CO_2 Shipping Interoperability

Briefing Report

D2.2.1

Author: Dr Philippa J M Parmiter

Release Status: Final

Dissemination level Public

Date: 4 November 2022

Filename and version:
EverLoNG_CO2ShippingInteroperability_Final (Version 1)

The EverLoNG project is funded through the ACT programme (Accelerating CCS Technologies, Horizon2020 Project No 691712). Financial contributions have been made by the Ministry of Economic Affairs and Climate Policy, the Netherlands; The Federal Ministry for Economic Affairs and Energy, Germany; the Research Council of Norway; the Department for Business, Energy & Industrial Strategy, UK; and the U.S. Department of Energy. All funders are gratefully acknowledged.

@everlong **www.everlongccus.eu**

Document History

This document is stored in the following location:

Filename	EverLoNG_CO2ShippingInteroperability_Final
Location	EverLoNG Sharepoint / WP2

Revision History

This document has been through the following revisions:

Version No.	Revision Date	Filename	Brief Summary of Changes
V0.3	03/11/2022	EverLoNG_CO2ShippingInteroperability_v0_3	Review by WP lead
Final	03/11/2022	EverLoNG_CO2ShippingInteroperability_Final	Corrections reviewed and agreed by author

Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
WP Leader	Ragnhild Skagestad	Ragnhild Skagestad	7.November 2022
Project Coordinator	Marco Linders		7 November 2022

Disclaimer

Executive summary

A number of carbon capture and storage projects are developing in Europe: climate neutrality targets; the incentives offered by the European Commission and national governments; and industry and businesses that are willing to invest are enabling the development of full-chain projects, capture clusters and storage hubs. Some of these capture projects and industrial clusters do not have adjacent CO_2 storage options (for example, South Wales in the UK, and German projects) and will need to access other regions' storage sites. There is also growing activity around the world, for example in the USA, Australia and China (SCCS 2022). For transport of CO_2 between a cluster and store, pipelines have low operational costs; but over longer distances shipping becomes a cheaper option. In addition, where flexibility is required, for example where there are different storage options available; where a project's captured emissions are not of a scale that would justify the investment in pipeline infrastructure; where the distances between cluster and store are too great; or where pipelines are not an option for geographical or socio-political reasons (such as terrain, population density, public acceptance); then shipping provides a versatile and scalable option (ZEP/CCSA 2022).

Furthermore, there is growing interest in ship-based carbon capture (SBCC) as route to decarbonisation of global shipping fleets. This leads to the need for the development of an international CO_2 shipping network, and hence interoperability between regions.

The EverLoNG project aims to set up a CO_2 Shipping Interoperability Group (CSIG) to review and discuss the barriers and drivers to achieving this international interoperability. Three workshops will be run over the duration of the EverLoNG project, looking at the learning from the transport of other liquified gases, especially LNG and LPG, the role of international standards and regulation, and techno-economic requirements.

Table of Contents

CO2 shipping interoperability

Why is there a need to discuss interoperability?

A number of carbon capture and storage projects are developing in Europe: climate neutrality targets; the incentives offered by the European Commission and national governments; and industry and businesses that are willing to invest, are enabling the development of full-chain projects, capture clusters and storage hubs. Some of these capture projects and industrial clusters do not have adjacent CO_2 storage options (for example, South Wales in the UK, and German projects) and will need to access other regions' storage sites. There is also growing activity around the world such as in the USA, Australia and China (SCCS 2022).

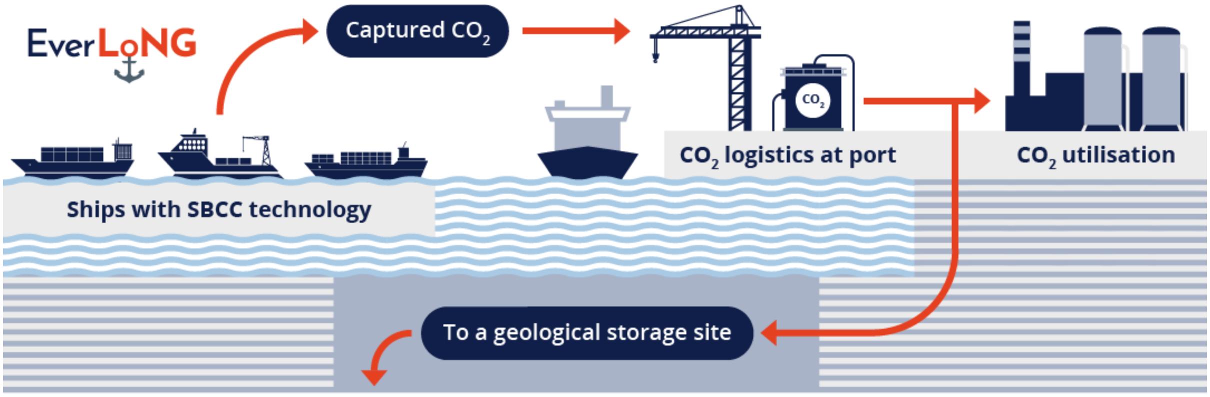
For point-to-point transport of CO_2 between a cluster and a nearby store, pipelines have low operational costs after the initial CAPEX investment. Over longer distances, however, such as for cross-border transport of CO_2, then shipping becomes a cheaper option: IEAGHG analysis found the distance threshold to be above about 650km for a flow rate of 1 Mtpa, increasing to 920km for a flow rate of 2 Mtpa (IEAGHG 2020). In addition, where flexibility is required: for example, where there are different storage options available; where a project's captured emissions are not of a scale that would justify the investment in pipeline infrastructure; where the distances between cluster and store are too great; or where pipelines are not an option for geographical or socio-political reasons (such as terrain, population density, public acceptance); then shipping provides a versatile and scalable option (ZEP/CCSA 2022).

Industrial clusters will deliver CO_2 captured from a range of sources, with a number of different impurities likely to be included in the gas stream. The scale of the CO_2 captured and the number of sources, the injection rate, storage type and capacity will all influence the requirements for ship size, portside infrastructure and CO_2 conditioning.

The majority of research and feasibility studies undertaken have focussed initially on a single point source connected to a single storage site. Over the last few years this has been expanded to looking at emission clusters and storage hubs. There are many reasons why the development of an international CO_2 shipping network will become important, including the development of onboard CO_2 capture.

The Norwegian Longship project is leading the way in Europe, particularly on CO_2 shipping, and has already selected the design of CO_2 carriers that will transport the CO_2 from shore to the offshore injection site (ZEP/CCSA 2022), and the Northern Lights project has commissioned the build of two 130m long carriers with a cargo size of 7,500m^3 (Offshore 2021). Other projects in other regions are also exploring the design of their own shipping solutions (Acorn, Cork Project, South Wales Industrial Cluster, PORTOS). Some storage operations will be operational before others, so CO_2 may be imported for storage from regions that already have capture in place (but no storage); in other cases where storage is operational there may nevertheless be a need for alternative stores to be used if for any reason a storage site is unable to take CO_2 for a period of time. Therefore, there is a need to understand and plan for interoperability of shipping in terms of readiness of ports to accept CO_2 ships from other regions and projects. Norway has already begun to forge agreements with international partners to take their CO_2, including the first commercial agreement for the cross-border transportation and storage of liquefied carbon dioxide from the Yara Sluiskil ammonia and fertiliser plant in the Netherlands (Mcculley 2022). To summarise, shipping interoperability may be needed for the following reasons:

- back-up storage: if one storage site is not operating then CO_2 may need to go to another site possibly in another region via an alternative port
- market growth: enabling alternative storage options and avoiding lock-in to one storage site or storage monopoly
- opportunity cost: enabling ships and ports to import CO_2 from capture projects to competitive storage sites in different regions
- international equity: ultimately storage sites should be accessible by all, especially those who have no storage of their own
- decarbonisation of shipping: onboard capture of CO_2 means that ships may need a number of alternative ports to offload CO_2 for storage or utilisation.



Shipping scenarios – connection modes and shipping conditions

This review of interoperability needs to take into account the different modes of use. For example:

- Offloading at port and transport through a pipeline to a storage injection site
- Offloading at an intermediate port and uploading to another ship for onward transport
- Offloading at an offshore, subsea injection point
- Offloading into temporary storage for onward transport to an injection site, moored storage at an injection site, or another port connected to an injection site
- Offshore ship-to-ship transfer is highly unlikely, and difficult to deliver, but should not be ignored

It is important to understand the entire system because this has an impact on the CO_2 conditioning required, where it needs to occur in the chain, and the temperature and pressure at which the CO_2 should be shipped.

Temperature and pressure

CO_2 has a higher density as a liquid than it does as a gas, so for economic reasons it is more practical to transport CO_2 as a liquid (Seo, Huh et al. 2016). This requires operating in a particular temperature and pressure range, Figure 1.

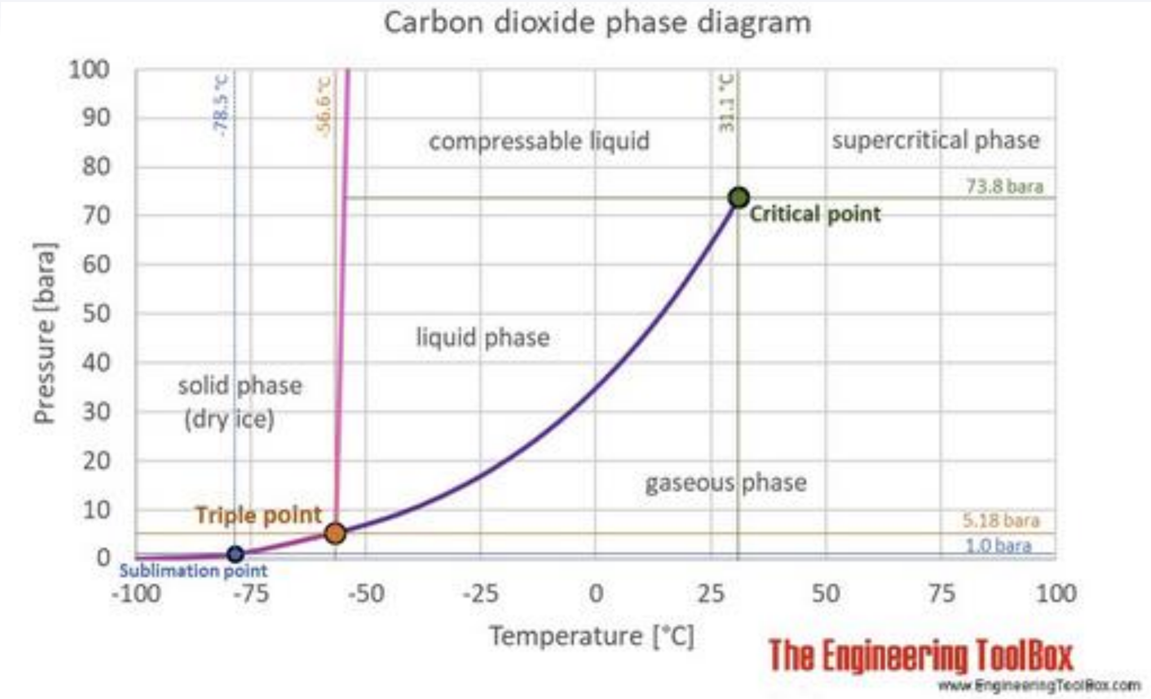


Figure 1: Carbon dioxide temperature-pressure chart (phase diagram). Courtesy https://www.engineeringtoolbox.com

A number of authors have looked at the ideal pressure and temperature conditions for shipping, with many looking at operation close to the triple point (5.18 bar, -56.6°C) but CO_2 can be liquified between the triple point and the critical point (73.8 bar, 31.1°C) and a whole range of suggestions have been explored in various studies, ranging from 6 bar, -52.3°C to 65 bar, 25.4°C (Aspelund 2010, Decarre, Berthiaud et al. 2010, Al Baroudi, Awoyomi et al. 2021). Hegerland *et al* state that to reduce investment costs of storage and ship tanks, operation should be as close to the triple point of 4.17 barg and -56.6 °C as practically feasible (Hegerland, Jørgensen et al. 2005). There are a number of issues to be explored in terms of the economics and the system design, for example, the trade-off between the cost of the refrigeration system (predominantly the energy consumption) and the reduced storage tank and ship tank costs at lower pressure (due to reduced steel thickness requirement) (Seo, Huh et al. 2016). Further implications to be considered result from the CO_2 quality and any impurities present.

There are a few small ships already shipping CO_2, each around 1,000 m^3 transporting the CO_2 at 15-20 bara and around -30°C (ZEP 2011).

Some projects have already selected their ship design parameters:

- the Northern Lights (Longship) project will use medium pressure, 15 barg at -30°C and 7,500m^3 capacity (ZEP/CCSA 2022)
- Carbon Collectors of the Netherlands propose ship transportation of CO_2 as a liquid at 40 bar and 5°C (ZEP/CCSA 2022)
- Cape Omega and Knutsen Shipping of Norway propose ship transportation of CO_2 as a liquid at high pressure, 35-45 bar and temperatures in the range of 0-10°C (Chambers 2022).

CO_2 Quality – the role of impurities

System design requires a trade-off between the cost of reducing impurities in the transported gas to avoid operational health and safety issues, and potential damage to carbon transport and storage infrastructure, and the cost of designs that can deal with greater levels of impurities. For example, to reduce the costs of purification a higher grade (more expensive) steel that is less susceptible to corrosion might be used in the manufacture of storage vessels. The presence of H_2S leads to risk of embrittlement, while SO_x, NO_x and O_2 present corrosion risks.

From the point of view of health and safety, even small amounts of H_2S or SO_2 have a large risk associated with them due to their toxicity. This was evidenced in a gas leak from a CO_2 pipeline in Mississippi where H_2S was present and led to long-term respiratory problems for residents (Rozier 2022).

Different impurities will arise from different CO_2 emission sources and capture processes: for example CO_2 emissions from a coal power plant have more impurities at higher concentrations than emissions from fertiliser production, while amines can be carried through from the capture plant and can contribute to corrosion. These impurities may have varying effects on parts of the full-chain system, including:

- Shifts in the phase equilibria
- Impacts on construction materials such as embrittlement or corrosion of steel components
- Health and safety impacts through leakage or contact during handling
- Impacts on operational function such as freeze-out in heat exchangers or dry ice formation

Table 1 shows a (non-comprehensive) summary of the effects of various impurities and recommendations for maximum concentrations in the CO_2 stream.

Table 1: CO2 quality recommendations for ship transport from CCUS PN report (adapted from Aspelund, 2010).

Component	Concentration	Limitation	Reason
Water (H_2O)	50 ppm	Design and operational considerations	Freeze-out in heat exchangers
Hydrogen sulphide (H_2S)	200 ppm	Health and safety considerations	Short-term exposure limit Highly corrosive when combined with water
Carbon monoxide (CO)	2000 ppm	Health and safety considerations	Short-term exposure limit
Methane (CH_4)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Nitrogen (N_2)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Oxygen (O_2)	Unknown	Literature not consistent	Challenges in the reservoir
Argon (Ar)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction

Component	Concentration	Limitation	Reason
Hydrogen (H_2)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Carbon dioxide (CO_2)	>99.7 % v/v	Balanced with other compounds	Dry ice formation Corrosive when combined with water

Additional impurities are covered in the ZEP Guidance on Shipping Report (ZEP/CCSA 2022).

Portside infrastructure

Offloading and uploading

According to Baroudi *et al* it will be valuable to learn from existing, well-established liquified natural gas (LNG) and liquified petroleum gas (LPG) transport systems, especially with respect to process safety and liquid cargo handling procedures (Skagestad et al. 2014, Al Baroudi, Awoyomi et al. 2021). LPG conditioning is the closest in terms of temperature and pressure to those likely to be used for CO_2: LNG conditions are usually -162°C at atmospheric pressure (Bai &Jin, 2016) and LPG at -50°C and pressures greater than atmospheric pressure (LGC , Skagestad et al.2014).

In addition to process safety and handling requirements, consideration needs to be given to the necessary footprint of large scale terminals for on- and offloading, as these need to accommodate liquefaction equipment on CO_2 onloading harbours, and pumping and heating equipment on CO_2-receiving offloading harbours (Norwegian Ministry of Petroleum and Energy 2016, ZEP 2017).

Storage

It is generally assumed that some intermediate storage capacity will be necessary and that a storage tank size of 1-1.5 times the vessel capacity is required (Bakken and von Streng Velken 2008, Skagestad et al 2014, Al Baroudi, Awoyomi et al. 2021). This sizing would have to be predicated on the maximum CO_2 transport ship size that the port could accept, and may be influenced by a number of the following factors:

- CO_2 availability (production rates)
- CO_2 temperature and pressure
- ship capacity, limited by the maximum ship-size that the port tanker jetty can accommodate, but also other factors such as port throughput capacity
- port throughput capacity, which may be limited by pump rates and pump capacity, and ship upload / offload frequency (and ongoing transport capacity)
- outage allowances due to bad weather, maintenance, tug and pilot service availability, tanker jetty availability
- ongoing transport capacity, such as pipeline capacity (injection rate and storage capacity)
- cost
- land availability

But storage may also enable the transition of what is essentially a batch process into a continuous process needed for some injection designs. There is no requirement for continuous flow into pipelines. For example, Brownsort found that for ships with a deadweight tonnage of 50,000t, the volume of buffer storage needed to enable continuous injection into a pipeline would be 20,200m^3 for average turnaround operations, and up to 90,000m^3 to cover a 24h delay between shipments (Peter Brownsort 2018). It was concluded that the capital costs to provide buffer storage and associated systems would outweigh any advantage gained and that downstream transport systems should be designed to cope with interrupted flow of CO_2.

Techno-economic assessments

As mentioned above, selection of the ideal pressure, temperature and density conditions are influenced by the whole system, such as the impact of higher pressures on the cost of tanks. For example, the CATO project looked purely at shipping combined with offshore injection which requires additional conditioning either onboard or elsewhere in the chain, and looked at a range of options (Kler, Neele et al. 2016):

- Direct injection from the ship into the injection well, with conditioning of the CO_2 taking place onboard
- Injection from an offshore platform, with installations to condition the CO_2 located both onboard and on the platform
- Offloading into temporary moored storage near the injection platform. No conditioning of the CO_2 onboard

Seo *et al* (2016) calculated that the lowest life cycle cost (LCC) was achieved for shipping conditions of 15 bar, -27.7°C. Recent work undertaken as part of the Northern Lights FEED study indicates that the ship cargo size also plays a role, with lowest end-to-end costs occurring for <15,000m^3 capacity at -15 bar and -30°C, and for >20,000m^3 at 7 bar, -50°C (ZEP/CCSA 2022). However, this is true for the selected parameters and assumptions of this project, but will not be the case for every project.

Regulation and policy

There are a number of existing standards and guidelines which will apply to the shipping of CO_2, listed in the ZEP Guidance on Transport by Ship (ZEP/CCSA 2022). The EverLoNG project will undertake a gap analysis on the existing regulatory framework and a safety study (Hazards Identification, HAZID), performed by three major Class Societies (BV, LR and DNV).

The EverLoNG sub-objectives related to embedding SBCC in the international regulatory framework are:

- to demonstrate the emission reduction potential of SBCC according to the EEDI and EEXI guidelines
- to identify the major safety hazards associated with SBCC technology (HAZID) and determine safeguards to mitigate those risks, developing safety system(s) concepts for SBCC
- to provide the basis for (near-)future class approval of the SBCC technology (EverLoNG 2021)

The role of the CO_2 Shipping Interoperability Group (CSIG)

The above overview gives rise to a number of questions that might be discussed and reviewed within the CSIG meetings:

- What learning is there from LNG and LPG shipping and liquid cargo handling that can support interoperability development?
- Is one universal CO_2 quality standard required, or should there be different standards for different parts of the chain / different full chain systems?
- Will different offloading / onloading equipment be needed for the ranges of pressure and temperature selected by different projects for CO_2 shipping?
- What is the role of temporary storage at portside – will it be needed and if so, how much?
- Will offshore (temporary) moored storage be useful?
- Regulation - what is missing, what already applies, is it fit-for-purpose, what is in development e.g. CO_2 standard for shipping?
- Pump capacities for different temperatures of CO_2

Port Readiness and Interoperability

In preparation for the shipping of CO_2 between regions and projects what are the steps that need to be taken to ensure interoperability?

There are issues that are largely outside the control of the port, but which they may be able to influence, such as:

- Regulation – planning, IMO codes, standards
- H&S guidelines and regulation
- Regional /national policy
- Public acceptance
- Supply chain availability
- Training and skills

There are also the steps that port authorities and owners can take to explore the potential for contributing to carbon emission reduction between regions and countries.

Level 1: Market

The port can assess the market and the potential for it to engage with CO_2 shipping by exploring the feasibility and requirements:

1. Are there local markets: propinquity of storage, adjacent capture clusters?
2. Are there international markets: import of CO_2 from other countries or regions for injection in local storage?
3. Is there potential to be part of a CO_2 supply chain: for onward transport to other ports or for utilisation?
4. Is there an opportunity to enable decarbonisation of shipping?

Level 2: Scoping

The port would review its potential to meet these markets:

1. Appropriate berth availability (dependent on ship size)

1. CO_2 handling facilities, experience of handling LPG, LNG or other low temperature gas transport
2. Land availability: footprint of CO_2 conditioning and temporary storage plant
3. Current capacity and throughput, and potential to scale up

Level 3: Feasibility

The feasibility stage would involve techno-economic studies and checks on the regulatory frameworks and policy:

1. More detailed analysis of market economics
2. Engineering studies (techo-economic)
3. Connecting with CO_2 clusters and storage projects (regional and international)
4. Assessment of regulatory and policy frameworks and identification of barriers

The levels beyond this would include FEED studies, contracts between parties, FID and operation.

This work in WP2 of the EverLoNG project aims to look at the status and awareness of relevant ports and explore their readiness levels for implementing a distributed network of CO_2 shipping between CO_2 emission sources (including onboard CO_2 capture on LNG-fuelled ships) and clusters, and a number of storage hubs. The barriers to the development of such a network will also be identified, including technical, socio-political and regulatory, for the countries involved in the EverLoNG project.

In order to assess 'port readiness' a template will be developed incorporating the different levels of action to enable assessment of the key issues and barriers to progress, and highlight the current status of ports working towards a future for CO_2 shipping.

Conclusions

The above overview of the status of CO_2 shipping raises a number of questions for discussion in the CSIG workshops which cover technical, socio-political, economic and regulatory aspects of developing ports that are ready to upload and offload CO_2. The objective of this is to identify the steps that need to be taken in order to form an international network of CO_2 shipping, providing transport for CO_2 captured from industrial clusters, large individual sources, offshore sources, and onboard LNG-fuelled ships, for onward transport to storage sites and storage hubs.

This is a first stage report which will be built upon and will have more detail added as the workshops with ports, ship builders, logistics companies and CO_2 storage projects are delivered through the period of the EverLoNG project.

Bibliography

Al Baroudi, H., A. Awoyomi, K. Patchigolla and E. Anthony (2021). "A review of large-scale CO2 shipping and marine emissions management for carbon capture, utilisation and storage."

Aspelund, A. (2010). Gas purification, compression and liquefaction processes and technology for carbon dioxide (CO2) transport. Developments and innovation in CCS technology. M. M. Maroto-Valer. Cambridge, Woodhead Publishing Ltd: 383-407.

Bai, Y, and Jin, W. (2016). Marine Structural Design (Second Edition)

Bakken, B. H. and I. von Streng Velken (2008). "Linear models for optimization of infrastructure for CO2 capture and storage." Transactions of Energy Conversion **23**(3).

Chambers, S. (2022). Knutsen NYK Carbon Carriers unveils new high pressure tanks to create larger CO2 ships. Splash247.

Decarre, S., J. Berthiaud, N. Butin and J.-L. Guillaume-Combecave (2010). "CO2 maritime transportation." International Journal of Greenhouse Gas Control **4**(5): 857-864.

EverLoNG. (2021). "Demonstrating carbon capture on LNG-fuelled ships." Retrieved 14/10/2022, from https://everlongccus.eu.

Hegerland, G., T. Jørgensen and J. O. Pande (2005). - Liquefaction and handling of large amounts of CO2 for EOR. Greenhouse Gas Control Technologies 7. E. S. Rubin, D. W. Keith, C. F. Gilboy et al. Oxford, Elsevier Science Ltd: 2541-2544.

IEAGHG (2020). The Status and Challenges of CO2 Shipping Infrastructures.

Kler, R. d., F. Neele, M. Nienoord, P. Brownsort, J. Koornneef, S. Belfroid, L. Peters, A. v. Wijhe and D. l. Loeve (2016). Transportation and unloading of CO2 by ship - a comparative assessment, CATO/TNO.

LGC. "Liquified gas carrier." Retrieved 15/10/2022, from http://www.liquefiedgascarrier.com/type-of-gas-carrier.html.

Mcculley, R. (2022). First cross-border deal for Northern Lights carbon capture and storage an "industry milestone". Upstream.

Offshore (2021). Dalian to build two CO2 carriers for Norwegian CCS project. Offshore.

Peter Brownsort, S. G. (2018). ACT Acorn - D18 Expansion Options

Ragnhild Skagestad, Nils Eldrup, Hans Richard Hansen, Stefan Belfroid, Anette Mathisen, Agnieszka Lach, Hans Aksel Haugen (2014). Ship transport of CO2 - Status and Technology Gaps.

Rozier, A. (2022). Carbon leak in Satartia prompts federal focus on pipeline safety. Mississippi Today.

SCCS. (2022). "Global map of CCS projects." Retrieved 13/10/2022, from https://www.sccs.org.uk/expertise/global-ccs-map.

Seo, Y., C. Huh, S. Lee and D. Chang (2016). "Comparison of CO2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain." International Journal of Greenhouse Gas Control **52**: 1-12.

ZEP (2011). The Costs of CO2 Transport. Brussels, European Technology Platform for Zero Emission Fossil Fuel Power Plants.

ZEP/CCSA (2022). Network Technology: Guidance for CO2 transport by ship: 50.