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Review article

Challenges in CO_2 transportation: Trends and perspectives

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ABSTRACT

Transportation of CO_2 is essential for multiple applications in Carbon Capture, Utilisation and Storage (CCUS), e.g., for utilisation in methanol production, enhanced oil recovery, or permanent storage. Currently, the CCUS industry is still in its fancy, and the transportation regulation is still defined from project to project, where the existing quality specifications are tailored to the specific storage or utilisation site. It is estimated that transportation accounts for ∼25% of the total costs of a CCUS project, and commercialisation cannot be achieved with an infrastructure of high-grade steel together with high purity CO_2. The current transportation infrastructure is based on point-to-point transport, where it is believed that it will be challenging to upscale CCUS without a common quality standard. This leaves a knowledge gap in the design, operation, and investment of CO_2 transportation. This study includes an evaluation of the challenges that halt the progression in CO_2 transportation based on a survey of the literature. Analysing the benefit of establishing an international quality standard for CO_2 transportation for CCUS to become a global industry. A detailed description of the initiative policies within CCUS along with the challenges associated with designing the CO_2 transportation infrastructure, which arises when chemical reactions form corrosive or scaling compounds. As a result, this study proposes a future action plan to make CO_2 transport more feasible by forming a common CO_2 quality specification and a material selection based on CO_2 quality.

1. Introduction

Climate change worldwide is caused by the increased concentration of various greenhouse gases (GHG) in the atmosphere [1,2]. One important GHG is carbon dioxide (CO_2), which must be reduced to achieve the Paris Agreements 1.5 °C or 2 °C pathway target [3]. According to the production gap report from 2021, there is a continued strong dependence on fossil fuels towards 2035 globally [4]. Additionally, it is expected that the dependency will be 45% higher than the global warming limiting target of 2 °C [4]. Furthermore, despite an increase in the renewable energy sector, most of the energy demand in developing countries is still expected to come from fossil fuels [5]. This emphasises the importance of Carbon Capture, Utilisation and Storage (CCUS) as a crucial tool for achieving the Paris Agreement, whereas the goal will be challenging to achieve without it, according to the UN's Climate Panel - Intergovernmental Panel on Climate Change (IPCC) [3,6]. In connection to the Paris Agreement, the EU agreed in 2015 to reduce their CO_2 emission by 55% before 2030 compared to 1990 [7]. The countries around the North Sea: The United Kingdom (UK), Scotland, Germany, France, Norway, Denmark, Belgium, and the Netherlands, have taken a step even further. Scotland has set the highest goal of 75% reduction followed by Denmark and the UK with the goal of 70% and 68% reduction in CO_2 emission by 2030, respectively [8–10]. Additionally, the UK has further established a subgoal of 78% by 2035 [8]. Table 1 shows the goal of CO_2 emission reduction by 2030 and 2050 for the North Sea countries. Germany has set the goal to 65% while Norway strives towards the EU agreement of reducing the CO_2 emissions with 55% by 2030, meanwhile, the Netherlands, France, and Belgium follow with a goal of 49%, 40%, and 35% reduction, respectively [9,11–14]. By 2050 the Netherlands, Belgium, together with Norway aims to reduce emissions by 90%–95% by 2050, meanwhile, the UK, France, and Denmark seek to become net-zero by 2050, while Scotland and Germany aim to become net-zero by 2045 [8,9,11,15,16]. While the North Sea countries differ in the emission target, they have one thing in common: they all have started investing in CCUS to reach their targets. In some of the countries, the exact investment amount is not specified, but for Norway, it is estimated to be 1.9 billion USD and 1 billion USD in the UK [17]. Besides these investments, the EU has launched its first call for CCUS projects under an Innovation fund for a total of approximately 10 billion USD [18].

CCUS is a technology where CO_2 from industries is captured, then compressed before transportation to either a storage site (onshore, nearshore, offshore) or utilised for the production of CO_2-based synthetic fuels or chemicals [19,20]. The type of transportation to storage

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Abbreviations

GHG	Green House Gases
CCUS	Carbon Capture Utilisation Storage
CO_2	Carbon dioxide
CO	Carbon monoxide
NH_3	Ammonia
SO_x	Sulphur oxide
SO_2	Sulphur dioxide
H_2O	Water
H_2S	Hydrogen sulphide
NO_x	Nitric oxide
NO_2	Nitrogen dioxide
N_2	Nitrogen
O_2	Oxygen
CH_4	Methane
H_2	Hydrogen
Ar	Argon
COS	Carbonyl sulphide
PtX	Power-to-X
CLC	Chemical Looping Combustion
DAC	Direct Air Capture
OPEX	Operational Expenditures
CAPEX	Capital Expenditures

Table 1
The North Sea countries expected CO_2 emission reduction by 2030 and 2050 compared to 1990 [8,9,9,11,11–16].

	By 2030	By 2050
Belgium	35%	95%
Denmark	70%	Net-zero
France	40%	Net-zero
Germany	65%	Net-zero
Norway	55%	90%–95%
Scotland	75%	Net-zero
The Netherlands	49%	95%
The United Kingdom	68%	Net-zero

or utilisation is typically governed either by trucks, ships, or a pipeline depending on the location of the site [20,21]. The costs of CO_2 transport highly depend on the distance and volume of CO_2 transported [22–24]. Pipeline transport is often estimated to be the cheapest way to transport large quantities of CO_2 onshore, whereas ship transport is, in most cases, estimated to be the cheapest method of transportation offshore with some exceptions [22,23]. One exception is that pipeline transportation becomes more economically beneficial at a greater distance based on different economic estimations [6,23,25,26]. For pipeline transportation, the cost in low-populated and remote areas would be 50%–80% less than in well-populated areas [27]. Extracting the data from six case studies by Skagestad et al. [22], where the CO_2 is captured by post-combustion and transported by either ship or pipeline to the storage site, the total expenses of CO_2 storage is comprised of ~65% capture, ~25% transportation, and ~10% storage. Other research highlights that transportation costs make up 21% of the overall costs, which also factor in the risk assessment of the project [27]. A separate study suggests that transportation costs are less than 25% of the total cost [23]. Therefore, topics related to CO_2 transportation are crucial for the total cost and, hence, the overall success of scaling CCUS to become an international industry. The transportation method and the determined legislative quality of the CO_2 will substantially impact the cost. For CO_2 capture deployment, the impact of impurities in the gas or dense phase CO_2 stream arising from fossil fuel power plants or large-scale industrial emitters is of fundamental importance to the safe and economical transportation and storage of the captured CO_2. A pure CO_2 target comes with a great cost that can elevate economic constraints on the industrial CO_2 emitters, whereas an untreated CO_2 stream can affect the material negatively by inducing corrosion or scaling inside the system [28,29]. CO_2 is not toxic or explosive, however, a rupture on a high-pressure pipeline will create a safety hazard no matter the transported media. At the same time, releasing a large volume of CO_2 into the air can be a health hazard to humans and animals [30]. The concentration of impurities, such as water (H_2O), hydrogen sulphide (H_2S), sulphur oxide (SO_x), nitric oxide (NO_x), nitrogen (N_2), and oxygen (O_2), which often is seen in the CO_2 stream, affects the corrosion rate of the pipeline, reducing the wall thickness [31,32]. Moreover, the transported CO_2 can contain a certain impurity level of compounds such as H_2S and SO_x, which is highly toxic [33]. Therefore, the transportation of CO_2 must be governed by safety, environmental, and economic considerations. The concentration level to which each impurity is required to be removed will depend upon several factors, such as corrosivity, limiting chemical reactions, selected transport material constraints, process requirements, toxicity, and geological storage constraints [28,29,34,35]. The restriction to the impurities is currently point-to-point specific, which is a balance between the cost of more corrosive-resistant material and the cost of purification [35–38]. The receiving reservoir can also influence the selection of CO_2 quality specifications, however, this is not analysed further in this work. This work will give an overview of the effect of the impurities on both the phase behaviour and corrosion, with the limitation of not giving detailed corrosion mechanisms that are affected by pressure, exposure time, and steel chemistry, which has been excessively reviewed by Xiang et al. [39]. For CCUS to become a national or international industry, agreed CO_2 quality specifications are necessary. It is furthermore predicted that if no common national or international CO_2 quality standard is established, then the upscale of the CCUS industry will be difficult to accomplish.

Previous studies have reviewed the challenges in pipeline transportation e.g. the impurities and their influences [27,33,40–44], the phase of transportation [27,31,45–47], techno economical cost estimation between ship and pipeline transport [17,22,25,27,45,46]. However, there is not a focus on the complexity of establishing a shared CO_2 transportation infrastructure compared to having a point-to-point specified transportation.

The studies by Porter [41] and Oosterkamp [48] show the CO_2 purity from different carbon capture technologies, but the two studies do not look into whether the CO_2 purity satisfies the newer CO_2 specification by, e.g., Northern Lights or consider the challenges in a shared infrastructure. The paper by Morland et al. [49] stresses the concern of mixing multiple CO_2 streams where even food grade CO_2 (99.95% CO_2) streams can produce acids that can negatively impact the system. However, the scope by Morland et al. does not further address the establishment of an infrastructure. Onyebuchi et al. [27] highlight some of the key challenges that are within CO_2 pipeline transportation, discussing the CO_2 quality recommendation from Dynamis, conditions for the transportation, sizing, and material choice. However, Onyebuchi et al. do not observe the variation between different CO_2 specifications that have been proposed, together with a view of CCUS projects that are expected up until 2020. Lastly, none of the presented studies are not looking into initiative policies such as carbon tax and trading. In this work, a plan of action for creating an international CO_2 transportation system with shared resources is proposed. The work examines the conflicting challenge of selecting the transport material and the CO_2 quality specifications that hinder the progress towards a national and international infrastructure. This is answered by investigating the current progress in building national or international CO_2 transportation infrastructure. Moving from individual point-to-point cases to establishing a national infrastructure comes with challenges, such as the gaps in

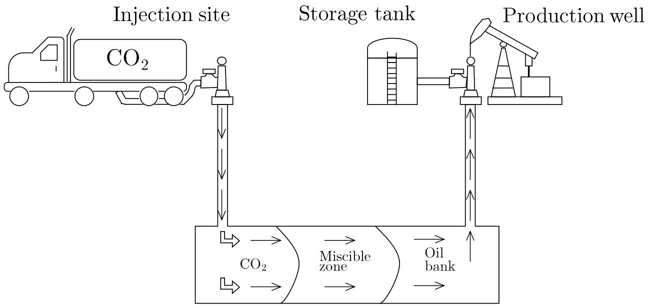

Fig. 1. Enhanced oil recovery by CO_2 injection.

knowledge associated with the design, operation, and financing of the CO_2 transportation.

The work is split into sections where the current status of CO_2 transport is described in Section 2, together with a selection of existing projects focusing on transportation, to show the current progress within this topic. Furthermore, a presentation of the initiative policies, such as carbon tax within establishing a CO_2 transport infrastructure, will be presented in Section 3. The challenges of designing an international infrastructure will be presented in Section 4, where the emphasis on a common standard for CO_2 quality specifications is highly relevant if establishing an international infrastructure, and how different cost estimations of CO_2 transportation coincide. Lastly, Section 4 will analyse how the impurities can affect the material selection and, thus, the economic balance between emitters and the receiving transport method.

2. Status of CO_2 transport infrastructure

CCUS is not a new technology. CO_2 has been injected into oil wells since the 1970s to increase oil production by Enhanced Oil Recovery (EOR), where the Terrell Natural Gas Processing Plant has been carrying out EOR utilisation for more than 40 years [50]. It can be discussed if EOR can be categorised as a climate-friendly initiative because EOR is a tool for increasing oil production rather than focusing on reducing CO_2 emissions by permanent storage [51]. EOR can help finance CO_2 storage considering that the dependence on oil and gas will increase towards 2035 [4]. Fig. 1 shows EOR by gas injection creating a miscible displacement that reduces the interfacial tension between the gas and oil. Thus, as a result, improving the oil displacement without increasing the pressure in the well [52,53]. Additionally, the CO_2, which is produced together with the oil, is captured and re-injected into the reservoir [53] (see Fig. 1).

Fig. 2 shows a timeline of nine selected projects, showing the development in projects from solely EOR to the introduction of permanent storage and projected projects focusing on the transportation infrastructure. The first permanent CO_2 storage facility was carried out 24 years after the first EOR project in 1996, called Sleipner, located in Norway, and has been operating since [54]. The second commercial permanent storage project was followed in 2018 by Snøhvit where as of 2021, there were reported 133 commercial CCUS projects worldwide, where 27 of them were operational [20]. Of the commercial projects, only six focus on permanent storage, while the rest benefit from EOR. Thus, 74% of the total CO_2 storage from the commercial project is achieved by EOR (cf. Fig. 3). This indicates that EOR is still driving the majority of commercial CCUS projects worldwide due to profit achieved from increased oil production in contrast to permanent CO_2 storage. Looking into the existing projects regarding CO_2 storage, Fig. 3 shows the amount of CO_2 stored per annum by commercial projects, where the USA constitutes 51% of stored CO_2 per annual, and relatively few countries cover all global storage projects. Furthermore, it can be seen that nine out of ten projects in the USA, utilise CO_2 for EOR instead of permanent storage due to the numerous onshore oil wells [55].

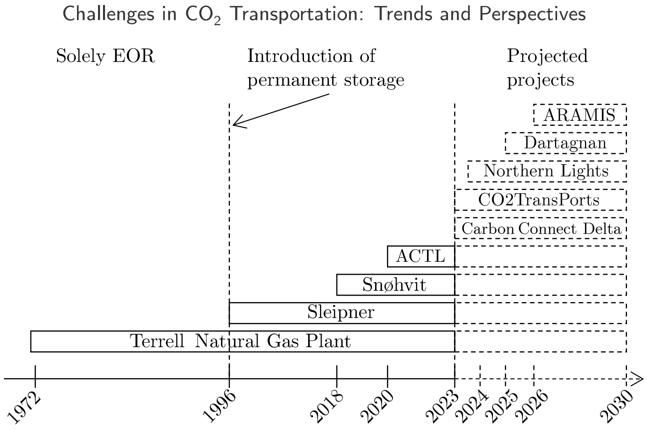

Fig. 2. A timeline of selected projects, showing the first EOR project, the first permanent storage project, and selected projects. A more comprehensive list of CCUS projects both commercial and projected, can be found in [20].

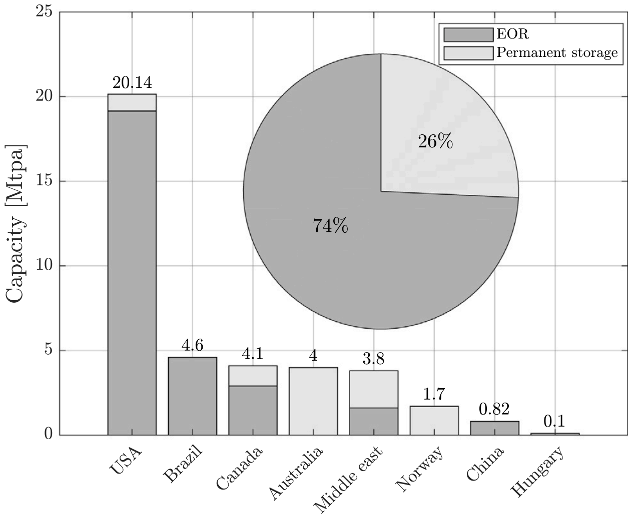

Fig. 3. The total amount of CO_2 stored in a million tonnes per annum (Mtpa) by commercial projects. The distribution between the geographical areas is shown as a bar plot and the distribution between EOR and permanent storage is shown as a pie chart (data extracted from Global CCS Institute (2021) [20]).

In most commercial projects, the focus is on the capture, storage, or utilisation of CO_2, and less on transportation [20]. However, transportation is an important aspect when the CO_2 is captured, as there is no storage or utilisation to be followed if there is no transportation. The global storage capacity was reported to increase by 32% from 2020 to 2021, emphasising the rapid interest for CCUS around the globe to reduce GHG emissions [20]. This is also seen in the number of academic peer-reviewed publications on CO_2 capture, which has been investigated using the Web of Science search engine. Fig. 4 illustrates the rapid publication rate within the last three decades, where the amount of publications regarding the subject has exceedingly increased in recent years (cf. Fig. 4). The following permutations in their title, abstract, or keywords: “Carbon Capture”, “CO_2 capture”, “Carbon dioxide capture”, “Capture of carbon dioxide” or “Capture of CO_2”. However, only a limited number of academic peer-reviewed publications include the additional words: “transport/ transportation” and “impurity/ impurities”, as seen in Fig. 4. 11.5% of the publications include "transport/ transportation" but only 1.8% also include "impurity/ impurities", which emphasises the less focus on CO_2 transport

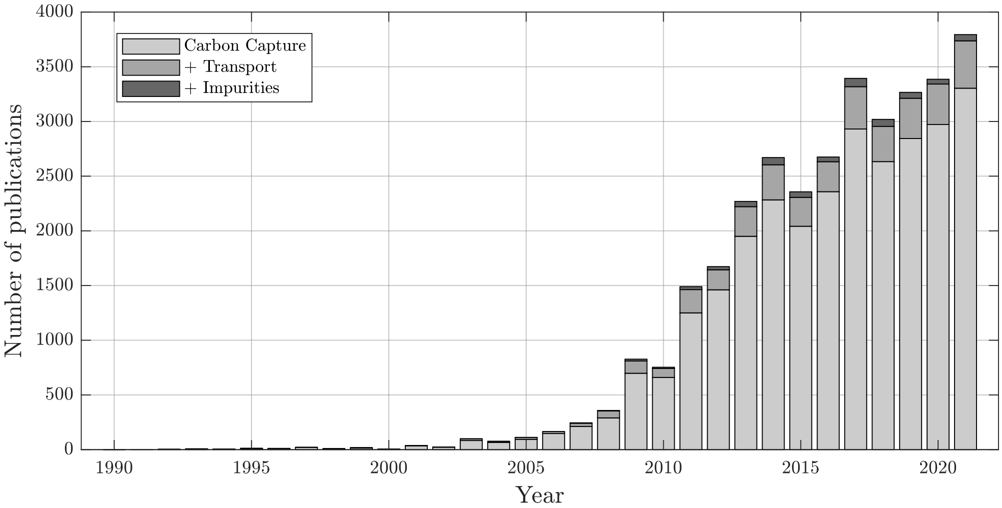

Fig. 4. Number of publications published from 1990 to 2021 including the following words: "Carbon Capture/CO_2 capture/Carbon dioxide capture/capture of carbon dioxide/capture of CO_2", in the title, abstract, or keywords. Additionally, publications that furthermore include the words "transport/transportation" and additionally also the words "impurity/impurities", respectively (Web of Science search engine used).

connected to carbon capture. Even though the cost of transportation accounts for a fourth of the total costs in CCUS projects, the number of peer-reviewed publications linking impurities in CO_2 to carbon capture is scarce [22,23].

Currently, there are announced 65 projects in Europe that aim to become operational before 2030 [56,57]. Many of these projects have determined to use depleted oil and gas reservoirs or deep saline formations in the North Sea [56,58,59]. Some of these projects focus on CO_2 transportation rather than storage, e.g., in Wales (UK), which has heavy industry without the option for geological CO_2 storage within its borders [60]. Therefore, Wales is looking into connecting to the HyNet CO_2 storage project by pipeline or shipping, which is in development in the North West of England [60]. Table 2 shows the current European cross-border network projects for CO_2 transport. The Belgian project Antwerp@C, neither do have suitable geological storage facilities. Consequently, collaboration across borders is necessary, where the CO_2 is captured in Antwerp (Belgium), then transported by pipeline to Rotterdam in the Netherlands or shipped to a suitable storage site in, e.g., Norway (Northern Lights) [61]. The projects focus on the feasibility of a cross-border network in Europe, where the two projects, Carbon Connect Delta and Dartagnan, explore the feasibility of CCUS from the Netherlands to Belgium and France, respectively. The Dartagnan project explores creating a hub to export CO_2 from Dunkirk harbour in France to Rotterdam in the Netherlands, where it is then transported to the North Sea for storage [58]. The Carbon Connect Delta project is a feasibility study looking into the potential of CCUS across the North Sea Port, stretching from Belgium to the Netherlands. Additionally, the project investigates potential connections to the Northern Lights and ARAMIS projects [59]. The announced projects indicate that the transportation of CO_2 is becoming an increasing focus area in the CCUS industry, especially in relation to countries where national storage capacity is not an option. All of these have in common that they are still in the developing phase.

The biggest CO_2 transport infrastructure so far, in the world is located in Canada under the project name "Alberta Carbon Trunk Line (ACTL)" with a 240 km long pipeline from capture to the site where the CO_2 is utilised for EOR [64,65]. The project has gotten strong support from the government to enable a CO_2 transport infrastructure and can increase the movement of CCUS in the future [64]. Different project partners are involved in this project to ensure a safe operation of CO_2 transport and storage [64]. The pipeline is designed to handle 14.6 million tons of CO_2 per year, while currently, only about 2 million tons per year are distributed [59,65,66]. Thus, the expansion of industrial partners for the capture and transport of CO_2 is planned for the future [59]. This project is the concept of a cluster. The transport system is oversized to be able to fulfil the needs of multiple users [67]. This is not only done to reduce the space of individual pipeline systems but also to reduce the cost by sharing the infrastructure to accelerate CCUS [67]. In connection to the ACTL project, a large-scale CO_2 transport project with a 1.000 km offshore pipeline from Belgium to Norway is planned to be ready for commissioning at the end of the decade [66,68]. This pipeline will give emitters from Belgium and the countries surrounding Belgium the opportunity to connect to the CO_2 storage facilities in Norway [68]. In contrast to this, the Norwegian "Northern Light" project will transport compressed CO_2 from the South-East of Norway to the West coast of Norway by ship, where a facility temporarily stores the CO_2 [63]. From there, the CO_2 is transported by a pipeline offshore into a reservoir 1–3.3 km below the seabed for permanent storage [63]. The Northern Light project is expected to expand to be a commercial transport of CO_2 across European capture plants for storage in the Norwegian continental shelf (west coast of Norway) [58]. Recently, the Northern Light project has signed the world's first cross-border CCUS project with a fertiliser plant located in the Netherlands [69].

Most of the projects presented in this section, focusing on transportation, are still in their early stage and do not mention the quality of the transported CO_2. So far, the Northern Lights project is considering pure CO_2 with limited impurities shown in Table 4 in Section 4.1. The limited impurities specified by Northern Lights will lead to an increased cost of purification of the captured CO_2. In summary, there is still limited knowledge and data about CO_2 transportation, even though CO_2 transportation constitutes ~25% of the total costs of CCUS projects. The quality specification of the transported CO_2 needs to be specified for the mentioned transportation projects to be able to proceed from their early stage. One of the challenges with designing an infrastructure for CO_2 transportation is, among others, the economic aspect and is primarily driven by political initiatives, which will be discussed in Section 3.

3. Initiative policies

Permanent CO_2 storage does not provide an economic benefit on its own, thus, only expenses are connected to CO_2 storage. This is mainly why the technology is not a widespread application for decreasing CO_2 emissions. This leads to the main challenge of when, how, and if CCUS will become feasible for commercial implementation through either CO_2 permits, CO_2 national taxes, or governmental support. As presented in Section 2, the amount of CCUS projects around Europe is accelerating. However, these projects are still driven by funding, governmental support, or investments from companies increasingly seeking

Table 2
Cross-border networks for carbon dioxide transport.

Project name	Countries involved	Transport	Injection capacity	Expected start date	Details
Dartagnan [58,59]	The Netherlands, France	Pipeline and ship	3 Mt CO_2/yr	2025	CO_2 export hub from Dunkirk harbour (France) to the port of Rotterdam (the Netherlands) for storage in the North Sea.
Carbon Connect Delta [59,62]	The Netherlands, Belgium	Pipeline	1 Mt CO_2/yr	2023	Part of the project is a feasibility study mapping the financial and technical aspects required for a large-scale infrastructure for CO_2 transport. Considering pipeline and ship transportation and option for both storage and utilisation.
CO2TransPorts [58,59]	The Netherlands, Belgium	Pipeline	10 Mt CO_2/yr	2023	Collaboration between ports of Rotterdam, Antwerp, and the North Sea Port. The CO_2 will be stored in a depleted reservoir in the North Sea.
Northern Lights [58,59,63]	Norway, The Netherlands, (Expected to expand to several European countries)	Pipeline and ship	1.5 Mt CO_2/yr	2024	Developing a transport connection between European clusters. Offshore storage from the coast of Norway.
ARAMIS [58,59]	The Netherlands, Belgium, France, Germany	Pipeline and ship	2.5 Mt CO_2/yr	2026	Transport from Rotterdam via pipeline or ship to depleted reservoirs in the North Sea for permanent storage.

to improve their economic resilience by investing in new markets and increasing their reputation by investing in the climate. Additionally, this also calls for a need to establish an assurance for the actors to dispose of their CO_2 continuously to a great coherent value chain between capture, transport, and storage. The interest for CCUS has been increased by deploying a cost of CO_2, whereas less conventional methods like Direct Air Capture (DAC) also can become commercially economical to deploy [70]. From a governmental perspective, carbon taxation or tax credits can introduce an initiative policy that can help finance CO_2 transport and storage. The first country to implement a carbon tax was Finland in 1990, where in 2021, the implementation of 35 carbon tax programs across the world was established [71,72]. The carbon tax is a fixed price of emissions of all greenhouse gases including CO_2, hence the carbon tax is written in CO_2e (carbon dioxide equivalent) (cf. Table 3) [72]. The price of the carbon tax is different from country to country, whereas Sweden has the highest carbon tax in Europe with 129.9 USD/t and Uruguay has the highest carbon tax in the world with 137.3 USD/t (cf. Table 3) [71–73]. On the contrary, of those with a carbon tax, Poland has the lowest of 0.08 USD/t, showing a huge difference between the lowest and highest determined carbon tax [73]. All members of the EU, including Norway, Iceland, and Liechtenstein, are affected by the European emission trading system (ETS), also referred to as the cap and trade system, which is different from carbon taxation. ETS is a market for the trade of emission permits, where there is a capped amount of GHG emission allowance [71,74]. This allows companies to trade with one another for CO_2 emission permits. By the end of the year, the CO_2 emissions are assessed, and if the company does not fulfil its limited values, they are fined [75]. The companies that are involved in the EU ETS system are the biggest emitters designated by the EU. The trading system is believed by the European Commission to bring flexibility but also ensures that the emissions are cut, increasing the interest and investment in CCUS [75]. On the contrary, challenges arise from the implementation of initiative policies where businesses with a high CO_2 emission will be sacrificed in the process or an increased outsourcing of industries outside of Europe is seen. In the USA, outsourcing industries to countries without an implemented carbon tax is already observed where firms seek foreign suppliers [76–79]. Carbon leakage is the outsourcing of GHG emissions or moving the production to other countries with lower or no obligations towards reducing GHG emissions [79]. Additionally, sectors with high energy demand would be more exposed to carbon leakage and will be put on the carbon leakage list, granting them free emission permits [80]. A limitation of the carbon taxation system is the difficulty in measuring the exact concentration of the CO_2 produced and, therefore, challenging to charge the correct carbon tax. Another limitation is that countries rely on other efforts to reduce carbon emissions. For example, the US left the Paris Agreement under President Trump but later rejoined the Paris Agreement under President Biden [81]. The carbon tax as of 2022 can be seen in Table 3. The carbon tax is specifically expected to increase for European countries, where the EU ETS is expected to increase from 86.5 USD/t to ~105 USD/t in 2030 [82,83]. Together with the increase in the EU ETS, an EU country like Denmark has prepared a new green tax reform, where the CO_2 tax is gradually increased through 2025 to 2030 [83]. The tax reform implies that companies subject to the EU ETS will pay an increased 53 USD/t on top of the ETS, amounting to 159 USD/t [83]. Additionally, the companies that the EU ETS does not imply will be charged the same price as the EU ETS by the Danish government [83]. Lastly, the heavy CO_2 emitters, like the cement industry, will pay a reduced price on top of the ETS of 14 USD/t to prevent outsourcing [83]. The Chinese ETS system was established in 2021 and covers only power generation, and the price is only a fraction of the EU ETS cf. Table 3 [84,85]. However, the coverage of the Chinese ETS was 4.5 billion tonnes in 2021 compared to the EU ETS covering 1.6 billion tonnes [85]. In summary, the regulations within ETS in China make it less attractive to establish a CCUS industry, e.g., compared to the EU.

Table 3
Carbon tax pricing of selected countries and emission trading systems (ETS) (2022) in USD per tonne CO_2e (carbon dioxide equivalent). CO_2e is used to compare GHG emissions by converting their global warming potential to the equivalent amount of CO_2.

Country	Carbon tax rate [USD/t CO_2e] [73]
Uruguay	137.3
Sweden	129.9
Norway	87.6
Finland	85.1(transport) 58.6 (other)
The Netherlands	46.1
Denmark	26.6
Poland	0.08
Area	**ETS [USD/t CO_2e] [73]**
United Kingdom (ETS)	99.0
EU (ETS)	86.5
China (ETS)	9.2

USA has chosen a different strategy. Instead of giving a penalty to the emitters, a reward in the form of a subsidy through the CO_2 tax credit sequestration referred to as the 45Q tax was introduced in 2008 [86,87]. The 45Q tax encourages the capture, utilisation, and storage of CO_2 and has resulted in increased investment plans

Table 4
CO_2 quality specifications.

	Northern light [92]	NETL recommended limits [38]	Dynamis [37,93]	Porthos [94]	ISO 27913:2016 [35]	EU Food-grade CO_2 [95]
CO_2	–	95%	>95.5%	≥95%	≥95%	≥99.9%
H_2O	≤30 ppm	500 ppm	500 ppm	≤70 ppm	<200 ppm	20 ppm
O_2	≤10 ppm	0.001%	<4%[a] <1000 ppm[b]	≤40 ppm	–	30 ppm
H_2S	≤9 ppm	0.01%	200 ppm	≤5 ppm	<200 ppm	0.1 ppm
N_2	–	4%	<4%	≤2.4%	–	–
SO_x	≤10 ppm	100 ppm	–	–	<50 ppm	1 ppm
NO_x	≤10 ppm	100 ppm	–	≤5 ppm	<50 ppm	2.5 ppm
CO	≤100 ppm	35 ppm	2000 ppm	≤750 ppm	<2%	10 ppm
NH_3	≤10 ppm	50 ppm	–	≤3 ppm	–	2.5 ppm
H_2	≤50 ppm	4%	<4%	≤0.75%	–	–
Ar	–	4%	<4%	≤0.4%	–	–
CH_4	–	4%	<4%[a] <2%[b]	≤1%	–	50 ppm
Acetaldehyde	≤20 ppm	–	–	–	–	–
Formaldehyde	≤20 ppm	–	–	–	–	–
Hg	≤0.03 ppm	–	–	–	–	–
Cd and Tl	≤0.03 ppm	–	–	–	–	–
Total sulphur (COS, H_2S, SO_x)	–	–	–	≤20 ppm	–	0.1 ppm
Methanol	–	–	–	≤620 ppm	–	10 ppm
Total (N_2, H_2, CH_4, O_2, Ar, CO)	–	–	–	≤4%	4%	–

[a] Aquifier.

[b] EOR.

in CCUS [87]. The 45Q tax plan provides a tax credit for each of CO_2 captured permanent storage and utilisation (e.g., EOR), with 85 and 60 USD/t CO_2, respectively [86–89]. The tax credit refers to the amount of tax the taxpayer can subtract from the tax owed to the government [90]. Interestingly, the 45Q tax credit also supports the DAC technology with a specific tax credit of 180 and 130 USD/t for storage and utilisation, respectively [86,89]. This further increases the interest for DAC, whereas the Global CCS Institute sees the development of the DAC technology as insurance towards net-zero [70]. The taxation and credit system show interest from a governmental point of view and can play a crucial role in new infrastructure for transport and storage by incentivising investment into CCUS [19,23]. Thus, the investment into CCUS and the taxation system can cover the cost of the transport infrastructure so that CO_2 can become a national trading product. Furthermore, the EU countries Belgium and Denmark have signed a national political statement to engage in cross-border CO_2 transport for geological storage [91]. The political statement does, however, only cover the importance of cross-border collaboration and does not describe the process of how and when the infrastructure should be established. A strong indication that the establishment of the infrastructure is still in the early stages. The dilemma with establishing the CO_2 transport infrastructure is who should build, operate, and pay for it. Additionally, common pipelines are needed to transport the captured CO_2 from the industrial sites to the storage or utilisation facilities, which need to be built and operated. Looking at an EU perspective, the ETS can positively affect the CCUS industry, where buying and selling the CO_2 permits can play a key role in further investments in CCUS. Additionally, there is also an increased shift in focus from "stand-alone" CCUS projects to the development of clusters and hubs where the CO_2 transportation system is shared together with the storage facilities [23,58,59,63,66]. This approach can increase efficiency together with economic benefits for CCUS. Examples are the Northern Light project, and the CO_2 pipeline from Belgium to Norway, which links CO_2 capture facilities in Europe to storage in the Norwegian continental shelf (cf. Section 2) [68,69,92]. The availability of the storage site in Norway can become the catalyst for CO_2 capture facilities around Europe, where storage sites are unavailable. This is also a statement that there is a need for a common CO_2 quality standard to be able to connect projects.

4. Challenges with designing an infrastructure of CO_2 transportation

Generally, when transporting large amounts of liquid or gas, pipelines are commonly used in, e.g., the oil and gas industry or wastewater treatment plants [96]. Liquid and gas transportation onshore can be transported in bulk by either trucks or rails, and offshore by ships; the transportation choice highly depends on the continuous quantity distribution, distance, and cost. This leads to the challenges of designing an infrastructure of CO_2 transportation. The complexity lies within the choice of transportation method, considering the distance and cost. After choosing the transportation method, the pressure and temperature to reach a certain phase of the CO_2 needs to be established. Besides, the purity of the CO_2 needs to be chosen to be able to choose the type of material of the infrastructure to achieve the highest CO_2 transport efficiency. This section is split into the four following subsections:

- Section 4.1: CO_2 quality specifications
- Section 4.2: Cost of CO_2 transportation
- Section 4.3: Transportation methods of CO_2
- Section 4.4: Effect of impurities on CO_2 transport
- Section 4.5: Origin of impurities from the CO_2 capture

4.1. CO_2 quality specifications

The quality specifications for CO_2 transport can either be:

- **Point-to-point specific**: The transportation only involves a few destination points. As such, a case-specific quality specification is only needed as it involves few emitters and a storage site.
- **Shared infrastructure (hub)**: The transportation involves more destinations, tying several emitters together to a shared infrastructure. A common standard considering the risk of chemical reactions between the different CO_2 streams is necessary to reduce the risk of corrosion and scaling.

The projects in Section 2 have a point-to-point specific quality standard, thus, these projects have their own quality specifications or tend to follow the Northern Light specification. Table 4 presents five CCUS CO_2 quality standards from Northern Light, National Energy

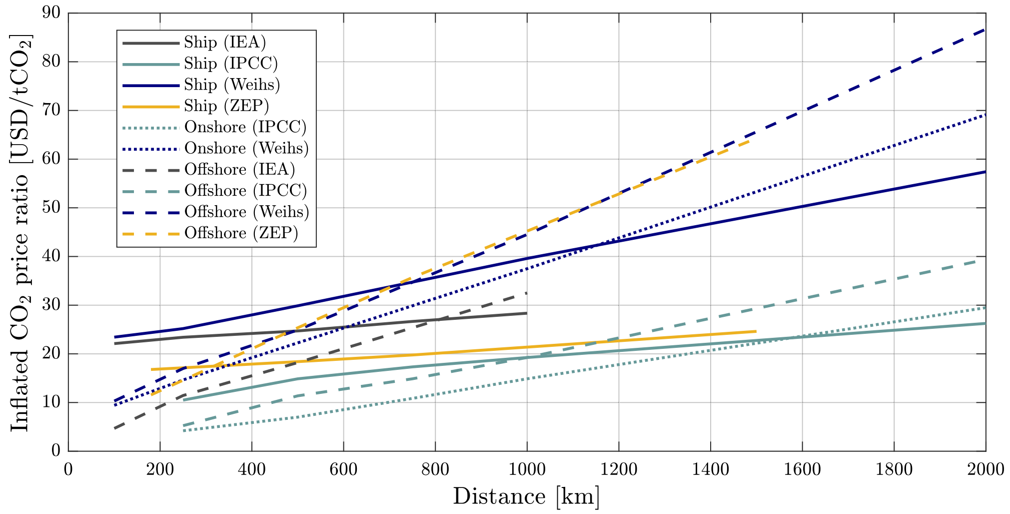

Fig. 5. The inflated CO_2 price ratio (USD/tCO_2) for ship (solid line), offshore pipeline (dashed line), and onshore pipeline (dotted line) transport comparing data extracted from IPCC 2005 [6] (green colour), IEA 2020 [23] (grey colour), Weihs et al. 2014 [25] (blue colour), and ZEP 2011 [97] (yellow colour). The inflated price is calculated based on inflation of 2% for each year up till 2022.

Technology Laboratory (NETL), Dynamis, Porthos, ISO, and EU food-grade CO_2. The two American standards, NETL and Dynamis, agree on many of the same quality specifications. However, the amount of O_2 and CO is allowed in much higher concentrations in the standard by Dynamis than in NETL and twice the amount for H_2S. The two standards agree on an H_2O limit of 500 ppm to avoid any presence of free water that can form hydrates or cause corrosion inside the system [37]. Observing the different quality specifications, it is difficult to make a comparison because not all specifications specify restrictions to the same compounds. E.g., Northern Light specifies the allowed concentration of heavy metals like mercury (Hg), cadmium (Cd), and thallium (Tl), which the other specifications do not state. Furthermore, the standard by ISO has given the total amount of non-condensable gases (N_2, H_2, CH_4, O_2, CO, Ar) of 4% instead of specifying a concentration of the specific compounds [35]. The NETL, Dynamis, and Porthos specifications advise limiting the non-condensable (N_2, O_2, Ar, CH_4, H_2) gases to less than 4% of the total volume (cf. Table 4), but also giving a specification for the different compounds individually [37,38,94]. Meanwhile, the Northern Light specification states that the concentration of the non-condensable gases will be limited by the solubility of liquid CO_2 [92]. Northern Light generally has a stricter quality specification, only allowing 30 ppm H_2O in the stream, which is close to the level in EU food-grade CO_2 (cf. Table 4). Interestingly, Porthos specifies a lower limit of NH_3, NO_x, H_2S than the Northern Light, which is close to the level of EU food-grade CO_2. The difference in the standards might be the result of the current CO_2 infrastructures being point-to-point specified, given that they only have to comply with known impurities from the emitters. The acceleration of the CO_2 industry needs general quality specifications that are unknown to date, as it is still in its early stage, and more experience is still needed to form the specifications. The quality specification created by Dynamis presents a level of O_2 and CH_4 for storage in aquifers and EOR, showing that the storage site and application have an influence on the quality of the CO_2. The ISO standard (ISO/TR 27921:2020) regarding CO_2 capture, transportation, and storage explains the impacts of the impurities [98]. The standard further states that the restrictions of the impurities are specific for each project, and a cost–benefit analysis should be conducted to obtain a balance between the cost of purification and material costs [98]. Furthermore, Det Norske Veritas (DNV) has developed recommended practices for each process in the CCUS chain: capturing, transporting, and storing of CO_2 [99]. In the recommended practice, DNV also states that the impurities in the stream should be assessed from project to project, and further referring to the quality specifications by Dynamis [36]. Considering the impurities from project to project instead of having a common standard will make it complicated to introduce hubs as a means of more efficient CO_2 transport. The reason is the chemical reactions that will occur when mixing CO_2 streams containing different levels and species of impurities, resulting in damage to the transport system (cf. Fig. 6) [29,49]. This will further be elaborated in Section 4. Another difficulty is the gap between the buyer's quality specification and what is feasible for the supplier to deliver. In summary, a cost–benefit analysis is needed to settle the CO_2 quality, which is a trade-off between the cost of purification and infrastructure material cost. The Northern Light quality specification is generally more strict than the other standards, meaning increased purification costs when choosing the Northern Light quality specification. However, a common quality agreement can positively affect the CCUS industry and the possibilities to upscale the industry.

4.2. *Cost of CO_2 transportation*

The cost of CO_2 transport is difficult to estimate due to the number of variables to consider. The study by ZEP [97] reported that a combination of ships and pipelines is the most cost-effective method for developing clusters [97]. When considering transport options, transportation by truck is only considered when having smaller volumes and short distances from capture to storage or utilisation site [100,101]. Another important thing to highlight is the emissions connected to CO_2 transportation, where truck transportation has the highest emission of CO_2 per volume of CO_2 transported [100]. Additionally, it is estimated to be four times higher than ship transport, while pipeline transportation has the lowest CO_2 emission [100]. This section will outline the complexity by comparing the transportation cost estimations from four different sources. Fig. 5 shows the estimated cost of the pipeline (onshore, offshore) and ship transport costs extracted from IEA [23], IPCC [6], Weihs et al. [25], and Zero Emission Platform (ZEP) [97]. All data in Fig. 5 is inflated with 2% annually until 2022 for a more accurate and fair comparison. The different studies all show the same trend that the transportation costs of ships eventually get cheaper than pipeline transport as the distance increases. The analysis by IPCC [6] showed that the transport cost by ships is cheaper than pipeline transport at distances greater than 1.000 km (cf. Fig. 5). Additionally, the transport pipeline onshore is significantly cheaper than an offshore pipeline system, where the same pipeline is around 40%–70% more expensive offshore than onshore [6]. Even though there is no agreement

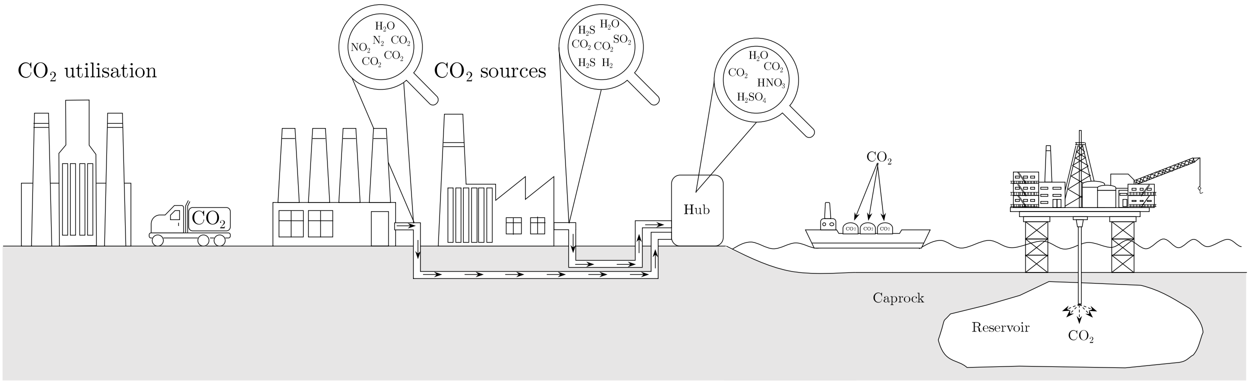

Fig. 6. Illustration of a CO_2 transportation infrastructure. A pipeline directly connected to a hub from the industry. Trucks exporting CO_2 from the hub to the utilisation site (PtX plant) and ship transport from the hub to the offshore storage site. The magnifying glasses show the impurities in the two streams going to the hub and the magnifying glass at the hub shows an example of chemical reaction products between the two streams.

between the studies when transport by ship is cheaper than pipeline transport where the International Energy Agency (IEA) [23] estimates that ship transport is cheaper before 800 km, Weihs et al. [25] before ~780 km, and ZEP [97] before ~300 km. The reason may well be the differences in what the price estimations cover. E.g. the type of material used for the cost estimation was not stated by IPCC [6] and IEA [23], however, ZEP [97] reported that carbon steel was used whereas Weihs et al. [25] used an X65 steel grade. The price from Weihs et al. [25] includes the CAPEX (capital), OPEX (operational), and decommissioning expenditures assuming a transportation capacity of 6 Mtpa, while IEA [23] assumes a capacity of 2 Mtpa but does not state what the costs include. IPCC [6] includes harbour fees, fuel costs, intermediate storage, loading and unloading, compression, and liquefaction, together with capital charges (11%) and assuming a transportation capacity of 6 Mtpa [6]. On the contrary, ZEP [97] assumes a transportation capacity of 2.5 Mtpa, including CAPEX and OPEX, where the costs are based on new investments, meaning no re-use of LPG ships or existing pipelines. Comparing the investigation from IPCC [6] and Weihs et al. [25] having assumed the same transport capacity of 6 Mtpa there is a huge price difference for ship and offshore pipeline transport, which could be due to IPCC [6] does not take into account the decommissioning cost as Weihs et al. [25]. Even though Weihs et al. [25] and ZEP [97] do not assume the same transportation capacity, 6 and 2.5 Mtpa, respectively the price ratio for offshore pipeline transport is relatively close meanwhile, there is a huge difference in the transportation by ships. Moreover, this shows that it is hard to estimate a price for pipeline and ship transport due to the many variables to consider such as distance, annual capacity, liquefaction, compression, and fuel cost. The price per ton CO_2 would also vary with different capacities of the pipeline or ship, where the price would depend on the project. From Fig. 5 it can be observed that the pipeline cost is proportional to the distance of transportation, where the shipping costs are not influenced at the same magnitude. Furthermore, it shows that pipeline transport costs in all studies eventually surpass shipping costs. The reason for this is that the costs for pipeline transportation consist of manly CAPEX, which normally covers 90% of the expenses [97]. Meanwhile, the CAPEX for shipping is less than 50% of the total costs [97]. Therefore, it is important to do an economic evaluation of the CO_2 transport infrastructure, where the different transportation options should be assessed for their total CAPEX and OPEX.

The presented cost estimations are based on the theoretical transportation of ships without any complications. In practice, unforeseen complications for ship transport and trucks can easily occur, e.g., harsh weather and tides can postpone transportation time, whereas bad traffic can easily disrupt truck delivery. Unlike pipelines, other transport methods rely on human involvement, requiring stable labour, management, and market. This means that failing to manage or deliver the transport causes increased costs to the transportation. More practical issues can also occur as the size of the ships can limit the location of where they can dock, although that will have been taken into account for point-to-point movement. Both trucks and ships have in common that they can only offer intermittent deliveries; an interim storage tank is necessary both at the loading and unloading location. The required capacity and cost for interim storage will largely be governed by the cycle time of the ship and truck delivery but could adversely be emptied or filled due to downtime. Known from the oil and gas industry, having a continuous steady flow reduces the complexity of managing the process tremendously, such as long start-up stabilisation of injecting the CO_2 and preventing CO_2 saturated brine from rising in the well when the injection process is interrupted [102,103]. At last, the impact of uncertainties in fuel cost and unplanned maintenance can also affect the delivery by ships. This even becomes more relevant as the energy used in the process must come from low-carbon energy sources to have the highest outcome on the CO_2 emission ratio (kg per CO_2 injected vs. kg per CO_2 released in the process of storing CO_2) [96]. Currently, access to green fuels, like methanol, is still very limited to cover ship transport, which can become a restriction to CO_2 ship transport if not increased substantially in the coming years [104]. Even if the pipeline has advantages in continuous transportation of large volumes at low operating costs, energy consumption, and emission, it also has some disadvantages. Transporting CO_2 by pipe comes with a high fixed investment cost compared to ships and trucks, which also requires an extensive approval procedure and long planning and construction time. Besides, it also has poor flexibility compared to trucks and ships, which can deliver to other locations if necessary. In the early stage of developing a CCUS industry, the flexibility and fast access to transporting CO_2 (point-to-point cases) favour the use of ships and trucks. Therefore, selecting a transport method is more than a question of the cost of transporting CO_2 from point to point. A study by Skagestad et al. [22] reports that ship transport has a higher degree of flexibility and would be a better option due to uncertainties in the future for utilisation plants and storage [22]. This, however, is in sharp contrast to a report by the Danish Energy Agency [105] conducted a cost analysis comparing different scenarios for onshore, nearshore, and offshore. The analysis concluded that the cost for offshore is generally more costly than onshore and nearshore, where onshore is more cost-efficient than nearshore. Furthermore, it was concluded that transport by pipeline opens the opportunities to upscale the CO_2 transport and, therefore, would be more cost-efficient. Additionally, instead of CO_2 transport from different emitters to the storage or utilisation site, the implementation of a hub can be more cost-effective in creating a shared transport infrastructure. However, the cost-effectiveness would be difficult to estimate. The implementation of collection and storage hubs is a great tool for accelerating CO_2 transport efficiency [23,67]. Here, hubs are defined as stations that are divided into collection and storage hubs, respectively. The collection hubs take in the captured CO_2 from the industrial sources, which is then transported to a storage hub that distributes the CO_2 to the storage or utilisation facilities, also known as Power-to-X (PtX) plants in countries like Germany and Denmark [67]. Fig. 6, shows an illustration of a hub system, where pipelines and trucks can transport CO_2 from the capture site to the hub depending on the economic feasibility. The CO_2 is then transported by ship or pipeline to utilisation or storage. There are aspects to consider when having a hub system, e.g., if the CO_2 should be pressurised, into a liquid, before being transported to the hub system or if the CO_2 should be transported as a gas to the hub and then pressurised. A report by the Global CCS Institute [17] showed that pressurisation at the hub was 5.55 USD/tCO_2 cheaper to operate when mixing ten gas streams before pressurisation instead of pressurising the ten streams individually and transporting them to the hub [17]. Whether this is more economically applicable for each project depends on several variables, such as the distance between the capture sites, hub, and storage sites and if the transport is done exclusively by pipeline or by a combination of pipeline, truck, and ship.

4.3. Transportation methods of CO_2

CO_2 can be transported in its gaseous, liquid, dense, or supercritical state. Some even hypothesise whether CO_2 transport in solid form by cryogenic could be more economical in some situations [106]. Without considering solid CO_2 transportation, according to several studies, gaseous transport is the least efficient and least economical transport method of all four stages due to a lower volume flow rate [45–47]. Hence, CO_2 is normally considered to be transported as either a liquid for ships, trucks, or rail transport and as a supercritical fluid for pipeline transport [27,31,46,107]. Fig. 7 shows a phase diagram of pure CO_2 with respect to temperature and pressure. When CO_2 is in its supercritical state, it has the same properties of both liquid and gas by having the same density as a liquid but having the high compressibility and low viscosity of a gas [45,108]. The liquid transport of CO_2 is operated below the critical point and above the triple point between −56.6 – 31 °C and 5.2 – 73.8 bar [100]. Conversely, pipeline transportation is operated above the critical pressure as a dense phase (below the critical temperature) or as a supercritical fluid (above the critical temperature) to avoid any liquid-to-gas phase changes [27,46]. One important factor of CO_2 pipeline transport is achieving a high density of CO_2, where a higher density indicates a higher mass of CO_2 in the same given volume [47,109]. The density and thus the mass transport of CO_2 increases with a decrease in temperature or increase in pressure [40]. For example, when transporting CO_2 as a dense phase in underground pipelines, the density can be 800 – 1000 kg/m^3 [100]. Compared to natural gas pipelines or gaseous CO_2, the mass transport is substantially greater for dense and supercritical CO_2, and therefore, a smaller pipeline dimension can be acquired to transport the same quantity of CO_2 hence reducing the material cost. However, the increased pressure when transporting dense CO_2 entails that the pipeline must have a certain wall thickness to withstand the pressure [47]. Hence, liquid CO_2 transport is more economical and efficient than gas transport, but higher safety measures have to be considered, such as the wall thickness and strict operating conditions to avoid phase changes.

4.4. Effect of impurities on CO_2 transport

Impurities, e.g., O_2, SO_x, NO_x, N_2, H_2 can affect the phase behaviour of the CO_2, induce corrosion and scaling in pipeline transportation [28,32,34,44,110]. The phase behaviour is affected by increasing the critical temperature and pressure of CO_2, whereas the non-condensable gases like O_2, Ar, N_2, H_2, and CH_4 greatly affect the phase behaviour [31,38,48,100]. Since CO_2 is often transported as a supercritical or a dense phase as discussed in Section 4.3, due to being the most efficient way of transport, the critical temperature and pressure of CO_2 are important [108]. Having these non-condensable gases in the system increases the possibility for a two-phase flow, leading to a need for higher operation pressure to maintain the dense or supercritical phase, and thus increasing the compression cost for transportation [38,41,100, 111,112]. A study by Zhao et al. [31] found that H_2 and NO_2 caused the largest deviation from the critical pressure and H_2 also caused the largest expansion of the two-phase region [31]. Additionally, even a low amount of N_2 has been shown to increase the needed compression power significantly, thus increasing the transportation costs [113]. The transportation of dense CO_2 is especially sensitive to impurities, which can impact the distance between re-pressurisation, which further increases the costs of compression power [27,113]. Besides the impurities, elevation changes can furthermore cause a pressure drop to such a degree that the pressure decreases below the dense phase region, leading to a two-phase system [27,31,114]. Therefore, pipelines typically operate at a higher pressure than the supercritical pressure while still minimising OPEX. Typically, at pressures between 83–152 bar to ensure one dense phase at every temperature, but it is not unusual to be even more in some projects [6,115]. Table 5 presents the expected composition of seven different pipelines in the USA and Canada, where the concentration of CO_2 varies from 85.0–99.7%, and the impurity that is mostly present is CH_4, ranging from 0.2–15.0% [47,48]. A pressure drop in the range 4–20% was observed across three different CO_2 transport pipelines (Cortez, Weyburn, Canyon Reef) in the USA and Canada due to the non-condensable gases (CH_4 and N_2) in the streams [40]. Even though H_2 has a heavy influence on the critical pressure and causes the highest pressure drop, it was not present in all four pipeline systems (cf. Table 5) [40,48]. The highest expected H_2O concentration is 257 ppm, which is under the two American quality specifications presented by NETL and Dynamis [48]. On the contrary, only one of the eight pipelines satisfies the Northern Light specification for the H_2O concentration, although it does not satisfy the specifications for the other compounds (cf. Table 4).

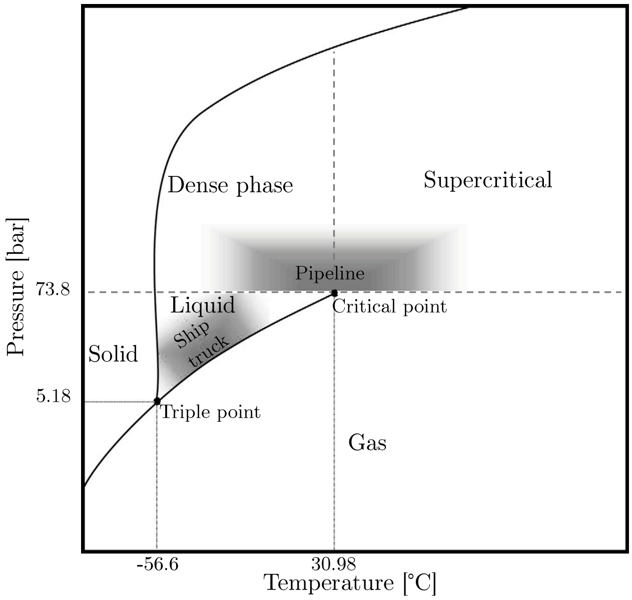

Fig. 7. Phase diagram of CO_2 together with a rough estimation of the operation areas for pipeline, ship, and truck transport indicated by the two grey boxes.

Besides the impurities effect on the phase behaviour, the impurities H_2S, SO_2, NO_x, O_2, and H_2O can induce corrosion. The problem occurs when the presence of these would form sulphuric acid (H_2SO_4), nitric acid (HNO_3), and nitrous acid (HNO_2), all of which can react with the pipeline wall and induce corrosion [42–44]. This would significantly increase the material costs of the pipeline due to a needed higher material grade. Additionally, if a lower material grade than the required is selected, corrosion may occur in the pipeline, which can

Table 5
The composition of seven operational pipelines in the USA and Canada.

	Canyon Reef Carriers (USA) [48]	Central Basin Pipeline (USA) [48]	Sheep Mountain (USA) [48]	Bravo Dome (USA) [48]	Cortez Pipeline (USA) [48]	Weyburn (Canada) [48]	Jackson Dome (USA) [48]
CO_2	85%–98%	98.5%	96.8-97.4%	99.7%	95%	96%	98.7-99.4%
H_2O	50 ppm	257 ppm	129 ppm	–	257 ppm	20 ppmv	–
O_2	–	<10 ppm	–	–	–	50 ppm	–
H_2S	<200 ppm	20 ppm	–	–	0.002%	0.9%	Trace
N_2	<0.5%	1.3%	0.6-0.9%	0.3%	4%	<300 ppm	Trace
SO_x	–	–	–	–	–	–	–
NO_x	–	–	–	–	–	–	–
CO	–	–	–	–	–	0.1%	–
NH_3	–	–	–	–	–	–	–
H_2	–	–	–	–	–	–	–
Ar	–	–	–	–	–	–	–
CH_4	2%–15%	0.2%	1.7%	–	1%–5%	0.7%	Trace

have consequences for the safety and reliability of the pipeline [28,29]. Furthermore, it is essential to limit the H_2O level in the stream to minimise the risk of hydrate formation. The hydrate formation can create additional costs to the transportation system by removing blockage and energy needed for shut-down and start-up [35–37,98]. However, the hydrate formations are normally only a concern for offshore pipelines due to lower temperatures than onshore pipelines although the hydrate formation can also be a concern for onshore pipelines if the pipeline crosses temperature regions [36]. H_2O can furthermore create a corrosive environment with acid gases (e.g., NO_2, SO_2, CO_2) [116].

The impurities can roughly be split into two groups: the corrosion-inducing impurities and the non-condensable gases that greatly affect the phase behaviour. The non-condensable gases such as O_2, Ar, N_2, H_2, and CH_4 increase the operating pressure as observed in pipelines in the USA and Canada, thus increasing the transportation costs. The corrosion-inducing impurities such as H_2S, SO_x, NO_x, O_2, and H_2O significantly increase the material costs of the pipeline, due to a needed higher material grade to withstand corrosion.

4.5. Source of impurities from CO_2 capture

As addressed in Section 4.4, the impurities in the stream can decrease the transport efficiency by increasing the energy required for compression and increase the investment cost of pipeline material to be resistant towards corrosion [31]. Thus, there is a need for quality specifications, but it is necessary to know what impurities to expect and where they are coming from. Different impurities are expected from different industries, e.g., for cement production the main components in the emitted gas are CO, NO_x, and SO_2 together with CO_2, whereas for steel production the main CO_2 emissions come from the blast furnace, where the emitted gas mainly consists of N_2, CO and CO_2 [41]. When separating CO_2 from natural gas H_2 can carry over to the CO_2 product stream due to natural gas containing significant amounts of H_2S together with CO_2 [41]. The stated composition and purity of the CO_2 depend on the source but also the capture process and can significantly impact all the subsequent stages of the CO_2 storage or utilisation processes which have been presented in Section 4.4. Fig. 8 shows the CCUS process where firstly, the CO_2 is captured from the source by, e.g., pre-combustion, post-combustion, oxy-fuel combustion, Direct Air capture (DAC), or Chemical Looping Combustion (CLC). After capture, the CO_2 is compressed before transportation by ship, pipeline, or truck to a utilisation or storage site onshore, nearshore, or offshore. The three most common technologies are post-combustion, pre-combustion, and oxy-fuel combustion, whereas DAC and CLC are promising processes that are gaining interest in many studies examining the topic [41,117–125].

In post-combustion, CO_2 is captured from the flue gas (exhaust gas), whereas in pre-combustion the CO_2 is captured before combustion [41, 48,123]. In oxy-fuel combustion, CO_2 is captured after combustion in almost pure O_2; CLC is similar, but instead, the O_2 is supplied by metal oxides also called oxygen carriers instead of a gaseous O_2 [122,123, 127]. DAC is a technology that directly captures CO_2 from the air by adsorption and releases the adsorped CO_2 again by desorption [117–119]. Table 6 shows a summary of the five technologies and the purity of the generated CO_2 stream, however, the industry where the CO_2 was captured is not stated by the specified authors in Table 6. Additionally, the values by Oosterkamp et al. [48] are the highest concentrations and not the most likely, where the levels of H_2S and SO_2 are normally lower than the stated values in Table 6. The values of post- and pre-combustion by Porter et al. [41] is a summarisation of different CO_2 capture technologies (adsorption, membrane separation, physical absorption, and cryogenic separation) and different industries. Generally, the cost of capturing CO_2 is energy-demanding and costly [128]. The purity of the CO_2 produced by post-combustion is the highest of the three conventional technologies according to the research represented in Table 6, with a purity of >99%, while the product of pre-combustion is a >95% pure CO_2 stream [41,48]. The purity and the cost of the carbon capture process by pre- and post-combustion depends on the separation method: adsorption, membrane separation, physical absorption, and cryogenic separation, where the energy requirements and purity of the stream vary significantly, cf. Table 7. Membrane separation and adsorption are less energy-requiring methods, however, this comes with a cost of the purity of 80%–90% and 80%–95%, respectively [129,130]. A higher CO_2 quality can be produced with absorption separation (90%–98% CO_2). However, the highest purity can be produced by cryogenic separation with a CO_2 purity of 95–99.99%, but at a high cost due to its energy requirement [129–131]. The main impurities generated from post-combustion are N_2 and H_2O, whereas the impurities mainly generated from pre-combustion are H_2S and H_2 (cf. Table 6) [41,48]. In the third conventional technology, oxy-fuel combustion, the purity is highly dependent on the method used (cf. Table 6), where the highest CO_2 purity is obtained through distillation 99.3–99.4% [41]. However, the high purity of CO_2 also comes with a higher energy demand [41]. The impurities with the highest concentration generated from oxy-fuel combustion are the non-condensable gases N_2 and O_2 [41,47,48].

The two other non-conventional technologies, DAC and CLC, have shown promising results in the form of the purity of the stream generated, where DAC using the high-temperature aqueous solution and the low-temperature solid sorbent method can produce a purity of 97%–100% and 88–99.9% pure CO_2, respectively [120]. The work on CLC reports that the carbon capture technology can produce a pure stream of CO_2. Although, the work on CLC and DAC in Table 6 does not report any or little information on whether the impurities were measured. The OPEX of CLC is linked to the replenishing of the oxygen carrier, where Iron(III)oxide (Fe_2O_3) has shown good capability as the oxygen carrier in CLC due to being low cost and environmentally friendly [121,122,126]. The main disadvantage of the DAC method is

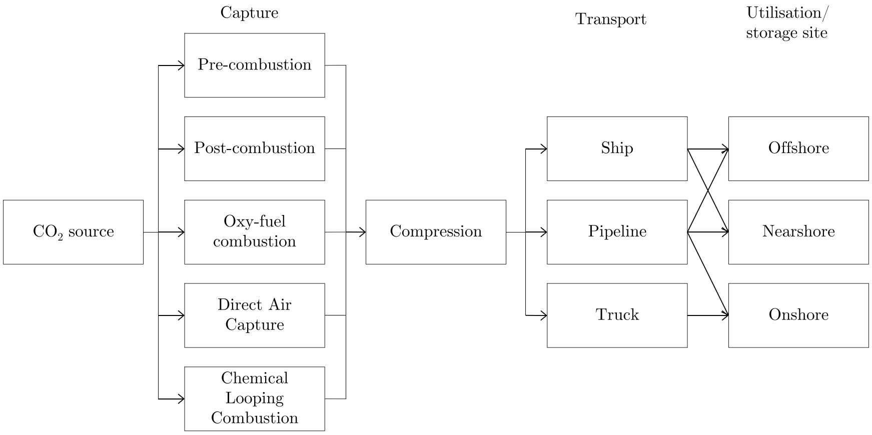

Fig. 8. The process of CCUS from capture to storage or utilisation is shown as a box diagram.

Table 6
Summary of the CO_2 purity of the five carbon capture technologies (post-combustion, pre-combustion, oxy-fuel combustion, direct air capture, and chemical looping combustion).

Technology (Source)	Post-combustion		Pre-combustion		Oxy-fuel combustion				DAC		CLC
	(Unspecified) [48]	(Unspecified) [41]	(Unspecified) [48]	(Unspecified) [41]	(Unspecified) [48]	Dehumidified [41]	Double flashing [41]	Distillation [41]	High temperature aqueous solution [120]	Low temperature solid sorbent [120]	(Unspecified) [122,125,126]
CO_2	>99%	99.6-99.8%	>95.6%	95%–99%	>90%	74.8-85.0%	95.8-96.7%	99.3-99.4%	97.1-100%	88-99.9%	>95%
CH_4	<100 ppmv	–	<350 ppmv	0-112 ppmv	–	–	–	–	–	–	–
N_2	<0.17%	0.045-0.29%	<0.6%	0.0195-1.0%	<7%	5.8-16.6%	1.6-2.03%	0.01-0.2%	–	–	–
H_2S	Trace	–	<3.4%	–	Trace	–	–	–	–	–	–
H_2O	0.01%	100-640 ppmv	0.06%	0.1-600 ppmv	–	0.01%	100-1,000 ppmv	0.0 ppmv	0.0-100 ppmv	–	–
CO	<10 ppmv	1.2-10 ppmv	<0.4%	0.0-2000 ppmv	Trace	50 ppmv	–	50 ppmv	–	–	–
O_2	<0.01%	0.015-0.0035%	Trace	0.0%	<3%	3.21-6.0%	1.05-1.2%	0.01-0.4%	–	–	–
NO_x	<50 ppmv	20.0-38.8 ppmv	–	400 ppmv	<0.25%	–	100-709 ppmv	0.0-150 ppmv	33-100 ppmv	–	–
SO_x	<10 ppmv	0.0-67.1 ppmv	–	25 ppmv	<2.5%	50-800 ppmv	0-4,500 ppmv	37-50 ppmv	–	–	–
H_2	Trace	–	<3%	20-30,000 ppmv	Trace	–	–	–	–	–	–
Ar	Trace	0.0011-0.021%	0.05%	0.0001-0.15%	<5%	2.3-4.47%	0.4-0.61%	0.01-0.1%	–	–	–
H_2S/COS	–	–	–	0.2-34,000 ppmv	–	–	–	–	–	–	–

Table 7
The energy requirements and CO_2 purity of absorption, adsorption, membrane and cryonic separation methods for the post- and pre-combustion technology (data extracted from [129,130], basing their numbers on comparing different studies).

	Absorption	Adsorption	Membrane	Cryonic
Purity	90%–98%	80%–95%	80%–90%	95-99.99%
Energy requirement [MJ/kg CO_2]	4–6	2–3	0.5–6	6-10

its high energy consumption due to the energy needed to release CO_2 after adsorption [23,100,119,120]. Regardless, the Global CCS Institute states that development in the DAC technology can be an insurance towards net-zero [70]. The IEA [23,132] has made a cost analysis, but instead of looking at capture technologies, they focused on the sector from which the CO_2 is captured. The lower cost of carbon capture was connected to a more concentrated CO_2 stream, e.g., in natural gas processing and syngas generation. On the contrary, a higher cost was seen in steel or cement production, power generation, or capturing CO_2 from the air using DAC, showing that DAC was by far the most expensive [23,132]. Choosing between the different capture methods is a question of the quality specification that must be fulfilled. This puts the design of a national infrastructure into a dilemma, where the choice between a higher purity of CO_2 or a higher material grade for the transportation infrastructure will be a choice between a higher cost for the industry if a higher purity is chosen. On the contrary, if a higher material grade is decided, it will come with a lower cost for the industry but an increased cost of establishing the infrastructure. Additionally, stricter requirements of the CO_2 can create issues for smaller industries and, in the worst case, end up shutting down the industry.

5. Conclusion and proposed future actions

In this work, the gaps in knowledge associated with the design, operation, and financing of CO_2 transportation have been identified and discussed. Currently, the CO_2 transportation accounts for ~25% of the total CCUS expenses. So far, no national or international regulation or common practice exists that determines the quality of CO_2 for transportation, which will be essential to establishing a safe and economic infrastructure. Many projects are proof of concept, meaning that they follow a low impurity CO_2 quality standard, whereas today's regulations and practices are point-to-point or project-specific and do not specify the same compounds or levels of restriction. However, there is a tendency to follow the Northern Light quality specifications in Europe in the absence of a national or international standard, even though it is very conservative, which increases the expenditures for industrial emitters having to purify their CO_2. The carbon trading system is believed to increase the investment in CCUS, however, it comes with challenges and limitations. The challenges are outsourcing businesses to countries without an implemented carbon tax or businesses not keeping up with the carbon tax and having to shut down. The limitations are that it is difficult to measure the exact concentration of CO_2 produced and, therefore, difficult to resolve the carbon tax. There are two types of impurities, the non-condensable gases, which increase the energy cost for pressurisation of the CO_2, and the corrosion-inducing impurities. The design of a national infrastructure will be a choice between a higher purity of CO_2 or a higher material quality, where the choice of higher purity will become an increased cost for the industry.

This work addresses the challenges of transitioning from point-to-point transportation to a shared infrastructure (e.g., hubs) that is a more cost-effective way of transporting CO_2, therefore more feasible. The following proposed future actions have been formulated:

1. Form a common CO_2 quality specification for the impurities that may be in the CO_2 stream to reduce the risk of corrosion and scaling. This must, however, be done with the industries in mind, as high-quality CO_2 has a substantial financial impact due to the need for costly separation processes. The level to which each impurity must be removed from the CO_2 stream depends upon several factors, such as corrosivity, process requirements, toxicity, and geological storage constraints.
2. A material selection based on the specified CO_2 quality specification to reduce the risk of corrosion. A cost-effective approach for testing the quality of materials can partly be conducted on a laboratory scale. This can provide valuable information about the materials' properties and help establish specifications for the material used in CCUS transportation.
3. Decide if the transportation should be conducted through pipelines or ships, together with the operating conditions, such as temperature and pressure, to achieve the desired phase needed. This is followed by deciding the material thickness to be able to withstand the conditions. The best method of transportation should be selected based on a thorough analysis of the cost and benefits of each option, i.e., considering the benefits of including hubs.

It can be discussed if some challenges can be resolved simultaneously or switch up the order so that the material is specified first and then the CO_2 specification. This should only be seen as a guideline to decrease the obstacles in designing an international infrastructure instead of having point-to-point specific cases.

Based on the investigation in this work, it is predicted that the CCUS industry can become more economically feasible in the future if the addressed challenges are solved. However, some of the challenges are difficult to solve due to political aspects and various national economic interests and, hence, demand further international collaboration.

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CRediT authorship contribution statement

Kenneth René Simonsen: Conceptualisation, Writing – review & editing, Visualisation, Data treatment. **Dennis Severin Hansen:** Conceptualisation, Review and editing, Funding acquisition. **Simon Pedersen:** Conceptualisation, Review and editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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