Transportation of CO_2

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Summary and key Drax take-aways undertaken by:
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Summary

Drax commissioned CSIC to provide a review of CO_2 transportation options and to summarise in particular the technical characteristics and readiness levels, costs, and safety considerations of each transport mode. The report also highlights a number of case studies of CO_2 transportation including two pipeline systems (Cortez and Denbury), one proposed integrated shipping and pipeline network (Northern Lights) and a pipeline leakage event (Satartia, Mississippi).

Key Drax take-aways

1. There are multiple methods of CO_2 transport, most of which are relatively mature or require transferring knowledge from well-established gas/liquid transport methods.
   - There is vast experience to date in transporting CO_2 by pipeline which is at TRL 9. Some 10,000km of pipelines exist and have been in operation since the 1970s across a wide range of landscapes including deserts, urban, mountains, and 2200m deep oceans.
   - Shipping has not yet been demonstrated at scale (TRL 3-9) but small-scale experience plus learning from LPG/LNG industries gives confidence that this can be achieved and in 2025 the first commercial scale CO_2 shipping network will begin operating in Norway.
   - Small scale trucking and shipping food grade CO_2 has high maturity (TRL 8-9) and has been occurring for decades.
2. Choice of transport methods is very dependent on project location (e.g. proximity to storage, onshore or offshore), volume and mode of delivery (continuous vs intermittent), and what other infrastructure is nearby (existing rail routes/ports, additional capture projects).
   - Road and rail transportation are possible for small volumes (<500kt/yr) and distances (<300km) but has high OPEX (labour and fuel) relative to shipping and pipelines.
   - Pipeline and shipping will likely dominate for large volumes and long-distance transportation. Shipping may be cheaper than pipeline at offshore distances greater than 3-800km and offers more flexibility than pipelines.
3. Standardisation of transport requirements (e.g. CO_2 specifications) will be needed to support scale up and safe operation.
   - Transportation can account for 20-25% of total costs of CCS and thus cost reduction through standardisation and shared infrastructure is critical to unlocking investment.
   - Non-pipeline transport in liquified state generally requires higher CO_2 purity and lower water content than pipelines which can add costs to the process.
   - The safety record of CO_2 transportation is largely good with the main concern being corrosion from impurities in the CO_2. Following international standards and specifications as well as regular monitoring and maintenance can ensure risks are managed and mitigated.

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Study undertaken on behalf of:

Drax Group Plc

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Disclaimer

Drax commissioned GEO3BCN-CSIC to provide a review regarding the feasibility of transportation, injection and underground storage of CO2 in geological reservoirs. Whilst GEO3BCN-CSIC had editorial control over the contents of this report, this report was written for and supported by Drax.

Transportation of CO_2

Glossary of abbreviations and units

Abbreviation	Meaning
€	euros
º C	degrees Celsius
% v/v	per cent on volume basis
BECCS	biomass with carbon capture and storage
BHP	Bottom-hole pressure
CAPEX	capital expenditure
CCS	carbon capture and storage
CO_2	carbon dioxide
CO_2-EOR	carbon dioxide enhanced oil recovery
EOR	enhanced oil recovery
JT	Joule-Thompson effect
km	kilometres
kPa/m	kilopascals per meter
kt	kilotons
kt/yr	kilotons per year
LNG	liquefied natural gas
LPG	liquefied petroleum gas
m	metres
mD	millidarcies
MEG	Methyl Ethyl Glycol
MMcf	million cubic feet
MMVM	measuring, monitoring, verification, and mitigation
MPa	megapascal
Mt	megatons
Mt of CO_2/yr	megatons of CO_2 per year
O&G	oil and gas
OPEX	operational expenditure
pH	acidity or basicity
ppm	parts per million
ppm w/w	parts per million on weight basis
ppmv	parts per million on volume basis
$scCO_2$	supercritical CO_2
t	tonnes
TRL	Technological Readiness Level
THP	Tubing-head pressure
USD	United States dollars
yr	year
wt.%	weight percent

1. Transportation of CO_2

An essential part of the Carbon Capture and Storage (CCS) chain is the transportation of captured CO_2 from the industrial point sources to the selected geological storage sites, which are often not located nearby (Figure 1). There are two types of CO_2 transport systems: modular transport and pipeline transport. Pipelines are the most common option for transporting continuous, large volumes of fluids (e.g. CO_2, natural gas, oil or water) at long distances, onshore and offshore. Modular transport involves using containers or tanks to transport CO_2, usually as a refrigerated liquid, carried offshore by ships or onshore by trucks or by rail. The choice between onshore and offshore storage significantly influences the transport method. For example, in the U.S., where there is an abundance of onshore storage resources, pipelines are predominantly used (Ho et al., 2024). In contrast, in Europe, storage resources are primarily located offshore in the North Sea (Akhurst et al., 2013). Hence, transport will probably involve a combination of shipping, pipelines, and other modes to transport CO_2 from onshore capture sites to offshore storage locations (Neele et al., 2017). Techno-economic aspects, including the scale (or volume of CO_2 to be transported), distance, and accessibility, all of which directly influence the subsequent cost, determine the best transport option for each CCS project (Smith et al., 2021). Pipeline and ship are the main options for large-scale transport of CO_2 (>1 Mt of CO_2/yr), with ships generally expected to be more cost-efficient in long distance routes (>600 km) (ZEP, 2011). Truck or rail transport are considered alternatives for shorter distances (<300 km) and smaller volumes (IEAGHG, 2020; Sani et al., 2022). Ultimately, the decision on the transport method depends on project-specific requirements, economic considerations, and geographical or regulatory constraints, with each method offering distinct advantages and challenges tailored to different operational logistics and economic models.

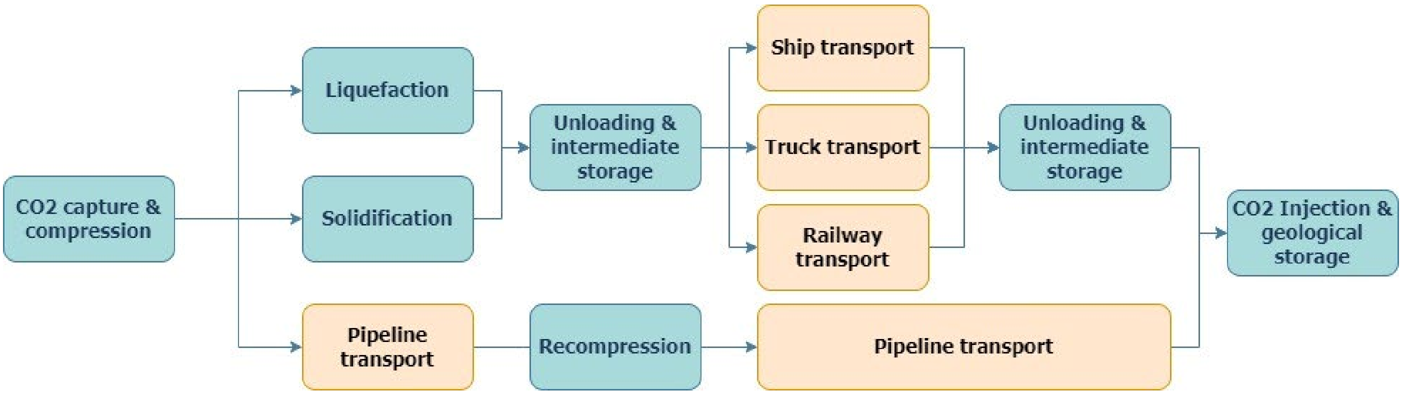

Figure 1: CO_2 transport chain. Transportation methods in orange. Modified from Sani et al., 2022.

A report commissioned by the Global CCS Institute (https://www.globalccsinstitute.com/) evaluated the Technological Readiness Level (TRL) of the different technologies involved in the CCS chain, including transport (Kearns et al., 2021). In their analysis, they report that transport of CO_2 at large scale has only been achieved through pipelines (TRL 9). The first CO_2 transportation through pipelines began in the 1970s for the purpose of CO_2-driven Enhanced Oil Recovery (EOR) (Dooley et al., 2009), and it is estimated that they currently transport 68 Mt of CO_2/yr across 8,000 km in USA alone (Wallace et al. 2015; Ho et al, 2024). These pipelines cover thousands of kilometres across various landscapes, including deserts, mountains, urban and rural areas, and even under the ocean at up to 2200 m deep (Doctor et al., 2005). Transport of CO_2 by pipeline for dedicated CCS storage is currently operational in Norway, USA, Canada, Australia, Japan, Brazil, China, Saudi Arabia and the Netherlands (Kearns et al., 2021). The pipeline lengths range from very short (< 1 km) subsidiary branches to the 145 km of offshore pipeline at the Snøvit facility in Norway, or the 808 km onshore Cortez pipeline in the US (Brownsort, 2019). There are currently more than 10,000 km of CO_2 pipelines in existence, mainly in North America (8,000 km) and Europe. It is estimated that the pipeline network will need to be increased to 43,000 km by 2030 hit net-zero targets (Friedmann et al., 2020).

CO_2 transport pipelines are usually made of steel and transport CO_2 in gas or as a dense-phase fluid (e.g liquid or supercritical) (Figure 2), typically ranging between 8.6 MPa to 15 Mpa of pressure (Martynov et al., 2015). The choice between these phases involves careful consideration of the balance between compression costs and the efficiencies gained from reduced volume transport. Gas-phase transport is the simplest and cheapest to implement but involves lower CO_2 densities, necessitating larger pipe diameters, and experiences high pressure drops (Zhang et al., 2006). Therefore, it may only be suitable for shorter distances or smaller volumes of CO_2, where the lower initial setup costs can offset the higher long-term operational costs from increased energy required for pumping larger gas volumes.

Transporting CO_2 in its dense or supercritical phase (Figure 3) is often considered optimal for long distances because it combines high density with low viscosity. These types allow for the transport of large volumes of CO_2 with reduced friction losses, which in turn lowers both the cost and energy requirements for transportation (Knoope et al., 2013). These modes, however, require robust pipeline materials and recompression facilities to manage higher pressures and maintain the supercritical state, leading to higher initial costs (Luo et al., 2014). In contrast, transporting CO_2 in the liquid phase might be preferable when conditions allow maintaining liquid state without excessive pressurization, striking a balance between infrastructure complexity and operational efficiency. Phase changes (liquid-gas) are not desirable. This phase change can present several mechanical challenges, such as causing fluctuations in CO_2 pressure and density within the pipeline, potentially leading to structural stress or damage (ZEP, 2011). Therefore pipelines are usually operated above the critical pressure of CO_2 to avoid two phase formation (DEA, 2021).

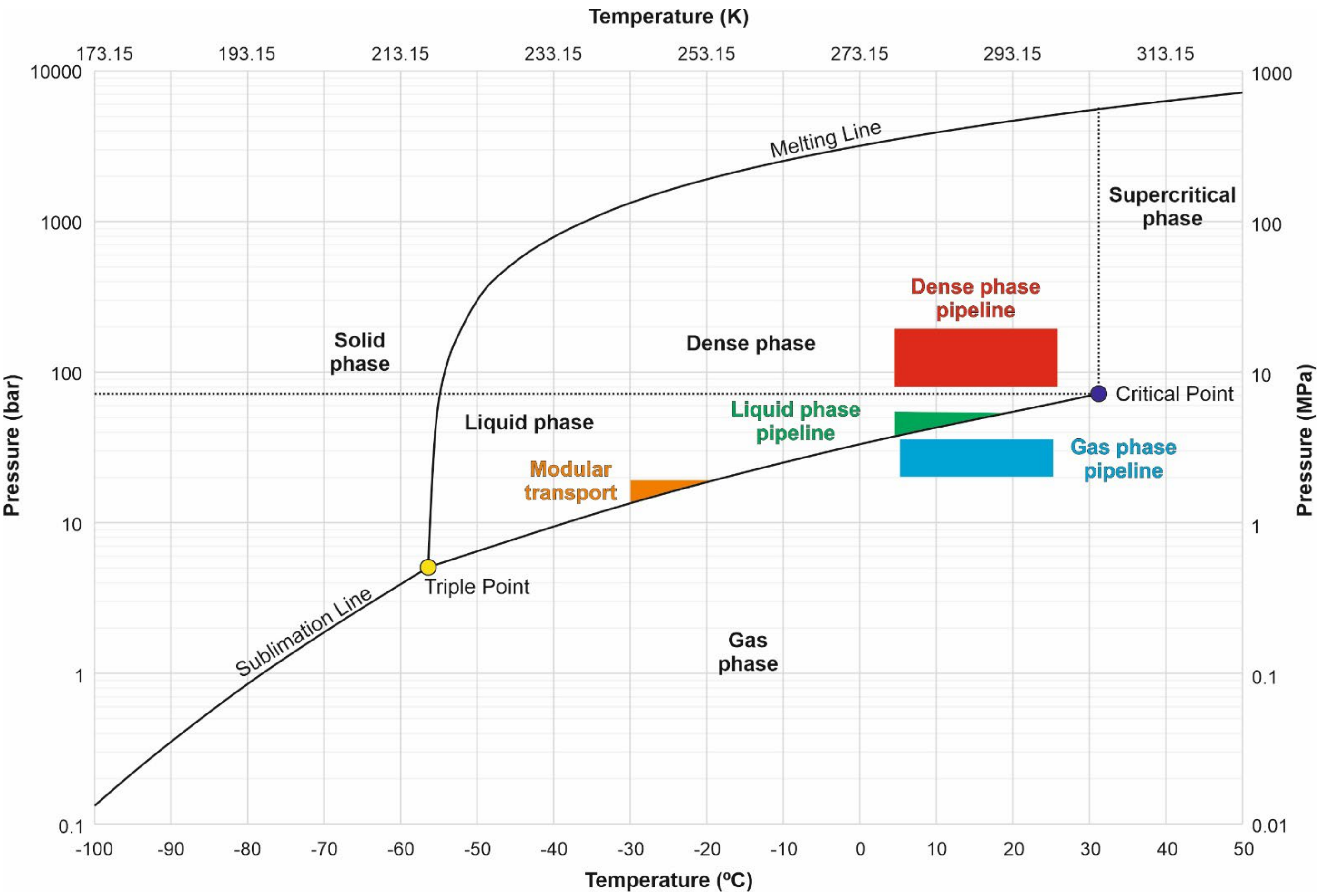

Figure 2: Phase diagram of CO_2, with ranges of pressures and temperatures used in each transport system. Modified from DEA (2021).

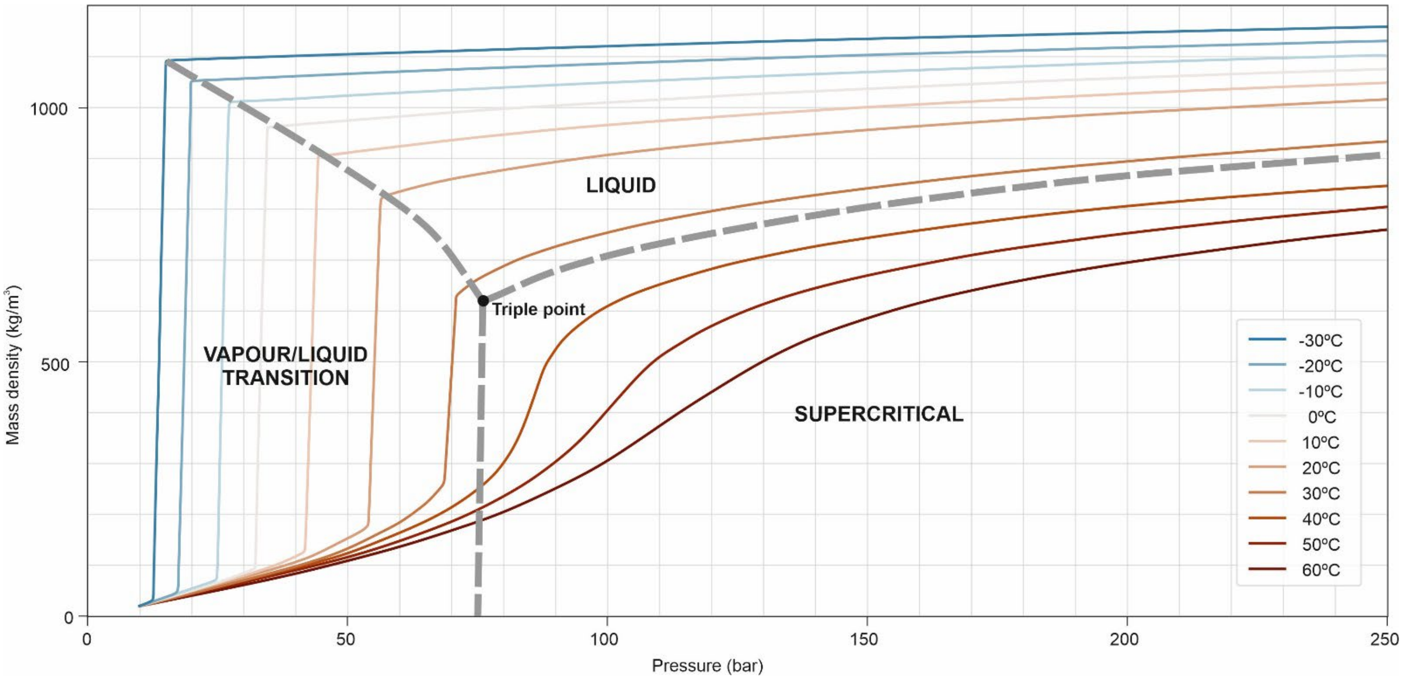

Figure 3: Mass density of pure CO_2 as function of pressure based on Peng-Robinson equations of state. Modified from: DNV, 2010.

Case study 1: the Cortez pipeline – the longest CO_2 pipeline in the world

The *Cortez* pipeline, operated by *Kinder Morgan*, is the longest CO_2 pipeline in the world at 808 km long. It connects the McElmo Dome and Doe Canyon in southwestern Colorado with the Denver City carbon dioxide hub, in West Texas (USA), where the CO_2 is used for EOR purposes. With a diameter of 762 mm and a pressure of 13.8 MPa, the pipeline can deliver up to 4.2 billion m^3 of CO_2 per day, or 19.3 Mt of CO_2/yr to the Wasson field (Huang et al., 2023). Built in 1984, the pipeline's completion remarkably spanned eight years, of which only two of actual construction, due to the prolonged process of obtaining state-by-state approval of the pipeline routing (Noothout et al., 2014). This prolonged timeline exemplifies the arduous and complex process of securing necessary permits and approvals, often encountered in large-scale infrastructure projects like pipeline construction. While this example dates back 40 years, current projects continue to struggle with similar permitting issues (Dura and Karnoski, 2023).

Shipping CO_2 is advantageous for sources near coastlines and offshore storage (Simonsen et al., 2024). Transport by ship is very flexible and allows combining CO_2 from several sources at different flow rates to one or more storage locations (Neele et al., 2017). A loading system transfers the CO_2 to the semi-pressurised ship, where the CO_2 is stored in tanks. The ship transports the CO_2 to the injection site or to an intermediate facility, where it is unloaded and sent to the injection site through a pipeline system (Aspelund et al., 2006).

Shipping of CO_2 at the scales required for CCS (i.e. in the kt-Mt scale) has not yet been demonstrated, but small-scale CO_2 shipping has been common for the last three decades (Kearns et al., 2021). The TRL for CO_2 shipping ranges from 3 to 9, as large-scale CO_2 shipping is often likened to the well-established practices of transporting liquified petroleum gas (LPG) and liquefied natural gas (LNG) (IEAGHG 2020; Kearns et al., 2021). LPG tankers are the better analogue to CO_2 transport via ship because they both require elevated pressures, whereas LNG is transported at atmospheric pressure (Smith et al., 2021). LPG tankers can be repurposed for CO_2 transport, but tankers specifically designed for CO_2 will be more optimised (IEAGHG, 2020). Given the experience from LNG and LPG, no major technical challenges are anticipated for the upscaling of the CO_2 shipping technology (Kearns et al., 2021). Recent initiatives, such as the CCS Greensand project, have showcased innovative approaches to CO_2 transport (Szabados and Poulsen, 2023). In this project, 4,000 tons of CO_2 were captured and liquefied at a chemical plant in Antwerp (Belgium), then loaded into 40 interconnected ISO-tanks mounted on a rack aboard a standard coastal carrier. The entire operation lasted 90 days and included seven shipments of CO_2. This cost-effective, custom-made transport concept effectively demonstrated interim solutions for CO_2 shipments, bridging the gap until dedicated, low-emission CO_2 cargo ships are developed.

CO_2 tankers can also be transported on land in trucks and trains. CO_2 tankers offer significant flexibility in terms of land-based transport options, catering to different logistical needs and geographical contexts. Trucks are highly mobile and adaptable, are ideal for shorter distances (less than 300 km) and lower capacities (below 500 kt/yr) (Sani et al., 2022). Truck-mounted tankers typically carry 25-30 m^3 of liquid CO_2 at 15-18 bar and -25ºC to -30ºC (DEA, 2021). Trucks can navigate a variety of road conditions, making them suitable for localized or regional transport. This adaptability is particularly beneficial in areas where pipeline infrastructure is either underdeveloped or non-existent. However, transportation of CO_2 by truck is vulnerable to weather and traffic conditions, and it incurs high and variable operational expenses, such as fuel and labour costs. Transportation of gasses and fluids through truck- or train-mounted tankers also have high TRL (8-9 and 7-9, respectively, Kearns et al., 2021), but their role in large-scale CCS deployment has not yet been fully established, particularly due to constraints in transport capacity and logistical challenges for widespread implementation.

On the other hand, rail transport offers an advantageous solution for longer-distance transport, capable of carrying larger volumes of CO_2 in a single journey (80-90 t of CO_2 per tanker, with several tankers per train Ho et al., 2024). This makes rail transport a cost-effective and energy-efficient option, especially for routes that are well-served by rail networks. Under certain circumstances (small volumes and medium to long distances), techno-economic models suggest that rail transport could be cheaper than onshore pipeline networks (e.g., Roussanaly et al., 2017). However, rail transport of CO_2 requires proximity of the gas source and destination to existing railway lines, and faces limitations in scalability due to the fixed capacities and schedules of rail transport.

Transport-related costs and economics

The cost of transportation accounts for around 21%-25% of the total costs in CCUS projects, although the price per ton of CO_2 transported is highly dependent on the project characteristics (Garnham & Tucker, 2012; Simonsen et al., 2024). Depending on the transport method, the costs depend on three aspects: (1) transport distance, (2) volume and rate of CO_2 transported, and (3) the underlying costs, such as the capital and operational expenditure (CAPEX and OPEX, respectively), the energy cost or the monitoring requirements (Smith et al., 2021). As an example, the study by Roussanaly et al., (2013) illustrates the variations in the proportion of these cost factors relative to the total costs, contingent upon the transport method selected. The study analyses the costs of transporting 13.1 Mt of CO_2/yr from capture hubs in Le Havre, France, to Rotterdam, Netherlands, using either pipeline or shipping methods. In this modelling work, the total costs are very similar for both transport options—17.1 €/t of CO_2 for the pipeline versus 18.9 €/t of CO_2 for shipping. However, there are differences in the distribution of costs: investment costs are higher for pipeline transport, while operational costs, such as energy and harbour fees, are higher for the shipping option.

Pipelines and ships are expected to play the main role in advanced development CCS projects, thanks to their capacity to transport large-scale (i.e. Mt/yr) CO_2 volumes, while truck and rail transport may be important in the early stages of onshore development (Smith et al., 2021). Onshore pipeline transport is considerably less expensive than offshore, with offshore pipelines costing 40% to 70% more (Doctor et al., 2005). In a cost review by Rubin et al. (2015), the transport costs for onshore pipelines ranged from USD1.3 to USD10.9 per ton of CO_2 transported over 250 km (in 2013 USD), whereas for offshore pipelines, the cost ranged from USD1.9 to USD14.8 under the same conditions. These costs are just illustrative and could be lower or higher than these ranges and will be unique to each project, depending on the characteristics of the project (e.g. CO_2 volume, distance, material and labour costs, land availability, regulatory requirements etc.).

In offshore systems, transporting the same volume of CO_2 by ship is generally cheaper than pipeline for long distances (greater than 300 to 800 km, depending on the project specifics) (Mukejord et al., 2016; Simonsen et al., 2024). Pipeline transportation normally has a high initial CAPEX, approximately 75% to 90% of the total cost, compared to the approximately 50% CAPEX for shipping (ZEP, 2011). This is because pipelines cannot increase their maximum capacity once built, whereas ships and utilities can be built to suit capacity demand at any time, provided it is cost-effective and the onloading and offloading capacities can accommodate the increase. Shipping is thus more suitable during the initial stages of development of offshore CCS hubs, when CO_2 volumes are not significant and/or fluctuating. Ships combined with temporary storage are particularly well suited for handling intermittent CO_2 supplies, enhancing the integrity of the injection well and equipment and also improving reservoir performance by ensuring a steady injection rate (Fraga et al., 2021). Shipping allows for easy route changes in response to new CO_2 sources or storage sites and scalable capacity through additional ships if demand increases (DEA, 2021). Standard carriers can also be repurposed (even if only once) for other goods like LPG or NH_3 if the CO_2 source stops production, increasing their "residual value" (Zahid et al., 2014; Al Baroudi et al., 2021), and carriers capable of transporting multiple gasses have also been proposed as a way to reduce cost (Larsen et al., 2022). As the CO_2 volumes increase, the network can transition to a more permanent pipeline network (Kjärstad et al. 2016; IEAGHG, 2020). This combination/alternation of ship and pipeline transportation is expected to reduce overall costs and risk, especially in early-development stages of the CCS projects (ZEP, 2011). Skagestad et al. (2014) highlight that the liquefaction and operational costs are the main cost drivers for the ship, whereas capital investment cost is the main driver for pipeline transport.

Transportation networks are more efficient than single systems, as aggregating CO_2 volumes reduces the per-ton cost of construction and operation. These networks facilitate the transport of CO_2 from various industrial emitters organized into capture clusters, increasing CO_2 availability, reducing infrastructure costs, and supporting the export of large quantities of captured CO_2 to storage areas (Roussanaly et al., 2013). The significant CAPEX required for pipeline building encourages the sharing of costs to create infrastructure that can serve multiple users (ZEP, 2011). Hence, the transportation system is a key element in the development of CCS clusters, which are more and more believed to be key to unlock CCS development in many regions in the world (e.g. Sun et al., 2021; Calvillo et al., 2022; Vishal et al., 2023).

Case study 2: the Denbury Pipeline Complex – an example of a CO_2 pipeline network

The Gulf Coast region is one of the largest CO2 emission regions in the US, and hosts a mature CO_2 pipeline transportation network, including the Denbury pipeline network. Now operated by ExxonMobil, Denbury is the largest owned and operated CO_2 pipeline network in the U.S., spanning 1,500 km across Texas, Louisiana and Mississippi (Meckel et al., 2021). It transports CO_2 from both natural and industrial sources to EOR facilities in the Gulf Coast (Soeder, 2021). Key segments include the NEJD pipeline, originally built by Shell, which transports CO_2 from natural sources at Jackson Dome to Mississippi oilfields. The network also comprises the 90-mile Free State pipeline, the 110-mile Delta pipeline, and the 102-mile SONAT pipeline, retrofitted from a natural gas pipeline (Dismukes et al., 2018). The most recent portion of that pipeline network was completed in 2010, a 320-mile segment from Donaldson, LA (near Baton Rouge) to Houston, TX (Meckel et al., 2021)

In a recent article, Stolaroff et al. (2021) analyse the transportation costs associated with biomass with CCS (BECCS). The authors conclude that, for large-scale projects (1 Mt of CO_2/yr or more), pipeline transportation is the most cost-effective method. Rail transport of CO_2 also proves to be the most economical choice for smaller projects or those with a lower fraction of carbon sent to storage. The study further reveals that for distances up to 1,000 km or more, shared CO_2 pipelines can connect biomass sourced CO_2 to storage sites within the same cost range of \$20 to \$40 per ton of CO_2 stored. Truck and rail transport emerge as feasible alternatives when pipeline construction is not possible, highlighting the adaptability of these modes in connecting biomass sources and storage sites across extensive distances.

There is considerable potential to re-use existing oil and gas pipelines for CO_2 transport, which could significantly reduce the cost of developing the CCS infrastructure (IEAGHG, 2020). There is an extensive network of oil and gas pipelines in the world, in the order of millions of km of pipelines (BTS, 2022). The costs of monitoring and maintenance of an existing pipeline are low compare to the cost of building a new pipeline (DECC, 2012). An example of the extent of this cost reduction was analysed in the Acorn CCS project (North Sea offshore Scotland): the repurposing of an existing gas pipeline was estimated to cost €38M, compared to the estimated €110M that would cost building a new one (Alcalde et al., 2019). The repurposing or reuse of pipelines can help alleviate the huge economic cost (estimated in USD104.5 billion by 2030) and potential environmental impact of oil and gas pipeline decommissioning, which is a remarkable challenge faced by the industry (Burdon et al., 2018). However, there is a limitation to the repurposing of natural gas pipelines because CO_2 requires higher pressure than natural gas to maintain the liquid state, and hence the natural gas pipelines are not suitable for transporting large quantities of CO_2 (e.g. 20 Mt/yr) over long distances (> 150 km) (Smith et al., 2021).

Case study 3: the Northern Lights project – an open-source CCS cluster

The *Northern Lights* project is part of the greater Longship CCS project, and is aimed at building a transport and storage infrastructure in the Norwegian North Sea (CCS Norway, 2023). In this project, liquid CO_2 incoming from different capture plants, a cement plant in Brevik and a waste plant in Oslo, will be shipped to a receiving terminal, where the CO_2 will be temporarily stored in pressurised tanks. The CO_2 will be then pumped through a pipeline to the Aurora storage complex (Furre et al., 2020). The receiving terminal has been designed with an expansion option in mind. The advantage is that other stakeholders in need of decarbonisation can connect to the existing CCS hub by shipping their CO_2 to the already developed storage site, hence reducing the cost of the process (e.g. the Antwerp@C consortium, Antwerp-Bruges, 2023).

Safety and Environmental Considerations in Transport

Safety in the transport of CO_2 is a key consideration in CCS projects. Although CO_2 is not toxic or flammable, the sudden liberation of pressurised CO_2 will create a safety hazard (Witowski et al., 2013). Furthermore, the liberation of CO_2 to the air, especially in high concentration (over 10% volume in air), poses a physiological hazard which can lead to asphyxiation (Gale and Davison, 2004).

Between 1986 and 2008, 29 CO_2 pipeline accidents were recorded, producing one fatality and two injuries (Johnsen et al., 2009). The accidents were mostly (46%) caused by corrosion of the pipeline steel. Corrosion of the internal surface is the primary cause of pipeline failure, potentially leading to wall thinning and overload fracture. Other failure mechanisms include stress corrosion cracking, sulphide stress cracking, corrosion fatigue and running ductile fracture (Barker et al., 2017). Gale and Davidson (2004) compared the frequency of incidents in U.S. pipelines for natural gas, hazardous liquids, and CO_2. Their analysis indicates that, statistically, CO_2 pipelines experienced a higher frequency of incidents between 1990 and 2001 compared to natural gas pipelines, though this conclusion is tempered by the smaller sample size of CO2 pipelines. Nonetheless, the authors conclude that the number of incidents in CO_2 pipelines was lower than that in hazardous liquid pipelines overall.

Ho et al. (2024) report incidents related to the release of carbon dioxide (CO_2) during onshore transport through highway trucking, pipelines, and rail systems covering the years 2003 to 2022 (data from PHMSA, 2022). During this period, highway trucking witnessed the highest number of incidents, averaging nearly 12 per year, followed by pipelines that saw an average of 5 incidents annually and rail systems averaging 3.25 per year. Pipelines were responsible for the largest volume of released CO_2, releasing 2,553.33 t of CO_2 /yr, followed by rail transport with 40.32 t of CO_2 /yr and trucking with 13.67 t of CO_2 /yr.

Case study 4: the Satartia event – piped CO_2 release near populated areas

On February 22nd 2020, Denbury's operated Delhi pipeline ruptured, causing the release of 31,405 barrels of liquid CO_2 (~5000 m^3 of CO_2), that began to vaporise at atmospheric conditions (PHMSA, 2022). Following the rupture, the emergency services shut down the nearby Highway 433 and evacuated approximately 200 people, including the entire town of Satartia and nearby homes. Forty-five individuals sought medical attention, there were no fatalities. According to the World Health Organization's Climate Change and Environmental Determinants of Health Unit, the Satartia gassing represents the first documented instance of an outdoor mass exposure to piped CO_2 gas anywhere in the world (Zegart, 2021). The failure occurred on a steep embankment by HWY 433, where a recent landslide, likely caused by heavy rains, put axial strain on the pipeline, leading to a circumferential girth weld failure. The Satartia incident, which received nationwide attention, highlights growing community concerns about the expansion of CO_2 pipelines, revealing a significant lack of preparedness for such events (Strong, 2023). Meanwhile, the U.S. is set for substantial growth in its carbon dioxide pipeline network, driven by recent incentives from last year's climate legislation, including a $251 million allocation for a dozen CO_2 transport and storage projects (Energy.gov, 2023). This juxtaposition underscores the need for enhanced safety measures and community engagement as infrastructure developments accelerate (Simon, 2023).

Achieving optimum pipeline safety and availability hinges on a combination of sound pipeline design and effective operational procedures (Eldevik et al., 2009). A well-planned design minimizes the risk of structural failures, while operational protocols aim to reduce the likelihood of unplanned events leading to pipeline shutdowns or the need for repairs. Monitoring systems include continuous observation of key operational parameters, such as flow rate, temperature, pressure, water content (Duncan et al., 2009). Besides the pipeline, inspection of auxiliary equipment takes places on a regular basis as well. This includes compressors, dehydration units, valves, cathodic protection system, monitoring systems and emergency systems. Maintenance can be done externally or even internally, using the so-called "pig runs", which can clean or detect leakage or corrosion of the pipelines from the inside (Noothout et al., 2014).

The CO_2 itself is non-corrosive, but the presence of impurities in the transported CO_2 can significantly alter its physical properties (Seevam et al., 2008). For example, the presence of water in the CO_2 stream can form solutions (e.g. carbonic acid, H_2CO_3) that can produce and hasten corrosion, leading to a reduction in wall thickness (Kairy et al., 2023). Other impurities commonly found in the CO_2 stream, such as hydrogen sulphide (H_2S), sulphur oxide (SO_x), nitric oxide (NO_x), nitrogen (N_2), methane (CH_4), carbon monoxide (CO), hydrogen (H_2) and oxygen (O_2), can also influence and exacerbate the pipeline's corrosion rate (Zhao and Li, 2014; Simonsen et al., 2024). Therefore, to minimise corrosion and other undesired effects such as reduced capacity or pressure, it is crucial to keep the level of impurities at very low levels (Cole et al., 2011). There are no standard specifications for CO_2 purity in pipeline transport, although different recommendations of acceptable CO_2 composition available exist. These are project-specific and are based on the avoidance of risks to health and environment, and of breaching other legislation (Brownsort, 2019). In 2016 an International Standard on *Pipeline transportation systems* (ISO 27913:2016) was created, which includes an appendix on the composition of CO_2 streams (ISO, 2016), although this is not publicly available. The requirements for modular CO_2 transport (e.g. through ships) is also not well discussed but generally driven by the needs of the liquefaction process for higher purity CO_2 that ensures that liquid-CO_2 is produced at the quality required for subsequent transport (Brownsort, 2019). Table 1 provides an example comparison of CO_2 component requirements for CO_2 pipeline and shipping transport.

Table 1: Typical CO_2 requirements for pipeline and shipping CO_2 transportation (after Brownsort, 2019).

Component	Concentration (Pipeline)	Concentration (Shipping)
Carbon Dioxide (CO_2)	≥ 95% v/v	>99.7 % v/v
Water (H_2O)	No free water; < 630 ppm in vapour phase	50 ppm
Hydrogen Sulphide (H_2S)	≤ 20 ppmv	200 ppm
Total Sulphur (S)	≤ 35 ppm w/w	Not specified
Methane (CH_4)	Included in hydrocarbons	<0.3 % v/v (all noncondensable gases)
Hydrocarbons	≤ 5%; Dew point ≤ -29°C	Not specified
Carbon Monoxide (CO)	Not specified	2000 ppm
Nitrogen (N_2)	≤ 4%	<0.3 % v/v (all noncondensable gases)
Oxygen (O_2)	≤ 10 ppm w/w	Unknown
Temperature	≤ 50°C	Not specified
Glycol	No liquid glycol; ≤ 0.3 gal/MMcf	Not specified
Argon (Ar)	Not specified	<0.3 % v/v (all noncondensable gases)
Hydrogen (H_2)	Not specified	<0.3 % v/v (all noncondensable gases)

As with other infrastructure, climate change can affect directly or indirectly pipeline, road, rail and shipping transportation. This includes the impacts of raising temperatures and precipitation levels, as well as extreme weather events (e.g. heat waves, flooding and storms) (Arent et al., 2014). These changes can lead to increased maintenance costs, disruptions in the CO_2 flux, and potential safety hazards. The indirect effects might include the need for redesigning infrastructure to cope with new environmental conditions and the adaptation of operational strategies to ensure the safety and efficiency of CO_2 transport in a changing climate.

Existing experience in CO_2 transportation has been in zones with low population densities, and safety issues will become more complex in populated areas if the transportation networks grow as expected (although this should not affect offshore transportation). If the trend towards shared transport networks becomes more widespread, then it is essential to establish a common standard that considers the risk of chemical reactions among various CO_2 streams from different sources, in order to minimize the risks of corrosion and scaling (Simonsen et al., 2024).

Transport method	Medium	Typical volumes	Suitable distances	Advantages	Disadvantages	TRL

Ship 	Offshore	>1 Mt of CO_2/yr	100s-1000s km	▪ Reduced CAPEX (>50%) ▪ Allows for international transportation, connecting distant sources and storage sites	▪ Requires stringent temperature and pressure control for the transport equipment ▪ Subject to maritime regulations and potential delays in ports or other facilities (e.g. Suez Canal)	3-9
Pipeline 	Offshore	>1 Mt of CO_2/yr	Up to 500-700 km	▪ The transportation volume is large and the transportation cost is low ▪ Enables continuous CO_2 transport	▪ The one-time investment of pipeline facilities is substantial (CAPEX = 75-90%) ▪ Requires ongoing maintenance and monitoring to ensure safety and efficiency	8-9
	Onshore		100s-1000s km			
Truck 	Onshore	20-30 t of CO_2/tanker	< 300 km	▪ Offers flexibility in sources and destinations ▪ No additional infrastructure investment required, except loading/unloading stations. ▪ Offers quick deployment for immediate transportation needs	▪ Transportation costs are high ▪ Vulnerable to weather and traffic conditions ▪ Operational expenses are high and variable (e.g. fuel and labour costs)	8-9
Rail 	Onshore	80-90 t of CO_2/tanker	Upon network availability	▪ Reliable transport regardless of weather and traffic conditions ▪ No need to build special railway facilities	▪ Requires proximity of the CO_2 source and storage destination with existing railway lines ▪ Scalability can be limited due to fixed train capacities and schedules	7-9

Figure 4: Summary of CO_2 transport methods and description of the medium, scale, suitable distance, advantages, disadvantages and Technological Readiness Level (TRL) of each option. Modified from Lu et al. (2020). TRL levels from Kearns et al., (2021).

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