CO_2 ship transport:

Benefits for early movers and aspects to consider

4th Report of the Thematic Working Group on:

CO_2 Transport, Storage, and Networks

Release Status: FINAL

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Date: 23 December 2021

Filename and version: CCUS Network TG3 inland shipping_v1QA .docx

EU CCUS PROJECTS NETWORK (No ENER/C2/2017-65/SI2.793333)

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Document History

Location

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Filename	CCUS-NETWORK-TG3- inland shipping_final.docx
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Revision History

This document has been through the following revisions:

Version No.	Revision Date	Filename/Location stored:	Brief Summary of Changes
1	17/12/2021	CCUS-NETWORK-TG3- inland shipping_v1QA	Comments and edits for consideration
2	20/12/2021	CCUS-NETWORK-TG3- inland shipping_v2_revised	Edited considering comments from version no. 1
Final	27/01/2022	CCUS-NETWORK-TG3- inland shipping_final	Final Version

Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
Consortium QA Manager	Jessica Yearwood		01/02/21

Distribution

This document has been distributed to:

Name	Title	Version Issued	Date of Issue
			00/00/0000

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About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects under way across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Our Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, our project members will drive forward the delivery and deployment of CCS and CCU, enabling Europe's member states to reduce emissions from industry, electricity, transport and heat.

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Executive summary

The aim of this report is to give an overview of the status, requirements, and issues for realising CO_2 ship transport within a CCS value chain. This report should aid emitters in early-stage project development, as well as policy makers and other stakeholders with understanding the role of CO_2 shipping for project development and its potential benefits.

Shipping is an attractive alternative for CO_2 transport, especially for early movers, because it is a flexible option that does not require fixed infrastructure. It is also scalable, and it is less sensitive to fluctuations in capture profile than piping.

Ship transport of CO_2 is mature and technically feasible. However, the optimal conditions for transporting CO_2 in a dedicated CCS value chain are still not defined, especially concerning transport pressure. While medium pressure (15 barg) has been traditionally used for commercial CO_2 shipping and will be used for pioneering projects such as the Longship project in Norway, research results as well as industry feedback signal that a lower pressure (7 barg) would be necessary for higher transport capacities. However, other transport conditions (e.g. 40 barg) may also be an alternative in some cases. This is further discussed in Section 3 of the report.

Further, some obstacles remain for large scale implementation of CO_2 ship transport. For example, there are some knowledge gaps regarding fiscal metering such as the ability of instruments to reach the accuracy required by the EU requirements for large flowrates. Therefore, a bottleneck for the verification of the performance of existing measurement principles for CCS is the lack of a primary reference and large-scale test facility for metering technologies. Informing the Commission about tailor-made monitoring plans for the CO_2 transported by ship is also critical.

Building a business case is key for the development of any CCS project, and transport is a core component of the CCS value chain. Contractual agreements, access to finance and coordinated timing of investment decisions along the CCS chain is essential

This report presents input from the CCUS PN project members, namely, Northern Lights, Carbon Collectors and Storegga (Acorn), and CCUS Shipping, powered by Victrol.

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1 Introduction

An aim of the CCUS Projects Network (CCUS PN) is to share knowledge and learnings, in order to drive forward the delivery of CCS and CCU and enable European countries to reduce CO_2 emissions from industry, electricity, transport and heat.

Documentation of learnings is important, both to spread a wider understanding of the current status of CO_2 capture projects and the lessons they have gathered, and to facilitate the implementation of these projects.

The present report aims to summarize the benefits and current status of CO_2 shipping as well as some issues that need to be considered by CCS projects that will incorporate shipping as a part of their value chain. Furthermore, the report presents input from the CCUS PN project members, namely, Northern Lights, Carbon Collectors and Storegga (Acorn), and CCUS Shipping, powered by Victrol.

1.1 CO_2 capture and storage value chain

Figure 1 shows examples of CCS value chains with ship transport. CO_2 is captured from industrial facilities which typically operate in a continuous manner. Then, CO_2 is conditioned for transport. Continuous transport of large CO_2 volumes is done via pipeline, with CO_2 as compressed gas, liquid or a liquid/dense-phase fluid. Modular transport of liquid CO_2 (LCO_2) is done by truck, train/railway, barges or ships. Ships and barges may carry CO_2 captured from one or several sources. This "milk round" approach may be used in scenarios where ships have sufficient storage capacity and emitter rates are low. In other scenarios, a large emitter may have a ship or multiple ships dedicated to servicing its needs.

CO_2 capture and conditioning is a continuous process. A solution to decouple modular transport with continuous processes is to have buffer storage at the industrial facility prior to transportation as well as between the modular means of transportation and permanent CO_2 storage, which is done via pipeline. Additional re-conditioning of the CO_2 may be required at some points of the value chains. The alternative at the bottom in Figure 1 depicts the situation with direct continuous ship loading and with the ship discharging its LCO_2 cargo straight into permanent storage, which can reduce the cost [1].

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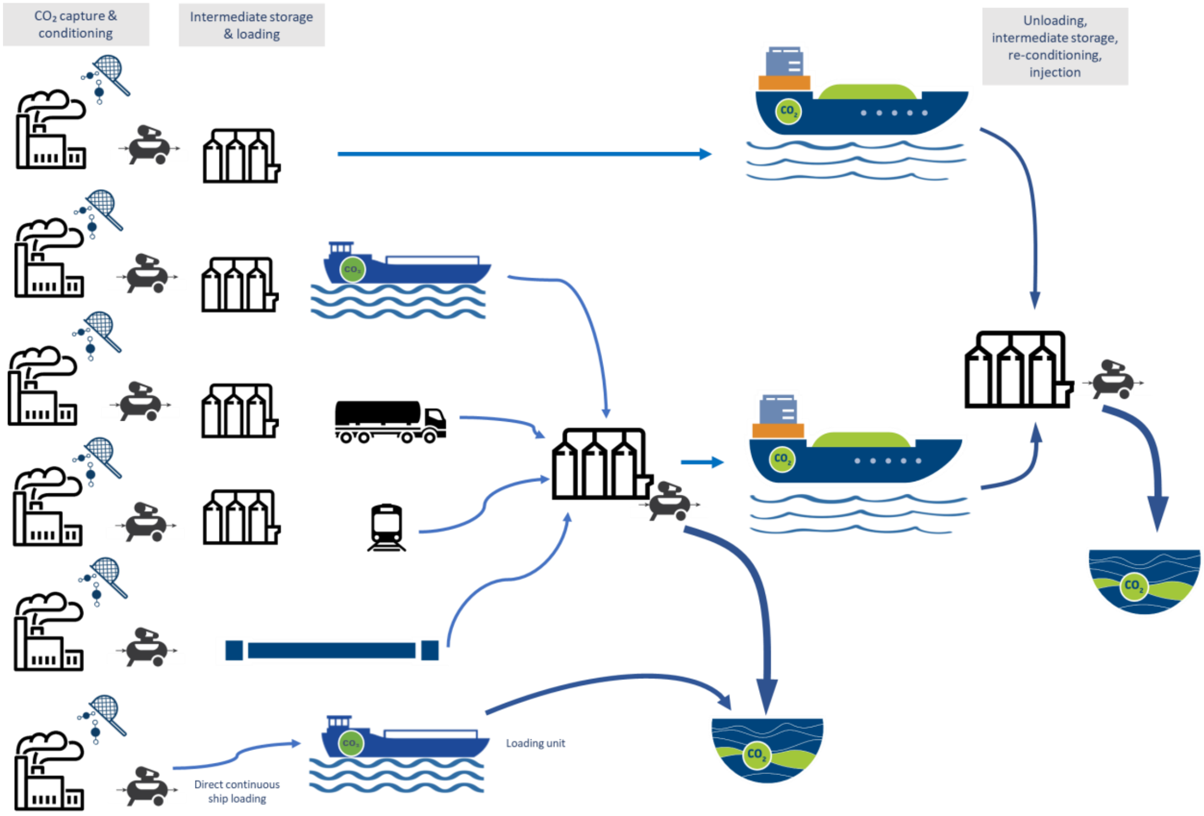

Figure 1 Simplified value chain alternatives for CCS. *Note: Pumping not shown. A list of icons is in Table 2.*

1.2 Current status of CO_2 shipping

CO_2 is used in beverage carbonization and in horticulture production (greenhouses). It is also used as working fluid for refrigeration and as chemical feedstock in chemical industries such as that of urea, polyurethane as well as acid and carbonate production processes [2].

The global carbon dioxide market size was valued at USD 7.80 billion in 2020 [3] and the food and beverage industry is the largest end user of CO_2 [4]. Commercial food-grade CO_2 is currently transported by truck, train or ship, and typically as refrigerated liquid. This is generally high purity CO_2, typically captured from hydrogen production facilities[1] or other fermentation or chemical processes with a high CO_2 concentration by-product [5].

For the food and beverage industry, CO_2 is usually transported in ships with capacities lower than 2 kt CO_2.For example, CO_2 is today captured from fertilizer producer Yara, and routinely shipped for commercial use (e.g. food and beverage) by Larvik Shipping for Praxair [6]. These ships have a capacity of up to 1.8-2. kt per shipment [6], [7]. This CO_2 is transported in liquid form at 15-18 barg and

[1] Steam reforming of hydrocarbons with CO_2 capture

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approximately -22 to -28°C [6]. This is a smaller scale than it would be necessary for CCS [8]. For example, with the current Northern Lights specifications, each shipment will carry more than 8.2 kt[2].

2 Benefits of Shipping

The technology for CO_2 shipping is ready and there are ongoing projects for building the ships that will transport the CO_2 for the early mover CCS projects. Some of these are described in Section 2.1. Some potential benefits of shipping which are attractive for early movers are summarized in Section 2.2, and the costs of shipping, with focus on aspects also relevant to early movers are discussed in Section 2.3. Technology readiness for short-term deployment

2.1 Technology readiness for short-term deployment

As mentioned above, LCO_2 shipping is done commercially, but at a smaller scale compared to what would be required for CCS. However, the shipping part of the CCS value chain is on time and advanced for the ongoing CCS projects.

Northern Lights in Norway adapted ship designs used for transporting liquefied petroleum gas (LPG), adding a liquefied CO_2 carriage system and insulation to maintain a temperature that keeps the CO_2 in a liquid state [9]. Northern Lights Joint Venture announced on 11 October 2021 [10] that they have ordered two dedicated LCO_2 carriers that will be ready for delivery by mid-2024. LCO_2 will be transported at cryogenic conditions (15 barg and equilibrium temperature). The ships will be built by Dalian Shipbuilding Industry and have a cargo size of 7500m^3 (~7.5 kt) and a length of 130 m. The primary fuel in this design is LNG.

Carbon Collectors in The Netherlands have received *Approval In Principle* for the design of their tug-barge combination and the offshore mooring system. LCO_2 will be transported at temperatures above 0 °C, pressures above 40 barg. The nominal capacity for each barge is 5500m^3 (~4.7 kt) and a length overall (LOA) of 130 m (barge only) and 150 m (tug-barge combination).

In addition, specialized companies for CO_2 seaborne transport are emerging. An example is Dan-Unity CO_2, collaborating with Carbfix (storage) [11], which recently announced they are able to build purpose-built CO_2 vessels with a capacity of 12500m^3 and 22000m^3 [12].

2.2 Flexibility of CO_2 shipping

Compared to pipelines, shipping of LCO_2 has some benefits in terms of flexibility which are especially attractive to emerging projects. For example,

- Scalable, for projects developed in more than one phase it will be possible to expand the ship fleet according to the project's needs.
- Ability to transport to different storage sites (if/when available), depending on costs and availability.

[2] The density of LCO_2 is 1101 kg/m^3 and the Northern Lights specification require a ship capacity of 7500 m^3 as can be seen in Table 1.

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- Flexible with respect to fluctuations in capture profile (utilization rate), which have less effect on shipping costs compared to pipeline [13].
- Water bound inland industry can be flexibly connected to seaports, giving access to several permanent storage sites.
- Barges can be "built to purpose", optimizing design and volumes, considering waterway restrictions. Ideally, ship size should be customized for each specific CCUS chain, also considering cost [14].
- Fast development cycle. Ships have in general shorter construction times than pipelines [15], [16]. As reference, the Northern Lights ships were ordered in October 2021 and are expected to be ready by mid-2024 [10] (~32 months). Barges have an average construction time of 26 months. In comparison, the construction time of pipelines usually lies between 1 and 4 years, depending on the length and complexity [17].

2.3 Costs of CO_2 shipping

Regarding costs, shipping has some advantages for emerging CCS projects. Shipping costs are dominated by OPEX, while costs for pipelines are dominated by CAPEX. In other words, shipping is less capital intensive [16]. In general, high transport capacity leads to a significant economy of scale for pipelines, which is less important for shipping [13]. In general shipping is more economically favourable than pipelines with lower CO_2 flowrates (less than ~5 Mtpa [8]), shorter project durations (less than ~20 years [8]) and longer transport distances [7], [8], [13].

The discount rates used for project evaluation and calculating impacts the CAPEX annuity depend on the type of project investors. National authorities use a lower discount rate than average companies, while oil and gas companies and companies dealing with risks use a higher discount rate and risk premium. This will lead to different net present values for the same project costs and revenues. At higher discount rates, the CAPEX annuity increases and marine transport becomes more cost-effective than pipeline [13].

3 Technical requirements and constraints for shipping

As the scale and logistics of CO_2 shipping for permanent storage, transport conditions, ship design and specifications do not necessarily need to be the same as current conditions for transport. Trade-offs between cost and operational complexity must be considered in choosing the most appropriate transport condition [7].

3.1 Dimensions for inland and offshore ships

Inland ships and barges are constrained in height (bridge clearance), breadth (canal and lock width limitations), length (lock limitations), and draught (highly variable, dependent on the waterways). Therefore, the waterways may limit inland ship capacity. Energy efficiency of inland and offshore transportation is influenced by the chosen transport conditions and the need to convert between different conditions for different sections of the transportation chain.

Table 1 Current requirements for CO_2 ship transportation and transfer to Northern Lights [18], [19]

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Parameter	Requirement
Type of ship	Cargo ship
Ship capacity	Maximum 7500 m^3
Transfer pressure	15 barg (within 13-18 barg)
Transfer temperature	Equilibrium
Loading and offloading rate	Maximum 800 t/h

Regarding offshore ships, the current concept is to use ships that resemble LPG ships [19]. Table 1 shows the current requirements for ship transportation and transfer to the Northern Lights infrastructure. The Northern Lights Project currently specifies that cargo ships, with a maximum capacity of 7500 m^3 should be used for the transport of CO_2 to Kollsnes (Øygarden) [19], which is larger than the capacities currently used in the transport of CO_2 in the food industry. However, the size of the ship in future value chains may still be different [8].

Ships can be built specifically for LCO_2 transport, but there is also the possibility of repurposing LPG tankers. It should be noted that due to differences in fluid density, only 50%-60% of a tank capacity designed for LPG can be used for LCO_2 [14].

3.2 Composition specifications

The maximum acceptable concentration of a single impurity will depend on the concentration of the other impurities, the pressure and the temperature, it is not possible to give universal recommendations for the safe CO_2 compositions. Considering ship transport in which LCO_2 is transported in carbon steel tanks, composition requirements should prevent the formation of corrosive phases for the steel, for example in the presence of water, hydrogen sulphide (H_2S), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and oxygen (O_2). Also hydrates may form in the presence of water and hydrogen sulphide [20].

Satisfying higher purity requirements may require additional investment and/or operational costs. It may also imply a higher energy intensity of the overall process. When different potential impurity scenarios are considered, impurities that are soluble in the liquefied CO_2 stream may need to be purged. As a consequence, the conditioning cost also increases [21]. If the purge is vented, it may carry some CO_2 and to compensate this and maintain the desired overall CO_2 capture rate, the capture rate in the CO_2 capture process may need to increase, with the associated cost. To remove some impurities, specific separation steps, with an associated investment and energy consumption, are required (e.g. dehydration).

Reference composition limits for CCS are included in the Appendix and in [20]. The 1st Report of the CCUS PN Thematic Group on CO_2 transport, storage and networks [5] presents the requirements specifications for transport and some end-uses.

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3.3 CO_2 transport pressure

In Figure 2 it can be observed that at atmospheric pressure, CO_2 only exists either on solid or gaseous state and it needs to be pressurized to be in liquid state. The theoretical limitation on minimum pressure for pure CO_2 is represented by its triple point of 5.1 absolute bar and -56.6°C [22], which in practice results in a transport pressure around 7 barg and -50°C to be considered a low-pressure condition for ship transport of CO_2. This limitation, as well as liquefaction and transport costs are affected by impurities [18], [23]. This can be identified in Figure 2, which shows the phase diagram for CO_2.

The overall cost is a trade-off between the cost of conditioning and the CO_2 storage in the ship. With conditioning, CO_2 is brought from the conditions of the CO_2 capture process to the conditions required for transportation. For amine-based post-combustion CO_2 capture, this means compressing CO_2 from a low pressure and then refrigerating it, as shown in Figure 2. Power requirement for liquefaction, and thus conditioning cost, decreases with increasing pressure because the liquefaction temperature increases. On the other hand, at higher pressure, the cost of storage tanks, and thus ships, increases [8].

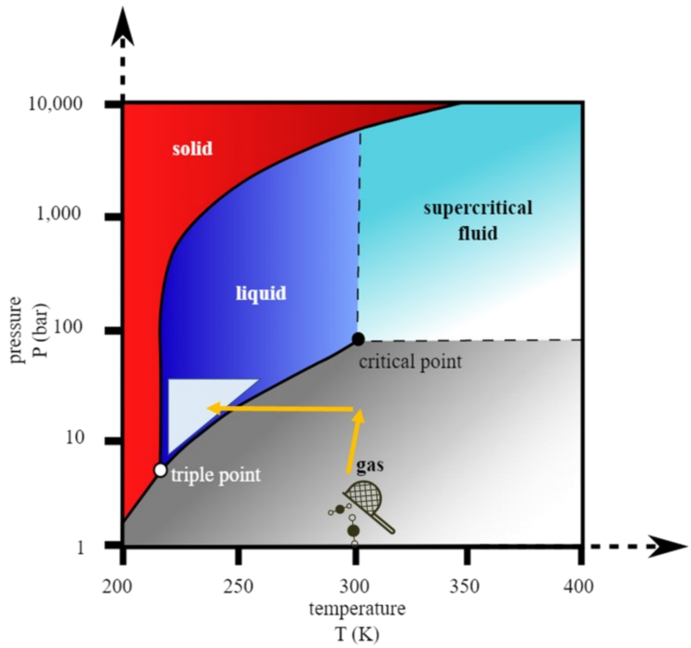

Figure 2 Phase diagram of pure CO_2 with ranges for CO_2 capture and shipping transport indicated. Figure modified from [24].

The Northern Lights specifications do not deviate from current standard CO_2 ship technology for small-scale food industry, which considers a transfer pressure of 15 barg [18], which is considered "medium pressure" for transportation. This has advantages such as accumulated experience, and existing standardization, and thus a lower risk. However, a lower transport pressure may be required for larger ship capacities [18], [19], for which cargo tank wall thicknesses would be uneconomic at 15 barg and -30˚C.

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Recent work has shown that transporting CO_2 at lower pressure could result in significant reductions in investment, operating cost, and overall cost [1], [21], [23], [25]. However, other studies [26] have found the optimal pressure to be 15 barg. With this, the optimal pressure would be determined considering the entire CCS value chain for each project.

It is possible that in the future, there could be two types of LCO_2 ships, those with capacities lower than 10000 m^3 and transport pressures of 15 barg, such as the current Northern Lights case, and ships with larger capacities and transport conditions of 7 barg and -50°C.

3.4 Fiscal metering for loading and offloading

Accurate measurement is essential along the CCS value chain for environmental monitoring and reporting on greenhouse gas emissions, as well as process control and leak detection. Technical performance of fiscal meters is, hence, key for the CCS business to provide fair financial transactions and traceable environmental compliance. However, this is an area where large knowledge gaps remain. Transport conditions for CCS shipping occur at close to liquid-vapour equilibrium at low temperatures, expectedly down to -50 °C. This poses a challenge for fiscal metering technologies, where no capacities to provide traceable fiscal metering exist worldwide [27]. Some of the most promising benchmarked technologies for CCS fiscal metering are Coriolis, Ultrasonic, and differential pressure – DP – devices ([28], [29]). The induced pressure drop, characteristics of Coriolis or DP's would require pressure boosting upstream the metering unit to avoid gasification of the fluid within the unit, and with it rapid changes in density and viscosity that preclude accurate measurement, and compromise the unit integrity. The only technology with published studies claiming accuracies below the EU requirements is Coriolis [[30]–[32]], but only for pure CO_2 at temperatures above 15 °C and flow rates (3600 kg/h) far below what will be required ahead (see Table 1). Early results of ultrasonic measurements for static CO_2 ([33]) show promise for conditions similar to ship transport, but dynamic effects that are known to influence the performance and accuracy, nor traceability are yet available.

As discussed above, the major bottleneck for the verification of the performance of exiting measurement principles for CCS is the lack of a primary reference and large-scale test facility for metering technologies ([27], [55]). Several early initiatives, which combine public and private investments, are ongoing to, at least partially, abate some of the pending obstacles with regards to measurement traceability and accuracy, e.g., (i) progress the development CO_2 liquid primary standard (Green deal - CCUSMet [56]), (ii) development of a primary reference for liquid CO_2 (Infrastruktur [57] ECCSEL V-lab proposal), (iii) development of a large scale fiscal metering test/verification facility FMet (NCCS [58], ECCSEL). However, the complexity of the market and the level of investment required would most likely entitle international cooperation and mixed public and private funding. Steps have been made at NCCS, via a Business Case for FMet, to identify stakeholders and possible investors for the life-cycle investments and the OPEX; where European funding streams like Horizon and Innovation Fund are attractive and necessary to help develop a large-scale facility.

3.5 Health, safety and environment

This section will provide a concise overview of potential threats of CO_2 shipping to health, safety and environment (Section 3.5.1) and existing regulation on the safety of CO_2 shipping in Section 3.5.2.

3.5.1 Identification and assessment of hazards and risks

The work done by Ter Mors (2011) [34] resulted in the identification and description of a number of threats for safe transport of CO_2 by ship. For the purpose of this report DNV executed a Quantitative Risk Assessment (QRA) of CO2 shipping infrastructure in the Rotterdam harbour area. The QRA results for CO2 shipping showed that risk stays within acceptance levels according to criteria in the Netherlands. The main findings of Ter Mors (2011) [34] are represented below, which in some instances have been expanded with information from Baroudi et al. (2021) [35] and Equinor (2019) [19].

Overall chain reliability and need for maintenance and repair

Venting will be necessary during maintenance and repair activities, which will lower the efficiency of the activity and will pose a risk to people and the environment near the CO_2 vent. A robust ship design with appropriate preventative measures will reduce the downtime of the ship.

Boil-off gas generation [35]

During loading, transport and unloading of LCO2 vapour is released in variable amounts. In particular during loading and unloading gas generation is enhanced. Also the sloshing of liquid CO2 in the vessels and the penetration of ambient heat may lead to an increase in gas generation. Re-liquefaction might be considered as a mitigating measure.

Degradation of metallic and polymer chain components

In the presence of free water, carbon steel will be subjected to corrosion. For the use of carbon steel CO_2 should be dry. For wet CO_2 conditions austenitic steel, 13% Cr steel or duplex stainless steels can be used. H_2S impurities can react with carbon steel [35] and enhance corrosion. Equipment on Seagoing ships may be protected by a coating and cathodic protection.

Polymers need to be resistant to CO_2 to avoid diffusion of CO_2 into the polymer, expansion or cracking [35].

Cool down and heat up effects

High or low temperatures may result in material failure. At temperatures down to -60 ^{o}C (near triple point temperature) one may use fine-grained steels to prevent brittle failure. At even lower temperatures of about -78.5 ^{o}C (near sublimation point at atmospheric pressure) 3.5% Ni steel might be used. Equipment must be designed such that it can absorb contraction or expansion as a consequence of temperature changes.

Waterhammer and slugging

As a consequence of fluid flow velocity changes a pressure wave may be generated, which could damage the equipment (water hammer). The design of flow velocities and opening or closing of the valves can help minimizing this effect. In addition safety valves can be installed.

Particular attention is required for the occurrence of two-phase flow and the creation of slugs in the fluid (see also hydrate and dry ice formation).

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Hydrate and dry ice formation

Formation of hydrates or dry ice is of particular relevance for shipping of low pressure CO_2 near the triple point. These solid substances may lead to clogging and pressurization of pipes, valves and vessels [19].

Careful management of operating pressure reduces the occurrence of hydrates or dry ice [35]. An appropriate safety margin with respect to the triple point and hydrate stability envelope is to be considered. Impurities influence the position of the hydrate stability zone.

Ship wave interaction

Sloshing of liquid CO_2 in partly filled tanks may be triggered by ship wave interaction. Devices to mitigate sloshing could be installed. Stabilisation of the ship is possible with the help of a Dynamic Positioning System when connecting the ship to loading/unloading infrastructure.

Accidental loss of containment

When an inland barge or seagoing ship collides with another ship or with a harbour or offshore terminal, this may lead to accidental loss of CO_2. This may also happen by accidents on the ship itself. The terminal area in the harbour is considered to be a zone of relatively high risk. For that reason an Emergency Shutdown System could be installed [35]. Furthermore, terminal areas should be at a suitable distance from vulnerable objects.

The accidental loss of CO_2 may result in the presence of a CO_2 fluid on the water surface and the creation of dry ice and hydrates. Personnel can get wounded because of freezing or by the impact of dry-ice projectiles. The presence of CO_2 may lead to breathing problems or even asphyxiation; combustion engines may stop [35]. Due to the formation of dry ice and condensing water, visibility decreases [19]. High evaporation rate and expansion of fluids from a ruptured pipe or vessel could cause a Boiling Liquid Expanding Vapour Explosion or BLEVE [35].

3.5.2 HSE regulation and standards

Seagoing ships

The international SOLAS Convention [36] defines the rules for safety of seagoing ships in addition to requirements for the design, construction and operation of the ship. Part C of Chapter 7 deals with ships for bulk transport including CO_2. This subtheme or code is referred to with the IGC code or in full “International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk” [37]. The code describes that a certificate must be required entitled “International Certificate of Fitness for the Carriage of Liquefied Gases in Bulk”. Requirements depend on the class of hazardousness of the transported substance. CO_2 falls in the lowest class 3G (from Element Energy, 2018) [38]. Chapter 17 sets special requirements for reclaimed quality CO_2. In addition to the rules for pure CO_2, CO_2 must be kept at a pressure of 0.05 MPa (about 0.5 barg) above the triple point, comply with specific monitoring requirements and measures to control corrosion.

Liability for loss of containment has been dealt with in the HNS Convention [39] but this treaty has not yet been enforced [40]. Liability is organized in two tiers, one compensation by the ship owner as an insurance and the second one as financial compensation from a HNS fund.

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Additional guidance for safety can be found in the International Safety Guide for Oil Tankers and Terminals (ISGOTT)" [41] and "Liquefied Gas Handling Principles on Ships and in Terminals [42].

Inland ships

For inland shipping in Europe, the ADN [43] is ruling. ADN stands for "European Agreement for Transportation of dangerous goods by inland waterways". The Agreement and associated regulations entered into force in 2008 and strives for a high level of safety and environmental protection, and facilitation of international transport and trade.

The CCNR & OCIMF (2010) [44] developed guidelines for safe inland barge transport but with little attention for CO_2 transport. The International Safety Guide for Inland Navigation Tank-barges and Terminals (ISGINTT) is an industrial best practice with additional recommendations for the safe transport of hazardous substances by inland ships and safe handling at terminals.

4 The London Protocol and transboundary CO_2 ship transport for storage

This section presents the legal framework for transboundary transport of CO_2 for geological storage under the seabed, that is provided by the London Protocol.

The London Protocol [45] was designed in order to protect the marine environment from dumping of wastes. This however turned out to provide a barrier to transboundary CO_2 transport for storage, since Article 6 of the protocol bans transport of wastes to other countries for dumping at sea. In 2006 an amendment was made to the London Protocol allowing storage of CO_2 under the seabed and in 2009 an amendment was made to Article 6 allowing for transborder movement of CO_2 for the purpose of offshore storage [46]. However, for the amended Article 6 to enter into force it must be adopted by 2/3 of the 53 parties of the protocol, which has not happened so far.

In October 2019, based on a suggestion from Norway and the Netherlands, the International Maritime Organization (IMO) decided to allow for provisional application of the 2009 amendment to Article 6 of the London Protocol. Therewith, countries who wish to use the amendment to Article 6 have the right to do so, while it has no legal bearing for the parties who do not wish to export or import CO_2 for permanent geological storage.

In practice, countries who wish to allow for export or import of CO_2 for injection and permanent storage under the seabed must *deposit a Unilateral Declaration* on the provisional application of the

2009 amendment to the London Protocol Article 6 to the Depositary (Secretary-General of the IMO). Thereafter, a *bilateral agreement must be established between the CO_2 exporting and importing countries*, which shall include confirmation and allocation of permitting responsibilities between the two countries, consistent with the provisions of the London Protocol and other applicable international law, to define a stable framework for the transboundary CO_2 transport. This agreement should be expected to cover items such as cost sharing, monitoring of the transport, reporting and liability in addition to the mentioned permitting regimes. This bilateral agreement shall also be notified to the Secretary-General of the IMO.

It is the authors' current understanding that the unilateral declaration of the provisional application of the amended Article 6 is only necessary for the two countries exporting and receiving CO_2, and for

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the purpose of offshore CO_2 storage, i.e. that a ship carrying CO_2 can pass through the territorial waters of a third country, without this third country having to deposit a unilateral declaration to the IMO or enter into an agreement with the countries exporting and receiving.

The London protocol does not regulate transport of CO_2 for other purposes, such as, for CCU. As mentioned in section 1.2, CO_2 captured from ammonia production is today being transported by ship for commercial use.

5 Financing Shipping in Early Mover Projects

5.1 Policy Support

5.1.1 Projects of Common Interest under the TEN-E regulation

The Trans-European Networks for Energy (TEN-E) is a policy that is focused on linking the energy infrastructure of EU countries. The EU helps countries in priority corridors and thematic areas to work together to develop better connected energy networks and provides funding for new energy infrastructure. Cross-border carbon dioxide network is one of the three priority themes in the TEN-E regulation.

Projects of common interest (PCIs) are key cross border infrastructure projects that link the energy systems of EU countries. The PCIs are intended to help the EU achieve its energy policy and climate objectives: affordable, secure and sustainable energy for all citizens, and the long-term decarbonization of the economy in accordance with the Paris Agreement. Every two years since 2013, the European Commission draws up a new list of project of common interest [47]. The fifth list, adopted in November 2021 [48], includes six CO_2 projects:

- **CO2 TransPorts**: aims to establish infrastructure to facilitate large-scale capture, transport and storage of CO_2 from Rotterdam, Antwerp and the North Sea Port
- **Northern lights project**: commercial CO_2 cross-border transport connection project between several European capture initiatives (United Kingdom, Ireland, Belgium, the Netherlands, France, Sweden) and transport the captured CO_2 by ship to a storage site on the Norwegian continental shelf
- **Athos project**: proposes an infrastructure to transport CO_2 from industrial areas in the Netherlands and is open to receiving additional CO_2 from others, such as Ireland and Germany. Developing an open-access cross-border interoperable high-volume transportation structure is the idea. However, this project was cancelled after Tata Steel, which was the main source of CO_2 for the project, decided to use an alternative technology (direct reduced iron, DRI) to produce steel [49], [50].
- **Aramis**: cross-border CO_2 transport and storage project (intake from emitters in the hinterland of Rotterdam harbour area and storage to location on the Dutch continental shelf)
- **Dartagnan**: CO_2 export Multimodal HUB from Dunkirk, France, and its hinterland (emitters from the industrial cluster in the area of Dunkirk with storage where available in the North Sea country territories)
- **Poland – EU CCS Interconnector:** emitters from the industrial cluster in the area around Gdansk, Poland, with storage where available in the North Sea country territories.

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Projects of common interest are eligible for funding from the Connecting Europe Facility (CEF). The new CEF Programme for 2021-2027 [51] allocates a total budget of €5.8 billion to the energy sector. The first CEF Energy PCI call for proposal under this new CEF programme was open for submissions from 7 Sept – 19 Oct 2021.

5.1.2 The EU ETS and ship transport of CO_2

Each year industrial installations that are included in the EU Emission Trading System (EU ETS) must surrender a number of allowances that are equal to the total amount of fossil CO_2 emissions from that installation during the preceding calendar year. The EU ETS allows subtracting emissions that are captured and thereafter transferred to a transport network with the purpose of long-term geological storage or directly to a storage site. Therewith the emission allowances need not be surrendered but can be traded and generate an income, and therewith contribute to building a CCS business case. However, transport network is in the CCS directive (Directive 2009/31/EC) defined as a network of *pipelines* for the transport of CO_2 to the storage site.

In order to get a clarification regarding whether CO_2 transported by ship for permanent storage can be covered by the EU ETS, Norway sent a request to the European Commission in April 2020 with an argumentation for this, that was summarized as follows: "*When transfer of CO_2 from a ship or truck to the pipeline transport network or storage site is completed, Norway's understanding is that the capture installation can subtract the CO_2 from its emissions*".

The Norwegian request was sent to EU with reference made to the Norwegian plans for full-scale CCS (the Longship project) where ship transport of CO_2 is part of the CCS chain. In a reply from DG CLIMA to Norway in July 2020 from the European Commission Directorate General Climate Action to the Norwegian Ambassador to the EU, the Commission agrees with the Norwegian view. "*The capture installation should be allowed to deduct from its emissions any CO_2 intended for the offshore storage facility.*" Furthermore, the letter states that the Commission needs to be informed by the measures put in place, including tailor-made monitoring plans that are to be developed for each capture installation, accounting for any CO_2 lost in transport. The measurement of CO_2 losses during transport would be made at the point of delivery, to the transport network or the storage site.

Responsibility for CO_2 emissions during transport with ship: The consequence of the answer from DG CLIMA to Norway in July 2020 would be that the capture installation would be fully responsible for CO_2 emitted to the atmosphere during ship transport. However, the suggested amendment to the ETS Directive (2003/87/EC), dated 14 July 2021[52], recital 41, says that:

> *As carbon dioxide is also expected to be transported by means other than pipelines, such as by ship and by truck, the current coverage in Annex I to Directive 2003/87/EC for transport of greenhouse gases for the purpose of storage should be extended to all means of transport for reasons of equal treatment and irrespective of whether the means of transport are covered by the EU ETS. Where the emissions from the transport are also covered by another activity under Directive 2003/87/EC, the emissions should be accounted for under that other activity to prevent double counting.*

The practical meaning of this amendment is that emissions of CO_2 during ship or truck transport will be the responsibility of the ship or truck owner/operator.

Summary: Provided that the suggested amendment of the ETS directive enters in force, the situation would be the following for ship transport of CO_2:

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- The CO_2 capture installation can subtract emission allowances for captured fossil CO_2 when it is delivered from a ship to a pipeline transport network or directly to a storage site (provided that the storage site is permitted under Directive 2009/31/EC). I.e. there is a time delay between when the CO_2 is captured and when the emission allowances can be subtracted.
- The owner/operator of the ship that is transporting the captured CO_2 from the capture installation to the transport network will be responsible for the CO_2 emissions during this transport.
- The CO_2 capture installation will not be able to subtract emissions that occur during ship transport to the pipeline network, i.e. the amount of CO_2 emissions to be subtracted would during normal operations be slightly lower than the amount of CO_2 captured – contractual agreements will be needed between the capture installation and the ship owner/operator to cover this. This, in turn, will call for accurate fiscal metering during on- and offloading. Also, CO_2 emissions from the ship propulsion system could be relevant to include in the contractual discussions/agreements.

5.1.2.1 EU ETS and fiscal metering

In Section 3.4, it was discussed that the technical performance of fiscal meters for liquid CO_2 is an open question, and more research is needed to address the existing knowledge gaps in aid of a fair CCS business. That is, fair financial transactions along the CCS chain and accurate subtraction of emissions under the EU ETS will depend on accurate CO_2 measurements throughout the CCS value chain, including on- and offloading on ships, that enable accurate emission monitoring and reporting. Emissions monitoring and reporting within EU ETS is regulated by the ETS M&R Regulation 2018/2066 [53], [54]. Continuous measurement systems (i.e., fiscal metering) with uncertainties below 2.5% are required for reporting of captured CO_2 at the capture site (article 49). In addition to the uncertainty of the measurement instrument, the uncertainty of the associated instrument calibration and specific use of the instrument are included in the 2.5 % requirement. As a result, the uncertainty of the measurement instrument must be lower than 2.5 %, probably below 1.5 %, which is the uncertainty specified by the EU measurement instrument directive (MID), Annex VII.

On the other hand, there are cases where it is technologically or financially infeasible to meet the 2.5 % requirement, in which case the regulations open for a relaxation to 5 % uncertainty. This is the case if the financial benefit is lower than the cost of complying with the highest tier. With regards to the technical feasibility, the lack of traceable calibration of fiscal meters for liquid CO_2 at transport conditions, yields uncertainty on whether the meters meet the strictest EU ETS requirements during CCS operations. Furthermore, it is unclear if the regulations controlling the type of measurements at the capture site apply for the emission control during shipping, even if the uncertainty requirements are expected to be the same. Thus, using less costly measurement methods (e.g. radar level gauging) than fiscal metering may be an option in shipping. This is, however, provided that they at least meet the 5 % requirement, and that no other feasible measurement methods have uncertainty lower than 1.5 % at realistic operation conditions. In other words, fiscal metering is likely to yield the lowest uncertainty, and is superior to other measurement techniques, but further research and development is currently necessary to establish the uncertainty of the fiscal meters at realistic operating conditions.

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5.2 Building a Business Case

CO_2 transport by ship is technically feasible, just as the other components along the CCS chain, and the two first vessels for transporting CO_2 intended for permanent geological storage have been ordered by Northern Lights. CCS needs to be deployed on a large scale to contribute to reaching EU climate goals and meeting the targets in the Paris Agreement. For early movers, initial small volumes or for long distances, CO_2 transport by ship provides flexibility, scalability and low initial capex.

In order for a commercial business for CO_2 shipping to actually evolve, there must be agreements on e.g. cost and risk sharing for CO_2 losses during ship transport, and agreements on the duration of the shipping contract. An important issue for contractual arrangements is the point of transfer of liability for CO_2 losses between the capture installation and the transport and storage operator (ref to the summary in section 5.1.2. Orchard et al. [7] identified metering as a cost driver, representing a conflict between legal obligation and cost-effective operation. Resolving this conflict through alternative contractual arrangements may be possible or necessary to consider in future [7].

CEF funding may be a means to fund the realisation of trans-boundary ship transport of CO_2, but there must also be funding for realising capture and storage at scale. However, the realisation of ship transport must be aligned with funding for capture and storage. Sale of emission allowances under the EU-ETS can contribute to realising such business cases in certain industrial sectors, and the Innovation Fund can support up to 60% of the cost for a capture project, but there are currently not sufficient long-term predictable financial/regulatory mechanisms that support CCS deployment on the scale that it is being deployed. In sum, contractual agreements, access to finance and coordinated timing of investment decisions along the CCS chain is essential.

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6 Conclusion

CO_2 transport is a key component of the CCS value chain. Experience from other industries (e.g., food and beverages) is at a smaller scale compared to the foreseen scale for CCS. However, this experience, combined with experience transporting other substances (e.g., LPG) is being used to define technical issues related to CO_2 ship transport. However, with more experience gathered and optimization of the whole CCS value chain, CO_2 specifications for shipping such as impurities, ship capacities, and especially transport pressure may change in the future compared to specifications for current projects.

Shipping offers a flexible solution for CO_2 transport, which is scalable and with lower investment costs compared to pipelines, especially with long transport distances and relatively smaller volumes. This can be especially attractive for early-movers and CO_2 shipping can thus enable early CCUS projects by reducing the cost and financial risk.

An aspect not discussed in this report is the means of propulsion for CO_2 ship transportation. For the Northern Lights project, the primary fuel will be LNG [9], which has a low environmental footprint compared to other fuels [59]. However, other alternatives such as batteries [60], carbon-free maritime fuels such as ammonia [61], [62] and hydrogen [63], or on-board CCS [64] are being developed for minimizing the environmental footprint of shipping. These alternatives will contribute to further increase the CO_2 avoided of the full CCS value chain.

Legally, it is since October 2019 possible to export and import CO_2 for the purpose of permanent geological storage under the seabed: countries who wish to allow for this must deposit a Unilateral Declaration on the provisional application of the 2009 amendment to the London Protocol Article 6 to the Secretary-General of the IMO. Thereafter, a bilateral agreement must be established between the CO_2 exporting and importing countries, which shall include confirmation and allocation of permitting responsibilities between the two countries, consistent with the provisions of the London Protocol and other applicable international law, to define a stable framework for the transboundary CO_2 transport. The amended Article 6 would enter in force when ratified by 2/3 of the London Protocol members. The unilateral declarations and bilateral agreements would then no longer be necessary.

With the suggested amendment of the ETS directive from 14 July 2021 in force, the situation will be the following for ship transport of CO_2 under the EU-ETS:

- The CO_2 capture installation can subtract emission allowances for captured fossil CO_2 when it is delivered from a ship to a pipeline transport network or directly to a storage site (provided that the storage site is permitted under Directive 2009/31/EC). I.e., there is a time delay between when the CO_2 is captured and when the emission allowances can be subtracted.
- The owner/operator of the ship that is transporting the captured CO_2 from the capture installation to the transport network will be responsible for the CO_2 emissions during this transport.

The CO_2 capture installation will not be able to subtract emissions that occur during ship transport to the pipeline network, i.e. the amount of CO_2 emissions to be subtracted would during normal operations be slightly lower than the amount of CO_2 captured – contractual agreements will be needed between the capture installation and the ship owner/operator to cover this. This, in turn, will

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call for accurate fiscal metering during on- and offloading. Also, CO_2 emissions from the ship propulsion system could be relevant to include in the contractual discussions/agreements.

Fiscal metering is crucial for transactions and monitoring emissions, and accurate measurements are necessary to achieve this goal. An important step to verify the performance of exiting measurement principles for CCS is the establishment of a primary reference and large-scale test facility for metering technologies.

It should also be stressed that contractual risk sharing is important. Contractual agreements should consider regulations, cost drivers, and ETS should be put in place. “Cluster-agreements”, with back-to-back long-term contracts can be a tool to avoid stranded assets

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7 Glossary and list of icons

˚C	Degrees Celsius
ADN	European Agreement for Transportation of dangerous goods by inland waterways
atm	Standard atmosphere. Unit of pressure defined as 101,325 Pa
bar	Unit of pressure corresponding to 100 000 Pa or approximately 0.9869 atm
barg	Unit of gauge pressure, which is zero-referenced against ambient air pressure
BLEVE	Boiling Liquid Expanding Vapour Explosion
CAPEX	Capital expenditures
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CCUS PN	CCUS Projects Network
CEF	Connecting Europe Facility
CO_2	Carbon dioxide
DRI	Direct reduced iron
ETS	(EU) Emissions Trading System
H_2S	Hydrogen sulphide
HNS	Hazardous and noxious substances
HSE	Health, safety and environment
IGC	International Gas Carrier Code. International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO	International Maritime Organization
ISGINTT	International Safety Guide for Inland Navigation Tank-barges and Terminals
kt	kilo ton
LCO_2	Liquefied CO_2
LOA	Length overall
LPG	Liquefied petroleum gas
m^3	Cubic meter
MID	Measurement Instrument Directive
MPa	Mega Pascal. Unit of pressure corresponding to 1 000 000 Pa
Mtpa	Mega ton per year (annum)
NO_2	Nitrogen oxide

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O_2	Oxygen
OPEX	Operating expenditures
Pa	SI derived unit of pressure, defined as one newton per square meter.
PCI	Projects of Common Interest
QRA	Quantitative Risk Assessment
SI	International System of Units
SO_2	Sulphur dioxide
t/h	ton/hour
TEN-E	Trans-European Networks for Energy
USD	US Dollars

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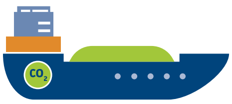
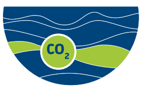
Table 2 List of icons used in this report

Icon	Description
	CO_2 emitter (e.g. industrial plant, refinery)
	CO_2 capture
	CO_2 conditioning (compression, liquefaction)
	CO_2 buffer storage
	Railroad for CO_2 transport
	Truck for CO_2 transport
	Pipeline for CO_2 transport
	Ship for CO_2 transport
	Barge for CO_2 transport
	CO_2 permanent storage
	Ocean
	River

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Appendix: CO_2 specifications

The 1st Report of the CCUS PN Thematic Group on CO_2 transport, storage and networks [5] presents the requirements specifications for transport and some end-uses. Here we present a summary for reference.

As CO_2 has a variety of uses in industry, there is also a variety of grades or purity specifications for commercial CO_2 [5].

Table 3 shows the maximum allowable concentration of contaminants in the CO_2 delivered to the Northern Lights infrastructure and the recommendations by Aspelund [65], based on the DYNAMIS project [66]. Aspelund [65] recommends a concentration of >99.7%v for CO_2. Therefore, the >0.3%v recommendation for non-condensable gases is for the sum of all non-condensables, including CO. It should also be mentioned that Northern Lights will entertain discussions with capture plants with other CO_2 compositions [66].

Table 3 CO_2 specifications for delivery to the Northern Lights infrastructure [18] and recommendations for ship transport by Aspelund [65] (adapted from [5])

Component	Northern Lights specification, ppm (mol basis)	Recommendation by Apelund,	Limitation	Reason
Water, H_2O	≤ 30	50 ppm	Design and operational considerations	Freeze-out in heat exchangers
Oxygen, O_2	≤ 10	-	Design and operational considerations	Challenges in the reservoir
Sulfur oxides, SOx	≤ 10	-	Health and safety considerations	-
Nitric oxide/Nitrogen dioxide, NOx	≤ 10	-	Health and safety considerations	-
Hydrogen sulfide, H_2S	≤ 9	200 ppm	Health and safety considerations	Short-term exposure limit

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Component	Northern Lights specification, ppm (mol basis)	Recommendation by Apelund,	Limitation	Reason
Carbon monoxide, CO	≤ 100	2000 ppm	Health and safety considerations	Short-term exposure limit
Methane, CH_4	-	<0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction
Amine	≤ 10		Design and operational considerations	
Ammonia, NH_3	≤ 10			
Hydrogen, H_2	≤ 50	<0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction
Nitrogen, N_2	-	<0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction
Argon, Ar	-	<0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction
Formaldehyde	≤ 20	-	-	-
Acetaldehyde	≤ 20	-	-	-
Mercury, Hg	≤ 0.03	-	-	-
Cadmium, Cd Thallium, Tl	≤ 0.03 (sum)	-	-	-

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