	EU [2] recommendations
Carbon Dioxide (CO_2)	Not defined	>99.7% by volume
Acetaldehyde	≤20	Not defined
Amine	≤10	Not defined
Ammonia (NH_3)	≤10	Not defined
Argon (Ar)	Not defined	<0.3% by volume
Cadmium (Cd) / Titanium (Ti)	≤0.03 (sum)	Not defined
Carbon monoxide (CO)	≤100	<2000ppm
Hydrogen (H_2)	≤50	<0.3% by volume
Hydrogen sulphide (H_2S)	≤9	<200ppm
Formaldehyde	≤20	Not defined
Mercury (Hg)	≤0.03	Not defined
Methane	Not defined	<0.3% by volume
Nitric oxide / nitrogen dioxide (NOx)	≤10	Not defined
Oxygen (O_2)	≤10	Not specified as literature inconsistent
Sulphur oxides (SOx)	≤10	Not defined
Water (H_2O)	≤30	<50ppm

Figure 12: Published CO_2 specifications for shipping

(1) The shipping specification for CO_2 to be transported as part of the Northern Lights project in Norway was published as part of the Northern Lights FEED study which is available here)

(2) The EU position on the acceptable shipping specification for CO_2 is set out in a "Briefing on carbon dioxide specifications for transport" – the 1st Report of the Thematic Working Group

on CO_2 transport, storage and networks published by the EU CCUS Projects Network (No ENER/C2/2017-65/SI2.793333)

The logic for the CO_2 specification for Northern Lights is the prevention of negative effects of combinations of impurities on materials in the value chain. An example: small amounts of H2S in combination with O_2 and SOx can lead to formation of sulphuric acid in case of production upsets. Sulphuric acid could eat a hole in the carbon steel pipeline in days potentially.

Further study and laboratory work is required for generic CO_2 specifications, as there is limited data available on solubility of combinations of impurities under the variety of pressure and temperature conditions.

6.3.5 Published Pipeline CO_2 specifications

Pipeline specifications tend to be less demanding than shipping as illustrated below: -

Component	Kinder Morgan pipeline (US) specification (1)	DYNAMIS CO_2 quality recommendation (2)
Components specified for shipping on previous table		
Carbon Dioxide (CO_2)	>95%	>95.5
Acetaldehyde	Not specified	Not specified
Amine	Not specified	Not specified
Ammonia (NH_3)	Not specified	Not specified
Argon (Ar)	Not specified	<4% by volume
Cadmium (Cd) / Titanium (Ti)	Not specified	Not specified
Carbon monoxide (CO)	Not specified	<2000ppm
Formaldehyde	Not specified	Not specified
Hydrogen (H_2)	Not specified	<4% by volume
Hydrogen sulphide ($H2_2$)	≤20	<200ppm
Mercury (Hg)	Not specified	Not specified

Methane	Not specified	<4% by volume
Nitric oxide / nitrogen dioxide (NOx)	≤10	<100ppm
Oxygen (O_2)	≤10	Not specified
Sulphur oxides (SOx)	Not specified	<100ppm
Water (H_2O)	No free water <30 pounds per mmscf in vapour phase (<630ppm)	<500ppm
Additional components specified		
Glycol	No liquid glycol <0.3 gallons / mmscf	Not specified
Hydrocarbons	<5 mol% Dew point <-20˚F (-28.9˚C)	Not specified
Nitrogen (N)	<4 mol%	<4% by volume
Sulphur oxides (SOx)	<35 ppm by weight	Not specified
Temperature	<120˚F (48.9˚C)	Not specified

Figure 13: Published CO_2 specifications for pipeline transportation

(1) Kinder Morgan data published in "Briefing on carbon dioxide specifications for transport" – the 1st Report of the Thematic Working Group on CO2 transport, storage and networks – part of the EU CCUS Projects Network.

(2) Above data published in "Briefing on carbon dioxide specifications for transport" – the 1st Report of the Thematic Working Group on CO2 transport, storage and networks published by the EU CCUS Projects Network (No ENER/C2/2017-65/SI2.793333)

The following pipeline specifications have been published by others: -

Component	Teesside (1)	CarbonNet lower (2)	CarbonNet upper (2)
Components specified for shipping on previous table			
Carbon dioxide (CO_2)	≥ 95 % v/v	Balance of stream (> 93.5 % v/v)	**100 % v/v**
Acetaldehyde	Not specified	Not specified	**Not specified**

Amine	Not specified	Not specified	**Not specified**
Ammonia	< 50 ppmv	Not specified	**Not specified**
Argon (Ar)	≤ 1 % v/v	Not specified	**Not specified**
Cadmium (Cd) / Titanium (Ti)	Not specified	Not specified	**Not specified**
Carbon monoxide (CO)	< 2000 ppmv	≤ 900 ppmv	**≤ 5000 ppmv**
Formaldehyde	Not specified	Not specified	**Not specified**
Hydrogen (H_2)	≤ 1 % v/v	Not specified	**Not specified**
Hydrogen sulphide (H_2S)	< 200 ppmv	≤ 100 ppmv	**≤ 100 ppmv**
Mercury (Hg)	Not specified	Not specified	**Not specified**
Methane (CH_4)	≤ 1 % v/v	Not specified	**Not specified**
Nitric oxide / nitrogen dioxide (NO_x)	< 100 ppmv	≤ 250 ppmv	**≤ 2500 ppmv**
Oxygen (O_2)	< 10 ppmv	Not specified	**Not specified**
Sulphur oxides (SOx)	< 100 ppmv	≤ 200 ppmv (SO_2)	**≤ 2000 ppmv (SO_2)**
Water (H_2O)	≤ 50 ppmv	≤ 100 ppmv	**≤ 100 ppmv**
Additional components specified			
Hydrocarbons	≤ 2 % v/v	≤ 0.5 % v/v (other than methane)	**Not specified**
Nitrogen (N_2)	≤ 1 % v/v	Not specified	**Not specified**
Particulates	≤ 1 mg/Nm^3	Not specified	**Not specified**
Particle size	≤ 10 µm	Not specified	**Not specified**
Total non-condensable	≤ 4 % v/v	≤ 2 % v/v	**≤ 5 % v/v**

Figure 14: Additional published CO_2 specifications for pipeline transportation

(1) Teesside values from (AMEC, 2015), includes additional mercury specification.

(2) CarbonNet values from Harkin et al, 2016, gives a lower and upper end of a range of acceptable specifications for different streams joining the network; additional hydrogen cyanide, temperature and pressure specifications.

Useful published guidance on the subject of acceptable composition of CO_2 include

- The GCCSI CarbonNET Project "Development of a CO_2 specification for a CCS hub network" published May 2016

6.4 Selecting the optimum conditions for an individual project

6.4.1 Key conditions to be considered

It is clear from the preceding sections that there is not an “ideal” or “correct” set of conditions that should be deployed on a particular project. The following table seeks to identify the key factors that must be considered as an individual project selects the appropriate conditions that they will design for.

Factor	Impact
CO_2 production rate by a cluster and the phasing of growth	What are the production rates in the initial phase and how can shipping support this and the longer-term projected growth
The acceptable CO_2 specification	The acceptable CO_2 specification needs to consider the whole CCS chain including: - • The different sources of CO_2 • The different methods of CO_2 removal • The different transport specifications (temperature and pressure) • The different characteristics of storage destination which result in different injection conditions (pressures / temperature during the injection start / operating and stop modes) as well as exposure to free water.
Optimal ship parcel size versus onshore storage requirements	Cost of liquified storage versus cost of ships Is there any land constraint for onshore storage? Dedicated ships that will provide regular turnaround times will support optimised onshore storage versus open market for LCO2 ships that will have variable parcel size

	and less predictable availability will drive larger storage requirements.
Shipping pressure and temperature that determines the liquefaction process required	Conditions of the CO_2 gathering network impact on the amount of processing required for liquefaction Availability of a suitable, preferably green, energy source for the liquefaction process Liquified CO_2 storage design CAPEX and OPEX of the liquefaction process
Specifications set by the CO_2 Storage provider	Will there be a long-term contract with a CO_2 storage provider that may set the allowable CO_2 pressure and temperature? Note that in general the CO_2 specification for shipping is more onerous than typical pipeline specifications.
Shipping travel times from the emitter / cluster to a CO_2 storage provider	Will there be dedicated ships for the cluster? What are the turnaround times and how will this impact on sizing liquified storage requirements onshore?

Figure 15: Key shipping conditions to be considered

6.4.2 Project specifications

When defining the CO_2 specification, it can be useful to think from the following perspectives:

- **The functional specification** - the impact the impurities have on the phase envelope that the transport and storage system can accept. This allows different quantities of different non-condensables to be acceptable rather than selecting arbitrary values for components that have different impacts or cannot be defined singularly when their impact needs to be additive.
- **Safety specification** - to not allow the concentration of any given impurity to have a greater impact on health, safety or the environment than the impact of much higher concentration of the CO_2. This would allow a specification of the maximum

concentration limits for each hazardous / toxic substance. It also simplifies the modelling / dispersion assessment as it only needs to evaluate the CO_2 concentration

- **Integrity specification** - including, transport, tank, pipeline, topsides and well integrity. It is likely that this evaluation will be a mixture of general guidelines and project specific evaluation. The levels of NO_x, SO_x and total sulphur may be definable generically, whereas water, oxygen and hydrogen may be more dependent on project specific parameters such as well operating conditions, transport temperatures and pipeline operating conditions. This will be especially important when considering repurposing of an existing pipeline.

This approach may give rise to different impurity specifications on a project-by-project basis.

6.4.3 Cross-chain specification impact

Any attempt to standardise on an impurity specification on a component-by-component basis so that a wide range of pipelines / wells could be re-used with a "tight" specification risks the emitters needing to purify the CO_2 to a greater extent than may otherwise be necessary. Conversely, if a wider, more relaxed impurity specification became the standard then some existing wells / pipelines may subsequently be assessed as unsuitable, where they could have been reusable had a tighter specification been adopted.

Existing pipelines which operate with a very wide range of impurity specifications provide a good indication of how project-by-project flexibility has been used.

6.4.4 Regulatory Considerations

The Directive on the geological storage of CO_2, implemented into law across the EU and retained by the UK, requires the storage operator to identify the source and quantity of CO_2 to be stored.

This approach may inhibit the development of a CO_2 market in the future.

6.5 Back-haul cargos

The nature of CO_2 shipping for CCS is that the ship travels from the emission source to the storage site with a cargo of CO_2 and travels back empty.

This has given rise to the notion of finding some alternative cargo for the return journey (backhaul).

Shipping triangulations, where a ship visits several ports and unloads one cargo and picks up another cargo can be cost-efficient but usually only on same trade/cargo types.

With emitter sites and CO_2 sinks at various locations, there is a possibility of some triangulations rather than true backhauls.

However, the workgroup regards true backhauls as impractical for early projects for several reasons:

- Cargoes that might be suitable for carrying on a liquefied CO_2 ship as a backhaul are LPG and ammonia, which are both transported at similar temperature and pressure conditions but very different densities (LCO2 is nearly twice as heavy as LPG/ammonia).

  Our view is that it is unlikely that LPG or ammonia would be available at the storage site and that it would need to be transported to the emitter site. The lost time/delays associated with traveling to a new load port after discharging LCO2 could drastically affect the economic viability of such a voyage plan.

  With restrictions involved with loading separate cargoes at different ports, the viability of such a backhaul operation will be difficult to plan appropriately and justify economically.

  Delays add up quickly for ship schedules and traders/voyage coordinators need maximum flexibility to ensure vessels are operated efficiently between load and discharge ports.

  A highly optimised vessel for a certain trade/cargo cannot be equally optimised for another trade/cargo.

  To lower ship CAPEX, it is only practical for an LCO2 vessel design to focus on cargoes with similar temperature and pressure conditions for transport.

  LNG

  Including LNG in this possible list of cargoes is not recommended due to the -163ºC required storage temperature. In contrast, LCO2 is only required to be cooled to -50ºC at low pressure conditions.

  In addition, LNG's density is approx. 450 kg/m3 while LCO2's density is approx. 1,100 kg/m3. Required cargo tank construction suitable for storing LNG and LCO2 would be extremely costly to design and build.

  Further, the vessel's draft will be highest when carrying LCO2. If carrying a lower density cargo such as LNG, ballast may need to be added to the vessel during the backhaul to ensure enough propeller immersion. Adding ballast would increase fuel consumption and make the vessel less efficient to operate.

To maximize the full efficiency of a vessel, it is recommended to carry similar temperature, pressure, and density cargoes to ensure the vessel is optimally designed to carry that specific cargo.

- If using medium pressure Type C pressure build up tanks, no heel is recommended to remain in the cargo tank after discharge to minimize possible increases in boil off rate during the ballast leg. At low fill %, the boil off rate can be extremely high preventing the vessel from operating without actuating the pressure relief valves to avoid over pressurizing the cargo tanks.

LPG and Ammonia

- Any routine changing of cargo (e.g. after every voyage) will require significant tank cleaning between cargos to avoid cross contamination.

  This is known to be a significant issue for existing ammonia carriers that can switch between carrying LPG and ammonia interchangeably.

  Most LPG vessels are dedicated to carrying only LPG or ammonia for a significant amount of time before they switch to another liquid/gas cargo. Any routine cargo switching is likely to carry a significant cost burden due to the time required for tank cleaning.

  Another issue is that the cross-contamination of LPG and CO_2 must be avoided. All cargo will need to be purged completely after every load/discharge. In addition, a warmup and cooldown before loading LCO2 must performed. The amount of time required to complete this warmup and cooldown will vary depending on the vessel size. As an example, a conventional LNGC requires a 36-hour cooldown process plus a standard loading time of 24 hours before loading LNG. Comparing this requirement to a LCO2 carrier, this additional warm up/cool down period may add a significant amount of berth time per voyage which in turn affects berth availability for all vessels. It takes time (on the order of 1 – 7 days) for purging/warm up/cooldown of CO_2 from cargo tanks before loading another cargo and vice versa depending on the cargo tank size and number of cargo tanks.

As a result of these factors the workgroup regards true backhauls as impractical for early projects.

7 Existing guidelines and standards

7.1 Overall ship standards

There is already a strong global framework setting out ship safety specifications regardless of the cargo.

Under the UN Agency the International Maritime Organisation (IMO) there are a series of Conventions which apply to all ships including: -

- SOLAS – the "Safety of Life at Sea" convention
- MARPOL – the "Marine Pollution" convention
- STCW – the “Training & Competence” convention
- A Documentation Facilitation Convention
- A specification of Standard Maritime English

SOLAS and MARPOL, in particular, are written into the rules of all the Classification Societies, so are widely implemented. These rules are well understood by ship designers and have to be followed for the ship to achieve approval from an accredited Classification Society.

No further action is required in this area.

7.2 Gas carrier standards

For the design and construction of liquified gas carriers IMO has published the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), which has been mandatory under SOLAS chapter VII since 1 July 1986.

The IGC Code applies to ships regardless of their size, including those of less than 500 gross tonnage, engaged in carriage of liquefied gases having a vapour pressure exceeding 2.8 bar absolute at a temperature of 37.8°C (liquified CO_2 meets this criteria). Sections 17.21 & 17.22 of the 2016 IGC Code deal with the carriage of CO_2.

The Code was most recently revised in 2014. The Revised Code was adopted at MSC 93 (May 2014) and entered into force on the 1st of January 2016. The revised code is not retroactively applied and only applies to vessels contracted / keel laid after 1 July 2016.

A further revision of the code has commenced. IMO’s Maritime Safety Committee met virtually for its 103rd Session (MSC 103) in May 2021. A SIGTTO paper (with Marshall Islands and IACS) proposing a focused review of the IGC Code was considered by the committee and the new work item agreed. It will be added to the Sub-committee on Carriage of Cargoes and Containers’ (CCC 8) agenda, which will be held in September 2022. Although a focused review was proposed, the scope of the review will be unlimited. This further revision will include more detail on CO_2 shipping and is not expected to be finalised and published until 2026.

7.3 Existing guidelines applicable to CO_2 carriage

7.3.1 Applicable SIGTTO & OCIMF Publications

The following publications may be relevant to an individual liquified CO_2 project: -

- Site Selection and Design for LNG Ports and Jetties (Information Paper No. 14) (SIGTTO)
- A Guide to Contingency Planning for Marine Terminals Handling Liquefied Gases in Bulk – 2nd Edition (SIGTTO)
- LNG Operations in Port Areas - Essential Best Practices for the Industry (SIGTTO)
- Liquefied Gas Fire Hazard Management - First Edition (SIGTTO)
- Hydrates in LPG Cargoes - A Technological Review (SIGTTO)
- LPG Shipping - Suggested Competency Standards (SIGTTO)
- Jetty Maintenance and Inspection Guide (SIGTTO/OCIMF)
- Liquefied Petroleum Gas Sampling Procedures (SIGTTO)
- Application of Amendments to Gas Carriers Codes Concerning Type C Tank Loading Limits (SIGTTO)
- Liquefied Gas Carriers: Your Personal Safety Guide - 2nd Edition (SIGTTO)
- The Selection and Testing of Valves for LPG Applications (SIGTTO)
- Ship to Ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases (CDI/ICS/OCIMF/SIGTTO)
- A Justification into the Use of Insulation Flanges (and Electrically Discontinuous Hoses) at the Ship/Shore and Ship/Ship Interface (SIGTTO)
- Support Craft at Liquefied Gas Facilities - Principles of Emergency Response and Protection - Onshore (SIGTTO)
- Support Craft at Liquefied Gas Facilities - Principles of Emergency Response and Protection - Offshore (SIGTTO)
- Liquefied Gas Handling Principles on Ships and in Terminals – 4th Edition (SIGTTO)
- LNG and LPG Experience Matrix (SIGTTO)

- LNG Emergency Release Systems - Recommendations, Guidelines and Best Practices (SIGTTO)
- LNG Marine Loading Arms and Manifold Draining, Purging and Disconnection Procedure (SIGTTO)
- Recommendations for Liquefied Gas Carrier Manifolds (SIGTTO)
- Guidelines for the Alleviation of Excessive Surge Pressure on ESD for Liquefied Gas Transfer Systems (SIGTTO)
- Ship / Shore Interface for LPG/Chemical Gas Carriers and Terminals (SIGTTO)
- SIGTTO Information Papers, Consolidated Edition 2019 (SIGTTO)
- Recommendations for Management of Cargo Alarm Systems (SIGTTO)
- Recommendations for Relief Valves on Gas Carriers (SIGTTO)
- Recommendations for Designing Cargo Control Rooms (SIGTTO)
- Guidance on Gas Carrier and Terminal Gangway Interface (SIGTTO)
- ESD Systems (SIGTTO)
- Recommendations for Cargo Control Room HMI (SIGTTO)
- International Safety Guide for Oil Tankers and Terminals (ISGOTT 6 – OCIMF)

SIGTTO General Purposes Committee has on its agenda to review these guidelines to accommodate liquified CO_2 transport.

7.3.2 International standards

The following international standards may be relevant to an individual liquified CO_2 project: -

- ISO 28460 Ship-to-shore interface and port operations
- ISO 31010, Risk management - Risk assessment techniques (IEC/ISO 31010:2009).
- ISO 21013, Cryogenic vessels - Pressure-relief accessories for cryogenic service
- ISO/TS 17969:2015 Petroleum, petrochemical and natural gas industries - Guidelines on competency for personnel
- Recommendations for the Design and Assessment of Marine Oil, Gas & Petrochemical Terminals (PIANC)

7.3.3 Alternative Cargoes on a Liquid CO_2 carrier

7.4 River and Inland Waterway standards and guidelines

The working group identified from the map of European emitters (see
) that significant amounts of CO_2 are likely to be transported by barges on rivers and inland waterways and possibly trans-shipped to ocean going ships at coastal ports. As a result, the Working Group elected to include reference to standards relating to inland waterways.

7.4.1 European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways

The most relevant standard appears to be the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways.

This agreement was developed by the United Nations Economic Commission for Europe (UNECE), entered into force on 29th February 2008 and was most recently updated in 2021.

The document is publicly available at:
https://unece.org/transport/documents/2021/01/adn-2021-enfrru

The Agreement focuses on the transportation of dangerous goods and includes carbon dioxide refrigerated liquid (item 2187).

7.4.2 International Safety Guide for Inland Navigation Tank-barges and Terminals

The International Safety Guide for Inland Navigation Tank-barges and Terminals (ISGINTT) was drafted by the Central Commission for the Navigation of the Rhine (CCNR) "Oil Companies International Marine Forum".

CCNR was created at the Congress of Vienna (1815) and is the oldest international organisation in modern history. It promotes the development of close cooperation with the other international organisations working in the field of European transport policy and with non-governmental organisations active in the field of inland navigation. The organisations website is at www.ccr-zkr.org/.

The purpose of ISGINTT is to improve safe transport of dangerous goods at the interface of inland tank barges with other vessels or shore facilities (terminals). The organisation's website is at www.isgintt.org.

The standard focusses on the transportation of liquified gases, but mainly refers to flammable hydrocarbon gases and chemicals. CO_2 is generally mentioned as an inert gas blanket for flammable gases or as a fire extinguishing agent.

7.4.3 Recommendation

It is recommended that ZEP requests that these existing standards be reviewed with a view to adding the transportation of bulk liquefied carbon dioxide to the standards.

8 Conclusions and Recommended actions

8.1 Conclusions

Broadly the working group has found that existing shipping regulations and standards are suitable for use in the CCS industry – either unchanged or with minimal adaptation (see section 8.2 Recommendations below)

The composition of CO_2 (specifically the trace components) is likely to vary between individual emitters, so there needs to be a clear understanding of the basis for each trace component limit, as significant cost may be added by requiring blanket adherence to a specific composition.

8.2 Recommendations

The following recommendations are made to ensure greater standardisation of liquid CO_2 carrier ships.

- IMO be requested to publish an update to their Conventions which apply to all ships including: -
    - SOLAS – the "Safety of Life at Sea" convention
    - MARPOL – the "Marine Pollution" convention
    - STCW – the “Training & Competence” convention
- SIGTTO be requested to publish an update to their “Recommendations for Liquefied Gas Carrier Manifolds” and “Ship/Shore Interface for LPG/Chemical Gas Carriers and Terminals” to incorporate any amendments or additions required to manage CO_2 transfer from ship to shore and vice versa.
- SIGTTO to be requested to work with industry to develop a CO_2-specific handbook for the Custody Transfer of CO_2.
- The Central Commission for the Navigation of the Rhine (CCNR) be requested to review the International Safety Guide for Inland Navigation Tank-barges and Terminals (ISGINTT) with a view to making any necessary modifications associated with a significant increase in the quantities of liquefied CO_2 to be transported on inland waterways,
- The RID/ADR/ADN Joint Meeting be requested to review their respective guidance with a view to making any necessary modifications associated with a significant increase in the quantities of liquefied CO_2 to be transported on roads, railways and inland waterways,

- ISO be requested to consider reviewing it standard ISO 28460:2010 “Petroleum and natural gas industries — Installation and equipment for liquefied natural gas — Ship-to-shore interface and port operations” with a view to with a view to making any necessary modifications associated with a significant increase in the quantities of liquefied CO_2 to be transported by ocean-going ships.
- GCCSI to be made aware of this workgroup and its findings.
- This workgroup to convert this document into a ZEP “Guidance Note” for publication.

9 Other CO_2 transport modalities – train, truck, etc.

Standards for the transportation of CO_2 by other modes of transport such as river barge, rail tanker and road tanker – are outside the scope of this report, and in many cases already exist.

We do however recognise that as CCS becomes more pervasive such transport modes will become increasingly relevant.

We have identified the following organisations as being potentially relevant, and suggest that they be made aware of this report

- **The Single European Railway Area** is an EU initiative to foster cross-border rail transport. Its website is at ec.europa.eu/transport/modes/rail/news/2019-05-16-single-european-railway-area_en.
- **UIC** is the worldwide professional association representing the railway sector and promoting rail transport. In particular, it promotes standards designed to ensure safety on the railway of the world. The organisations website is at www.uic.org/freight/dangerous-goods/.
- **The Energy Institute** publishes the "Petroleum Road Tanker Design and Construction", which provides recommendations for the design and construction of road tankers intended for the conveyance of the main petroleum fuels: petrol; kerosene; diesel, and gas oil.
- **The Transportation Research Board** (TRB) is part of the US National Academies of Sciences, Engineering, and Medicine. They publish a range of scientific guidance documents including on road transportation of hazardous fluids. The organisations website is at www.trid.trb.org.
- **RID/ADR/ADN Joint Meeting –** is organised twice per year by
  - OTIF (the Intergovernmental Organisation for International Carriage by Rail). It has been active since 1893 and is the oldest international organisation in the sector. It now has 50 Member States and 1 Associate Member. The Organisation has its headquarters in Berne, Switzerland, and has legal personality under international law and in the national laws of its Member States. OTIF develops unified railway law to connect Europe, Asia and Africa for 125 years (www.otif.org)
  - UNECE (the United Nations Economic Commission for Europe) – one of 5 UN Regional Commissions. Its Transport Division aims to improve competitiveness, safety, energy efficiency and security in the transport sector. At the same time, it focuses on reducing the adverse effects of transport activities on the environment and contributing effectively to sustainability (www.unece.org/transport)

The purpose of the joint meeting is to ensure harmonisation of the regulations relating to the dangerous goods provisions for European land transport:

- ADN – European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterway. This document does refer to the transport of CO_2.
- ADR – European Agreement concerning the International Carriage of Dangerous Goods by Road. These regulations do cater for the transport of liquified carbon dioxide in bulk.
- RID – Regulation concerning the International Carriage of Dangerous goods by Rail. These regulations do cater for the transport of liquified carbon dioxide in bulk.

The objective of harmonising these three regulations as closely as possible to simplify and promote multimodal transport was largely achieved when restructured editions of RID and ADR, were published on 1 January 2001, reducing the differences to a minimum.

The RID/ADR/ADN Joint Meeting also examines amendments arising from the UN Model Regulations, which apply globally, and proposals which only concern European land transport, such as the provisions for RID/ADR tanks.

10 References and further reading

10.1 Map of major European emission sites and potential storage sites

"Development Scenarios for a CO_2 Infrastructure" published February 2014 and available from https://www.researchgate.net/publication/259998544_Development_Scenarios_for_a_CO_2_Infrastructure_Network_in_Europe/download

10.2 Map of major European waterways

"Identification of the fleet, typical fleet families & operational profiles on European inland waterways" published by PROMINENT (funded under the Horizon 2020 Programme) and accessible here https://www.researchgate.net/publication/320347490_PROMINENT_-_D11_List_of_operational_profiles_and_fleet_families/download

10.3 Acute Health effects of high concentrations of CO_2

www.epa.gov "APPENDIX B – Overview of Acute Health Effects of Carbon Dioxide"

10.4 Dangerous Toxic Load Limits for CO_2

DNV GL Recommended practice DNVGLK-RP-F104 - Relevant document - https://www.hse.gov.uk/foi/internalops/hid_circs/technical_osd/spc_tech_osd_30/spctecosd30.pdf

10.5 Carbon Dioxide Phase diagram

https://www.engineeringtoolbox.com/CO2-carbon-dioxide-properties-d_2017.html

10.6 Close up photograph of a CO_2 leakage

From the rupture of a Denbury Resources CO_2 pipeline in Yazoo County Mississippi, USA 22 February 2020 showing to localise freezing caused by the Joule Thompson effect

Mississippi Emergency Management Agency and https://eu.clarionledger.com/story/news/local/2020/02/27/yazoo-county-pipe-rupture-co-2-gas-leak-first-responders-rescues/4871726002/

This hazard is described in greater detail in the UK Health & Safety Executive publication "Assessment of the major hazard potential of carbon dioxide (CO_2)" https://www.scribd.com/document/82879884/Major-Hazard-Potential-Carbon-Dioxide

10.7 CO_2 Transport conditions

- A July 2021 SINTEF paper entitled "At what pressure shall CO_2 be transported by ship? An in-depth cost comparison of 7 and 15 Barg Shipping" concludes that 7barg / -46C is the optimal condition for large volume shipping due to the lower vessel cost (~30%) Source: https://www.mdpi.com/1996-1073/14/18/5635/pdf

- A June 2016 paper by researchers at the Korea Advanced Institute of Science and Technology, the Korea Maritime and Ocean University, and the Korean Register entitled "Comparison of CO_2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain" which concluded that "the optimal liquefaction pressure was 15 bar (−27 ◦C), which had an appropriate pressure, temperature, and density. As the liquefaction pressure increased, the costs of the liquefaction and pumping system decreased, and the costs of the storage tanks and CO_2 carrier increased. The cost of the liquefaction system was the largest contributor to the LCC" Source: https://www.sciencedirect.com/science/article/pii/S1750583616303012

- "Techno-economic evaluation of the effects of impurities on conditioning and transport of CO_2 by pipeline" by Geir Skaugen, Simon Roussanaly, Jana Jakobsen, Amy Brunsvold of SINTEF Energy Research, Norway (2016)

  International Journal of Greenhouse Gas Control, 54, 627-639, 2016. https://doi.org/10.1016/j.ijggc.2016.07.025:

- "Key findings and recommendations from the IMPACTS project" by Amy Brunsvold, Jana P. Jakobsen, Marit J. Mazzetti, Geir Skaugen, Morten Hammer of SINTEF Energy Research, Norway, Charles Eickhoff of Progressive Energy UK and Filip Neele of TNO The Netherlands – published in the International Journal of Greenhouse Gas Control, 54, 588-598, 2016. https://doi.org/10.1016/j.ijggc.2016.07.003

- ISO 27913, Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems, 2016.

10.8 CO_2 Composition

- Phase diagram for binary combinations of CO_2 and 2mol% H2, H2S and NO2 (calculated using the Peng Robinson equation of state) - the Effect of CO_2 Purity on the Development of Pipeline Networks for Carbon Capture and Storage Schemes published in International Journal of Greenhouse Gas Control, 2014.and available here

- Global energy related CO_2 emission by sector dated March 2021 https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector

- The shipping specification for CO_2 to be transported as part of the Northern Lights project in Norway was published as part of the Northern Lights FEED study which is available here)
- The EU position on the acceptable shipping specification for CO_2 is set out in a "Briefing on carbon dioxide specifications for transport" – the 1st Report of the Thematic Working Group on CO_2 transport, storage and networks published by the EU CCUS Projects Network (No ENER/C2/2017-65/SI2.793333)
- Kinder Morgan data published in "Briefing on carbon dioxide specifications for transport" – the 1st Report of the Thematic Working Group on CO_2 transport, storage and networks – part of the EU CCUS Projects Network.
- Above data published in "Briefing on carbon dioxide specifications for transport" – the 1st Report of the Thematic Working Group on CO_2 transport, storage and networks published by the EU CCUS Projects Network (No ENER/C2/2017-65/SI2.793333)
- Teesside values from (AMEC, 2015)
- CarbonNet values from Harkin et al, 2016, gives a lower and upper end of a range of acceptable specifications for different streams joining the network; additional hydrogen cyanide, temperature and pressure specifications

10.9 Carriage of Dangerous Goods by Inland Waterways

- This agreement was developed by the United Nations Economic Commission for Europe (UNECE), entered into force on 29th February 2008 and most recently updated in 2021. The document is publicly available at: https://unece.org/transport/documents/2021/01/adn-2021-enfrru