



A Trans-European CO₂ Transportation Infrastructure for CCUS: Opportunities & Challenges


June 2020

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This document has been prepared on behalf of the Advisory Council of the European Zero Emission Technology and Innovation Platform (ETIP ZEP). ZEP exists to advise the European Commission on Carbon Capture Utilisation and Storage Technologies and associated policies. The information and views contained in this document are the collective view of the Advisory Council and not of individual members, or of the European Commission. Neither the Advisory Council, the European Commission, nor any person acting on their behalf, is responsible for the use that might be made of the information contained in this publication.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 826051

Executive Summary

Setting the scene

In December 2019, the newly appointed European Commission released communication on the European Green Deal¹, outlining a comprehensive policy initiative to lead the pathway towards a low-carbon continent by 2050. President Ursula von der Leyen defined it as Europe's growth and climate strategy. Other communications, such as the proposed European Climate Law for climate neutrality by 2050, followed and set the ambitious target of net-zero greenhouse gas (GHG) emissions by 2050 across all economic sectors in the European Union. Additionally, the European Taxonomy for Sustainable Finance provided a list of economic activities that will comply with 2050 climate neutrality, citing carbon capture and storage (CCS) among these activities and listing the retrofitting of natural gas pipelines for carbon dioxide (CO₂) and hydrogen transportation as a net-zero compliant economic activity.

The European Climate Law and the European Taxonomy are real turning points. The European Union's target of net-zero GHG emissions by 2050 will require the deployment of a wide range of low-carbon, readily available technologies such as CCS and carbon capture utilisation and storage (CCUS). Existing regulations and directives – such as the Trans-European Network for Energy (TEN-E) regulation, the

EU Emissions Trading System (ETS), the Innovation Fund – and upcoming European strategies – such as the Strategy for Integrated Energy Systems and Hydrogen – are likely to extend their scope, encompassing all low-carbon technologies that can support the EU's climate objectives.

Relevance and mission

CCS and CCUS applications can make a significant contribution to climate change mitigation. Their potential for carbon emissions abatement and removal is scientifically proven and acknowledged by the European Taxonomy for Sustainable Finance² and the Clean Planet for All³ reference scenarios. Commercial, full-chain CCS projects have been operational since the 1980s, with more than 260 million tonnes of CO₂ emissions from human activity being captured and stored over 40 years, with an estimated 40 million tonnes of CO₂ captured and stored per year⁴ today. When applied to industrial processes and power plants, CCS can also preserve and decarbonise existing energy-intensive value chains, which lie at the core of the European economy and provide products that are the basis of our lifestyle. By preserving these industrial value chains, CCS/CCUS can help create and secure jobs, and maintain European industrial competitiveness in international markets whilst moving through the energy transition.

¹ European Commission, [Communication on European Green Deal](#), 2019

² European Commission, [Taxonomy Report: Technical Annex](#), 2019

³ European Commission, [A Clean Planet for All](#), 2018

⁴ Global CCS Institute, [2019 Global Status of CCS Report](#), 2019

Investing in the large-scale deployment of CO₂ transportation and storage infrastructure will be a strategic and instrumental policy decision, necessary to reach the EU's climate objective – future-proofing Europe for a global low-carbon economy. As several large-scale CO₂ capture projects are near-ready, a CO₂ transportation network and storage infrastructure would connect CO₂ emitters in industrial clusters and power plants to storage sites and enable a timely and extensive decarbonisation needed to meet the net-zero target.

Europe benefits from privileged conditions. The North Sea basin area is a world-class region for storage; industrial clusters – such as those around the Ports of Rotterdam, Antwerp, Amsterdam, Le Havre, Dunkerque, and the North Sea Port, as well as the Ruhr, Cork, Teesside, Yorkshire, Humber, North West, South Wales and Grangemouth regions – would be able to capture CO₂ from industrial processes and power plants and use CO₂ transportation networks and storage infrastructure to securely store the CO₂ under the North Sea.⁵

Securing political support for the five cross-border CO₂ Projects of Common Interest⁶ (PCI) is vital. These projects are on the right track to become operational before 2025. A solid policy framework providing a degree of predictability for long-term investments should be a priority for European policymakers. CO₂ infrastructure projects call for European legislators to extend the scope of existing legislation – such as the TEN-E regulation and EU ETS directive – to prepare for the rollout of CO₂ and clean hydrogen infrastructure. As rightfully indicated in the European Taxonomy for Sustainable Finance, all modes of CO₂ transportation to permanent geological storage – pipeline, ship, barge, train, truck – should be allowed. This outcome is critical and should be reflected in revised TEN-E regulation and EU ETS directive, as it will allow near-ready CO₂ transport and storage projects to be realised and to create

opportunities for numerous CO₂ emitters throughout the entire EU area to have access to low-cost decarbonisation pathways.

Content

The report “A Trans-European CO₂ Transportation Infrastructure for CCUS: Opportunities & Challenges” aims to provide a technical overview on CO₂ transportation, in particular the use of pipeline networks in industrial clusters, and it stresses the importance of developing dedicated business models for CO₂ transportation.

The report highlights the need for further development of the key principles underpinning the development of CO₂ transportation pipelines and large-scale deployment and identifies legal barriers to CO₂ pipeline transportation. While the role of CCS/CCUS and its contribution towards mitigating climate change are acknowledged, a strong signal from European policymakers in support of European cross-border CO₂ infrastructure will be necessary.

- Chapter 1 highlights the opportunities and the challenges namely, how to roll out cross-border CO₂ transportation and storage infrastructure.
- Chapter 2 reviews the main features of some of the main operational and planned CCUS projects in Europe to demonstrate the high level of technical maturity already achieved.
- Chapter 3 develops throughout several subchapters. Technical matters around operational aspects of CO₂ pipeline transportation are addressed in five separate subchapters. Subchapter 6 expands on marine transportation of CO₂, a key element of some European CO₂ transport and storage projects that are being developed.
- Chapter 4 addresses three overarching topics: the need for a better understanding

⁵ Zero Emissions Platform, [Identifying and Developing European CCS Industrial Hubs](#), 2016

⁶ European Commission, [Fourth list of Projects of Common Interest](#), 2019

of the properties of CO₂-rich mixtures, the need for business models for CO₂ transportation networks and, finally, legal and regulatory aspects.

Conclusions

The report concludes that the transportation of CO₂ by pipeline and ship is technically feasible, as demonstrated through operating CCS projects and upcoming ones. Further development of knowledge and operational experience, along with dedicated business models to encourage investment, will help optimise the design, construction and operation of CO₂ transportation networks.

The report establishes that cross-border CO₂ transportation infrastructure has a major role to play in delivering a cost-efficient transition to a low-carbon economy. Developing such infrastructure at large-scale presents challenges from a technical, legal and economic perspective, but it can equally unlock many opportunities for the decarbonisation of core sectors of the European economy, industry, power generation to preserve their production, to safeguard jobs and to create new, sustainable economic growth. It will also play a key part in establishing CCUS industrial clusters as a game changer in mitigating global warming.

For the European Union, CO₂ infrastructure is a no-regret investment opportunity that would support the production of early, large volumes of low-carbon hydrogen and deliver CO₂ removal, allowing the EU to become a global leader in low-carbon economic growth and paving the way for a clean hydrogen economy.

Policy recommendations

Building on the findings of the technical report and discussions with members and partners, ZEP would like to put forward the following policy recommendations:

- All CO₂ transport modalities – pipelines, ship, barge, truck, and train should be included in the revised TEN-E regulation, allowing for all European regions and

industries to connect to the European infrastructure and thus be eligible for funding under Connecting Europe Facilities (CEF). This should (as is the case in the European Taxonomy for Sustainable Finance) also be harmonised in relevant pieces of legislation connected to the TEN-E regulation such as the EU ETS and funding programmes.

- In the revised TEN-E regulation, CO₂ storage should be included as an essential component of a CCS/CCUS project and as part of the CO₂ infrastructure. CO₂ storage is a key element, as it delivers real climate change mitigation.
- Once cross-border CO₂ infrastructure is in place, the production of early volumes of low-carbon hydrogen from natural gas with CCS can be initiated, paving the way for a clean hydrogen economy by securing a stable hydrogen supply from beginning on.
- A revised TEN-E regulation should include the development of hydrogen pipeline networks. This will support the production and transportation of hydrogen, supporting EU's decarbonisation pathway.
- Repurposing and retrofitting of natural gas pipeline networks for the transportation of CO₂ and clean hydrogen should be included in revised TEN-E regulation.
- In order to create a level playing field and the conditions for long-term investments for CO₂ emitters across Europe, at the least non-discriminatory third-party access to cross-border CO₂ transportation and storage infrastructure should be regulated.
- As the revised TEN-E regulation will drive the selection of the Projects of Common Interest (PCI), it is vital to ensure that the next PCI lists are in compliance with climate neutrality by 2050, creating opportunities for cross-border CO₂ and hydrogen infrastructure projects to be further developed and scaled up.

- Funding mechanisms such as the Connecting Europe Facilities (CEF) and the EU ETS Innovation Fund should consider these principles.

A revised TEN-E regulation should ultimately drive the transition towards a low-carbon economy, capitalising on the potential and opportunities of large-scale decarbonisation of European industrial and energy sectors.

Technical Summary and R&D Recommendations

A number of carbon dioxide (CO₂) transportation and storage projects are in operation within Europe. In Norway two projects are operational; Sleipner and Snøhvit, injecting at rates of about 1 million tonnes of CO₂ per year into saline aquifers which have been operational since 1996 and 2008 respectively. Several Carbon Capture and Storage (CCS) projects are being developed that connect onshore capture facilities to offshore geological storage locations. These include Northern Lights (also in Norway), Porthos and Athos (The Netherlands), ERVIA (Ireland) and ACORN and HyNet (both in the UK). Several of these new projects plan to start transportation and injection activities well before 2030 and are planned to operate at a scale of the order of 1 million tonnes of CO₂ captured per year.

Most of the aforementioned projects use or plan to use high-pressure CO₂ transportation pipelines operating at pressures in the range of 80 -110 bar. Transport by ship is an integral part of the Northern Lights project (Norway) and a key element of the ERVIA project (Ireland).

These projects demonstrate that in the CCS chain, CO₂ transportation and storage are key technologies that are sufficiently mature to be used at commercial scale. In principle, there are few technical barriers to implementing large-scale CO₂ transportation.

In the past, CCS has largely focussed on power plants as large point sources of CO₂ emissions. Consequently, in many cases the focus for transportation has been on '*point to point*' type arrangements, i.e. from the CO₂ source to a storage site.

To meet the challenging net-zero emissions target set in 2018, according to the IPCC report⁷ ratified by the EU and many other countries under the Paris Agreement, the focus across Europe has now shifted to the decarbonisation of large industrial clusters. Capturing, collecting, transporting, utilising and storing CO₂ from such industrial clusters (CCUS) represents new challenges as it involves CO₂ streams with different compositions, flow rates and intermittency and with possibly varying capture technologies requiring the development of safe, resilient and cost effective CO₂ transportation networks. Given the economies of scale, shared high-pressure pipelines will likely be the backbone of such networks, although gaseous phase transportation at lower pressures and ship transport to and from strategic hubs and to remote offshore storage sites will also have a key role to play.

Facilitating the technical and commercial operation of such networks under clear legal frameworks, along with fully developed business models and regulatory structures, needs to be the focus of further CO₂ transportation development. Success here will accelerate the large-scale role out of CCUS

⁷ <https://www.ipcc.ch/sr15/>

as investors will be more willing to invest in capture plants and storage sites where there is certainty regarding the availability of viable transportation infrastructure. *The feasibility of industrial CO₂ transport networks needs to be demonstrated as soon as possible to gain technical experience and to strengthen confidence in this solution.*

A central requirement for the efficient, safe design and operation of CO₂ pipeline transportation networks is the accurate transient flow modelling of fluid phase and composition of the CO₂ rich mixture along the pipeline network and at the point of injection into the storage site. Such capability will allow the real-time control of CO₂ impurities tolerance levels from each emission source, smooth out flow fluctuations through line sizing and avoid 2-phase flows to prevent compressor operation issues and large pressure drops.

Multi-source pipeline network models aimed at addressing the above have been developed. However, these require extending to account for fluctuating CO₂ mixture compositions and CO₂ supply taking account of the feedback from the injection site.

The careful control of the pressurised CO₂ injected into low-pressure gas fields is important in order to avoid operational issues such as blockages of the well along its length or of the bottom-well perforations due to solid CO₂ (dry ice), water ice or hydrate formation. Saline aquifers and depleted gas or oil fields are considered as prime targets for CO₂ storage. Apart from considerable storage capacity, depleted fields are especially attractive given the possibility of utilising existing pipeline and platform infrastructure if practicable, thus reducing capital costs.

Taking account of the well design and the storage geology, excellent progress has been made in developing fully coupled fluid/structure interaction models to propose optimum stepwise injection protocols to minimise such risks. However, these models need to be extended to handle impurities in

the CO₂ stream and to cover the full range of flow regimes occurring along the injection well. In addition, the validation of such models based on realistic-scale tests is necessary in order to gain credibility.

The use of existing natural gas pipelines and offshore platforms is an attractive option for CO₂, since these significantly reduce initial infrastructure costs. However, this will entail a detailed assessment of design and construction requirements to establish if they are suitable for use with a different product and potentially at different operating conditions.

Such assessment will need to consider several key areas. These include the impact of the phase behaviour of CO₂ on the design and operation of the existing facilities, safety design factor limits, identification and probability of failure/damage/deterioration mechanisms with CO₂ at the proposed operating conditions, hazard distances and an evaluation of consequences, individual and societal risks posed. The assessment will need to demonstrate that the risks posed under changed operational conditions satisfy the ALARP (As Low As Reasonably Practicable) principle.

The necessary assessments are complex and require detailed technical information on the existing pipeline, as well as on aspects such as population density around the pipeline. General statements are difficult if not impossible, case by case assessments are therefore required. The development of clear technical criteria, social acceptability / mechanisms for public participation, and regulatory framework should be addressed.

Any assessment of existing or new pipelines needs to include a detailed consideration of fracture control. Pipelines transporting pressurised compressible fluids must be designed so that a defect does not lead to a long running ductile fracture. For natural gas, this is done using empirical correlations which have been found not to work well for CO₂ given its unique phase equilibrium behaviour. At present, engineers take care of this by performing full-scale

experiments and using safety factors.

The challenge is to develop physics-based design tools that will prevent over-designing to ensure pipeline safety. These design tools should take into account the properties of CO₂ and CO₂-rich mixtures as well as for modern pipeline steels.

Identifying the appropriate size of the pipelines required for a CO₂ transportation network is a challenging and complex task that has to balance a wide range of factors whilst ensuring assets are not under or over utilised.

Important considerations that must be taken into account during the design stage include the inevitable change in the energy supply landscape arising from the co-deployment of intermittent renewable energy generators, additional emitters joining CCUS industrial clusters as decarbonisation progresses and business models being in place, accounting for the rate of return on investment and the approach taken to pre-investment options.

Further work should address the combination of scenarios relating to changes in future energy supply mix and industrial landscapes alongside the development of CO₂ pipeline transport networks.

An important pre-condition for the long-time integrity of pipelines is the avoidance of internal corrosive phases. Defining a suitable operating regime which limits the possibility of corrosion in complex transportation networks is challenging. The number of possible impurity combinations and operational conditions (pressure, temperature, flow velocities) could be large in CO₂ streams with different compositions commingling. The purity of the CO₂ is affected not only by the various types of capture technologies and processes, but also by economics (i.e. the increased cost associated with the removal of impurities to low levels), legislative and regulatory requirements, specifications and safety considerations. There is currently insufficient operational data available in Europe to derive a failure rate based on operational experience of CO₂ pipelines, so unless the transported CO₂ is confirmed not to precipitate corrosive aqueous

phases, application of a high internal corrosion failure rate would be expected. The quality requirements specified should engineer out potential problems relating to the failure scenario due to internal corrosion through the control of the impurity levels, such as water (H₂O), hydrogen sulphide (H₂S), and oxides of sulphur and nitrogen (SO_x and NO_x), and traces of capture agents like amines and ammonia (NH₃) while accommodating the various carbon capture technologies and impurities resulting from these capture technologies. The phase envelope needs to be considered to ensure single-phase transportation during normal operation; 'non-condensable' components in the CO₂ stream change the phase envelope.

Whilst there has been significant research on vapour-liquid equilibria that are critical for gaseous phase transportation, liquid-liquid equilibria with one aqueous corrosive phase may pose a challenge for liquid phase transportation. Beside this, the geological interaction of impurities within the storage site is complex, resulting in CO₂ composition specifications that are different to those tolerated in the pipeline. Such complex interactions must be better understood under the framework of techno-economic assessments with safety being the overarching factor.

Routine analyses will be required to verify that the CO₂ stream compositions comply with the approved CO₂ specifications for the pipeline transportation network and the storage site. A monitoring plan must be set up and sampling procedures and instrumentation will have to be developed, evaluated, calibrated, certified and be routinely inspected and maintained.

Real-time measurement techniques are needed to enable the close monitoring of CO₂ compositions at strategic locations along the pipeline network and quickly take measures in case a CO₂ source delivers out of specification CO₂. At the same time, understanding the impact of impurities that may react to form new species and separate aqueous phases on such measurements is important.

Ship transport will likely be an important element of CO₂ transportation networks. Small scale ship transportation of food grade CO₂ (mostly 1,000-2,000 tonnes) has taken place for decades. Larger-scale ship transport is considered particularly relevant for transportation to offshore Enhance Oil Recovery (EOR) sites or for collecting CO₂ from industrial sources along rivers. Small-scale ship transport relies on high-pressure CO₂ at temperatures close to ambient (45-60 bar, 10-22 °C). However, in the recent literature there is a consensus that low-pressure and low temperature (6-8 bar, about -50 °C) is the techno-economically optimal condition for large-scale transportation. For an economic operation the allowable concentration of impurities specified needs to be as high as tolerable with regard to phase behaviour – this requires an improved understanding of the impact of impurities on the properties of liquid CO₂ and precipitated aqueous phases at low temperatures. Existing loading and offloading systems can likely be adapted to large-scale LCO₂ transport.

Current design codes for Liquefied Petroleum Gas (LPG) and Liquefied Natural Gas (LNG) tankers do not cover the transport of liquid CO₂ (LCO₂), as the pressure and density ranges are different. Such codes need to be developed.

Accurate mass flow metering is critical in CCUS cluster networks to ensure appropriate allocation of costs and flows between sources and the storage site. The large volumes, high values and possible taxes/payments involved make this a fiscal application. Several fiscal metering standards and directives specify varying requirements for CO₂ measurement but there is not a dedicated standard that prescribes a uniform approach. Orifice plates, ultrasonic and Coriolis flow meters have been identified as potential technologies for CCUS applications. Each of these meter types has both strengths and limitations; none are suitable for multi-phase flows. Accurate knowledge of density and acoustic properties of the CO₂ rich mixture are required at least for orifice plates and ultrasonic flow meters.

Testing the different technologies with representative CO₂ compositions and flow rates is necessary to determine the best metering solution. The key enabler for this and the eventual formulation of industry standards is a large-scale test facility for CCUS pipeline and metering technologies. Such a facility is not yet available.

Thermodynamic properties of CO₂ transported at liquid state are substantially different from properties of natural gas or LNG. Uncertainty and complexity of property models are greater than for the transportation at gaseous states and the impact even of minor impurities can be relevant. The influence of 'non-condensable' components like nitrogen (N₂), argon (Ar) or oxygen (O₂), which are typical for oxyfuel capture processes, can be described with sufficient accuracy. Only the sufficiently accurate description of mixtures containing hydrogen (H₂) is still a challenge. The accurate description of mixtures containing minor components like H₂O, H₂S, O₂, SO_x, NO_x, CO, monoethanolamine (MEA), diethanolamine (DEA) and ammonia (NH₃) is challenging as well. For direct connections from sources to storage sites with essentially a constant composition, resulting engineering problems can be solved – if necessary, by strict limits on the allowable concentrations of impurities. In pipeline networks connecting multiple sources of CO₂ captured with different technologies, the composition of the resulting mixture will vary over time. To avoid overly strict and correspondingly expensive requirements on the purity of the supplied CO₂, an improved prediction of relevant phase equilibria would be required. In CO₂ pipeline networks, accurate custody transfer and the avoidance of allocation errors require similar level of accuracies for composition, single-phase density and speed of sound determination as those currently available for natural gas transported in comparable networks. Such level of accuracy has not yet been achieved for the CO₂-rich mixtures typical in CCUS applications.

Thermophysical property models need to be improved to provide a sufficiently accurate and consistent prediction of vapour-liquid (VLE), liquid-

liquid (LLE), and solid-liquid equilibria (SLE). A data base needs to be established that allows both for development and validation of such models.

The development of appropriate business models for CO₂ transportation infrastructure is one of the key enabling requirements for the successful rollout of CCUS industrial clusters.

The CO₂ transportation market will likely be determined by a monopolistic structure due to the significant up-front capital costs of transportation and storage (T&S) infrastructure, high operational costs for shipping, a lack of commercial incentives for T&S infrastructure development and operation and uncertainty regarding long-term storage liability. Other factors include lacking regulatory frameworks for onshore CO₂ transportation, and coordination and timing alignment with capture and storage. Key business model options for T&S deployment in Europe include Regulated Asset Base where the costs of projects are tightly regulated and passed to the emitter as T&S fees, Public Ownership models or Public Private Partnerships models, where the ownership of T&S infrastructure is shared between the public and the private sector.

Challenges include feasible business models for CO₂ ship transport and road/rail transport infrastructure for dispersed industrial sites (e.g. cement and lime) that may require linking to industrial clusters or pipeline networks.

In order to meet decarbonisation targets across the EU, it will be necessary to extend deployment of CCUS to small emitters (less than 0.5 million tonnes of CO₂ per year) and to stranded emitters for which direct connection to a pipeline transportation network infrastructure may not be feasible. In the case of UK for example, small emitters such as hydrogen production plants, refineries, gas fired process heaters, paper and food industries account for as much as 30% of the overall CO₂ emissions. Indeed, for some of these emitters, the cost incurred in providing transportation infrastructure may be so high that in order to decarbonise, the relocation of operations may be preferable.

Various transportation options, including the use of low-pressure pipelines connecting to the CCUS transportation cluster network, trucks and rail, alongside business models and socio-economic aspects for decarbonising small and stranded emitters must be investigated. An important consideration is the cost of capture which may be disproportionately high.

The current legal situation is not well developed for the installation and operation of cross border CO₂ pipeline networks.

Yet, these issues can be resolved in time as long as a strong political signal is given by policy makers. A promising example is the now possible application of the 2009 amendment to the London Protocol, which enables the export of CO₂ for offshore storage, provided the exporting and the receiving countries mutually agree on the application of the amendment. The current legal framework for CO₂ pipelines rather hinders a coordination of requirements, e.g., on the composition of different CO₂ streams than supports it. Appropriate coordination mechanisms are primarily relevant for the operation of pipeline networks, in which different CO₂ streams are mingled. With regard to possible issues due to differing national legal requirements, there are no relevant specific requirements for CO₂ pipelines in place yet. This is not necessarily an advantage, because in the absence of clear provisions, different national approaches will likely be applied.

Clear legislative rules for CO₂ pipelines at least on a European level should now be developed so that any changes in the design and operation of pipelines crossing borders become unnecessary.

Conclusion

It is clear that the transportation of CO₂ rich mixtures in 'point to point' type pipelines and also in transportation networks using pipelines and ships is technically feasible, as evidenced by existing operating CCS projects and those under development. Further development of knowledge and operational experience along with dedicated business models to encourage investment will help

optimise the design, construction and operation of CO₂ transportation networks. At the same time, co-operation between Member States is needed to create a legal framework to support cross-border transportation. Such concerted effort will play a key part in establishing CCUS industrial clusters as

a game changer in mitigating global warming and facilitating industrial decarbonisation with Europe setting the pace as the front runner.

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1. Introduction

Carbon Capture Utilisation and Storage (CCUS) industrial clusters involve the capture of carbon dioxide (CO₂) from a variety of energy intensive industrial emission sources, followed by its storage, and where possible, utilisation using a shared CO₂ transportation infrastructure. In the UK for example, it is estimated that CCUS could provide up to 37% of the total CO₂ abatement potential by 2050 (Department for Business Energy and Industrial Strategy, July 2019).

Despite its importance, as of 2020, there are only a few CCUS facilities operating in Europe (Global CCS Institute database); examples are the Sleipner and Snøhvit operations (Norway; natural gas processing; CO₂ stored in an offshore storage site⁸), Port Jerome (France: hydrogen production; CO₂ utilised⁹) and OCAP (Netherlands, Organic Carbon dioxide for Assimilation of Plants which collects CO₂ from industrial sources and delivers to greenhouses) (IOGP, May 2019).

Currently the majority of CCUS operations are located in the United States (IEAGHG, January 2014); the largest being the Cortez (with 24 million tonnes of CO₂ per annum (Mtpa) capacity) and the Central Basin (27 Mtpa capacity) CO₂ clusters. These have been developed on an ad-hoc basis, with each cluster having its own standards for CO₂ purity, and operating pressure and temperature.

In order to accelerate the development of CO₂ infrastructure in Europe, the European Commission has recently widened the scope for Projects of Common Interest (PCIs) to include CO₂ transportation pipelines, opening the Connecting Europe Facility (CEF) funding (INEA, 2019) scheme to CCUS. Five cross border CO₂ transportation networks are currently on the fourth PCI list (European Commission, October 2019).

Table 1. Industrial CCUS clusters in Europe

Industrial cluster/region	CO ₂ emitted (Mtpa)	Reference
Antwerp (BE)	18	(IOGP, May 2019)
Skagerrak/Kattegat (North Sea)	14	(IOGP, May 2019)
Marseille (FR)	35.5	(IOGP, May 2019)
Le Havre (FR)	14.5	(IOGP, May 2019)
Firth of Forth (UK)	7.6	(IOGP, May 2019)
Yorkshire & Humber (UK)	72.4	(IOGP, May 2019)
Rotterdam (NL)	17.5	(IOGP, May 2019)
Teesside (UK)	3.1	(Industrial Strategy, 2019)
Grangemouth (UK)	4.3	(Industrial Strategy, 2019)
North Rhine-Westphalia (GER)	30.5	(Viebahn <i>et al.</i> , 2009)
North Sea Port (BE)	21.5	(C4U H2020 Project, 2020)
Oltenia Region (ROM)	24.5	(AGERPRES, 2012)

With a total capacity for handling up to 10 Mtpa CO₂ by 2030, the CO₂TransPorts PCI is the largest, intending to develop infrastructure to facilitate large-scale CCUS at emission sources in three of the most important Dutch and Belgian ports: the ports

⁸ <https://www.ice.org.uk/knowledge-and-resources/case-studies/sleipner-carbon-capture-storage-project>

⁹ <https://chemicalparks.eu/parks/port-jerome>

of Rotterdam, Antwerp and Terneuzen.

In several industrial regions in Europe, the deployment of CO₂ capture is being considered, with plans for CO₂ transportation and storage networks being at various levels of development. Table 1 lists these along with their total estimated CO₂ capture potential per annum.

1.1 The Challenge

The large-scale implementation of CCUS clusters in Europe will require the development of appropriate infrastructure capable of transporting significant quantities of captured CO₂ for geological storage. In the majority of cases, the most practical and economic mode of transportation involves the use of shared high-pressure pipeline networks, although on occasions, the use of ship transportation, such as that for the Northern Lights project in Norway¹⁰ may be the more cost effective option.

A number of studies have proposed such networks.

An example is given in Figure 1 for a European CO₂ pipeline network infrastructure by the year 2050. An important conclusion of the study was that the required rate of growth to reach the projected transport is within the reach of current network pipeline development industry (Neele, et al., 2011).

The physical properties of CO₂ differ from those of natural gas, creating some important design and operational challenges. For example, the most practical cost-effective option for transporting CO₂ is at high-pressure in the dense or liquid phase, i.e. above 75 bar given the lower pressure drop along the pipeline as compared to transporting the CO₂ in the gaseous phase. However, this requires pipelines to operate at higher pressures than most existing natural gas pipelines, whilst requiring low levels of stream impurities. Water concentrations and other impurities (e.g hydrogen sulphide (H₂S) and oxygen (O₂), and oxides of sulphur and nitrogen (e.g SO_x and NO_x)) facilitating precipitation of aqueous phases, have to be very low (p.p.m) to avoid corrosion. Concentrations of non-condensable

Offshore-only scenario 2050

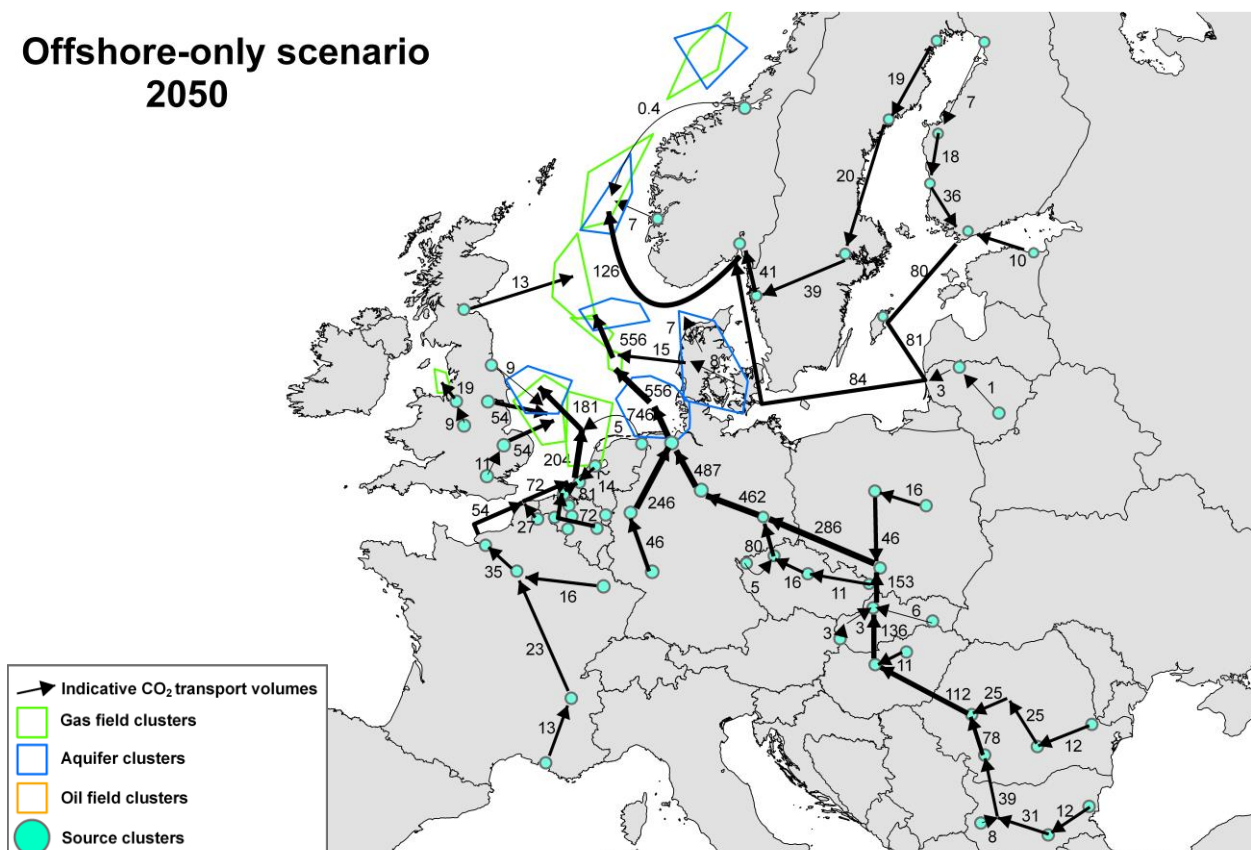


Figure 1. Transport corridors and corresponding CO₂ amounts (in units of Mtpa), for the year 2050, assuming only offshore storage (Neele et al., 2011).

¹⁰ <https://northernlightsccs.com/en/>

gases such as nitrogen (N₂) or hydrogen (H₂) should be low to avoid two-phase flow resulting in compressor/pump issues, and also to avoid the use of pipeline materials with high fracture toughness. Given that CO₂ at high concentrations is hazardous (at concentrations about 25% or more by volume, asphyxiation can occur rapidly (Harper, et al., 2011)), there are also important safety concerns in the unlikely event of an accidental release.

It should be noted, however, that pipeline transportation of CO₂ is a relatively well-established technology. Most of the CO₂ pipelines currently in operation are in the US where more than 7000 km of CO₂ pipelines have been in operation for almost four decades (e.g. IEAGHG, January 2014). These pipelines mostly transport CO₂ from natural sources for Enhanced Oil Recovery (EOR).

CCUS cluster pipeline networks are significantly more complex, presenting a new set of challenges. Such networks take CO₂ from a variety of sources, which are characterised by varying flow rates, process conditions and compositions. These flows are blended and delivered to one or more, potentially quite different storage sites. CO₂ impurities that may be tolerated in the pipeline, may not necessarily be acceptable for a storage site even if present in relatively small proportions given their long-term cumulative effects (Porter et al., 2016).

1.2 Aims and Objectives

Clear and actionable plans are needed for the development of CO₂ pipeline transportation networks to support the rollout of CCUS for industrial clusters in Europe.

This report presents an overview of the state-of-the-art, the opportunities along with remaining research and development topics that must be undertaken to facilitate the timely rollout of CO₂ transport networks to enable CCUS for industrial clusters. Onshore, high-pressure CO₂ pipelines may require updated regulations in some Member States. The report also considers the harmonisation of such regulations to enable cross-border projects along with business models needed to facilitate public and private investment whilst minimising the financial risks.

While the main focus of the report is on CO₂ transportation by pipeline, ship transportation is also considered as an alternative mode of transportation.

Working closely with the transport subgroup of European Energy Research Alliance (EERA) CCS¹¹, to ensure its credibility and relevance, the report includes contributions from key industry stakeholders, academia, ISO groups, regulatory and policy bodies.

1.3 Reading Guide

This report is laid out as follows.

Chapter 2 places the report into context by providing an overview of a number of CCUS projects in Europe, covering those currently operating, those under development along with those approved for implementation.

Chapter 3 highlights the main technical and operational challenges related to the implementation of CO₂ transportation networks in industrial CCUS clusters.

The impurities in the CO₂ stream depend on the type of fuel used and the type of capture technology employed. In the case of a power plant, the composition of the exhaust CO₂-rich mixture may be considered to be relatively fixed and known. This is different in industrial clusters. Section 3.1 deals with the issues associated with handling multi-source CO₂ streams in an industrial cluster, where CO₂-rich mixtures result from different fuel types and processes, captured using different technologies, and processed in different ways. While some of the CO₂ sources will yield a relatively constant flow, others may fluctuate on a weekly, daily or even hourly basis. Consequently, both the CO₂ mass flow rate and the composition of the CO₂-rich mixture in the pipeline transport network will fluctuate. To operate the network safely and to avoid problems at the injection site, it is essential to be able to model the transient flow conditions in the network in real-time and with sufficient spatial resolution. The above is dealt with in Section 3.1.1.

In principle, problems with differing CO₂ flow compositions can be overcome through CO₂ purification. However, the associated additional energy costs may become prohibitive. Section 3.1.2 deals with the related techno-economic aspects to determine the optimum balance.

CO₂ quality management requires means for reliable online monitoring of the impurities in the flow. This is a challenge that is commonly underestimated, in particular if impurities from different CO₂ sources react once mixed or when two-phase flow occurs. Section 3.1.3 deals with the relevant challenges.

The accurate 'closure of mass balances' of the flowing CO₂ within the CCUS cluster pipeline network is important for both leak detection and for economic reasons. The operation of CO₂ transport networks involves complicated owner and customer structure, high costs, complex liability questions, and substantial fiscal relevance.

¹¹ <https://www.eera-set.eu/>

Thus, avoidance of misallocation of cost and liability based on traceable mass and composition tracking is mandatory to develop mutually agreeable contractual models. Technologies available for accurate flow measurements are described in detail in Section 3.1.4.

Whilst the captured CO₂ is so far mostly injected in saline aquifers, depleted gas fields are attractive storage options because of their significant capacity, the availability of detailed historical geological data and their relatively close proximity to a number of European industrial clusters. However, the injection of the compressed CO₂ into highly depleted gas fields presents specific challenges, in particular during the start-up phase, since it involves the rapid expansion of the CO₂ resulting in its significant cooling at the well head and along its length. These issues are addressed in Section 3.2.

In the context of pipeline safety, much work has been dedicated to corrosion and running ductile fracture as the most prominent failure scenarios for CO₂ pipelines. A review of the state-of-the-art and the remaining challenges is given in Section 3.3.

The reuse of decommissioned oil and natural gas facilities, such as pipelines and offshore platforms will reduce initial investment costs for storage. Section 3.4 deals with the relevant technical and safety considerations.

CO₂ Infrastructure needs to be designed in a way that balances potential for future extension and initial investment. The right sizing of CO₂ pipeline networks in order to cope with future developments such as changes in the energy supply landscape with renewables gaining further dominance and additional emission sources joining industrial clusters is dealt with in Section 3.5.

As CO₂ may be collected from industrial emitters along rivers or close to the coast, transport by ship is likely to be an attractive alternative as compared to pipelines, in particular because the initial investment costs will be lower and the authorisation process is considered less

complicated. While CO₂ transport by ship is well-established on a small scale and for almost pure CO₂, transport of CO₂-rich mixtures at large-scale raises a number of technical questions. Section 3.6 deals with such aspects.

Stranded emitters account for a substantial proportion of global CO₂ emissions. For example, about 30% of the CO₂ emitted by industry in the UK comes from small distributed sources. To realise deep cuts in atmospheric CO₂ emissions, this CO₂ needs to be considered for abatement. Some of the relevant processes can be adapted to the use of electricity or hydrogen, but, in many cases, it will be necessary to rely on CCUS technology. This may require that CO₂ from small emitters needs to be collected by low-pressure pipelines, truck or train. Processing of this CO₂ at central hubs is likely to be an economically attractive option, but this increases the challenges for transport to the hubs due to higher levels of impurities and more complex phase behaviour of the unprocessed CO₂. Section 3.7 deals with such aspects.

In chapter 4, a number of overarching questions are discussed, which are relevant for CO₂ transport in general, but for set up and operation of CO₂ transport networks in particular. These include the issues related to CO₂ thermodynamic properties (Section 4.1), the development of sound business models that need to work without public support in the long run (Section 4.2), and last but not least, the multitude of legal and regulatory aspects that have to be considered (Section 4.3). The latter is particularly challenging for cross-border pipeline transport networks, since legal and regulatory constraints are different from country to country even within the EU.

The set of challenges discussed above is certainly not complete; many other aspects have to be considered in the design and operation of CO₂ transport networks. This report cannot give the final answers with regard to any of the raised questions. However, it attempts to summarise the state-of-the-art with respect to the most important challenges to be overcome to enable the rollout of

such networks. In doing so, the report highlights the substantial differences in the challenges involved between CO₂ transport in *source-to-sink* type connections as compared to CCUS industrial clusters. The discussed aspects do not question the feasibility of CO₂ transportation networks; these can be built based on today's knowledge. Our report shows that additional scientific knowledge, technical solutions, and operating experience along with clear economic and regulatory considerations are required to rollout the optimal CO₂ transportation network solutions.

2. Examples of Designs of Operational and Planned Systems

The following sections highlight a number of ongoing CO₂ transport and storage projects in Europe. Two projects are operational in Norway; Sleipner and Snøhvit. Several projects are being developed, including Northern Lights (also in Norway), Porthos (The Netherlands), Athos (The Netherlands), ERVIA (Ireland) and ACORN and HyNet (both in the UK). While most projects involve high-pressure pipelines (upwards of about 80 bar) for the transport of CO₂, transport by ship is an integral part of the Northern Lights project and a key element of the Cork CCS project.

The following describes the main features of some of the important CCS/CCUS projects demonstrating that large-scale CO₂ transport and injection at relatively large scale is technically feasible.

2.1 In Salah (Algeria)

The In Salah CO₂ storage site, Algeria, was part of an industrial scale capture and storage project within the In Salah Gas (ISG) Joint Venture (seven gas fields in the central Sahara of Algeria). High natural CO₂ content required CO₂ stripping to meet ISG Gas export specifications of 0.3 % CO₂ in the export gas. After treatment at the Central Gas Processing Facility (CPF), using an MEA amine process, the CO₂ was compressed, transported and stored underground in the approximately 1.9 kilometre deep Carboniferous sandstone unit at the Krechba field.

Three long-reach near horizontal injection wells were used to inject the CO₂ into the down-dip aquifer leg of the gas reservoir and injection commenced in 2004. Two 1 kilometre long, 200 mm (8") Inside Diameter (ID) pipelines were used to connect the pump station and the well heads. The pressure at the well head was maintained above 100 bar, up to about 180 bar (Eiken et al., 2011). The ambient temperature was around 34 °C at the surface and the CO₂ fluid in the system from pump station to the reservoir was in the single-phase flow condition. Based on an integrated study of new geological data, CO₂ injection ceased in June 2011 due to concerns related to integrity of the storage formation cap rock and the risk of contaminating the freshwater aquifer.

The ISG CO₂ injection project is now in the closure phase. Partners of the ISG Joint Venture are BP, Equinor and Sonatrach.

https://sequestration.mit.edu/tools/projects/in_salah.html



Figure 2. The In Salah site (Algeria). Picture courtesy of Equinor.

2.2 Sleipner (Norway)

Sleipner is a gas field on the Norwegian Continental Shelf with 5-9% CO₂ content, while the specification for the export gas is 4%. It is a first in the world capture and storage offshore project and injection started in 1996. Project partners are Equinor, ExxonMobil, LOTOS and KUFPEC.

Sleipner was the first of its kind to implement an offshore gas treatment and CO₂ removal (amine based) unit. The injected CO₂ contains between 0.5% and 2% CH₄. Since 1996, about 1 Mtpa of CO₂ has been captured annually from the produced gas and reinjected into the Utsira formation about 800 to 1000 metres below the seabed. The formation contains a 200-300 metre thick saline sandstone layer with high porosity (38%) and permeability (1-8 Darcy), and is covered by a thick layer of shale rock, which prevents the CO₂ from migrating upwards. The storage capacity of the formation is about 16 Giga tonnes. Since 2017 the project also includes processing of CO₂ from Gudrun and it is currently injecting 0.9 Mtpa of CO₂.

At Sleipner, the CO₂ is injected directly from the platform into the well without subsea installations. There is a limited length of pipe segments between the pump station and the well head of the injection well. The CO₂ fluid is in the two-phase flow condition at the well head at conditions of typically about 30 °C and 70 bar (Eiken et al., 2011), and single liquid phase is maintained at a lower section of the well.

<https://www.ice.org.uk/knowledge-and-resources/case-studies/sleipner-carbon-capture-storage-project>



Figure 3. The Sleipner platform (Norway). Picture courtesy of Equinor.

2.3 Snøhvit (Norway)

The Snøhvit field is located approximately 150 kilometres off the coast of Norway and is connected to three major gas fields, Snøhvit, Askeladd and Albatross, which were discovered in 1984, 1981 and 1982, respectively. The gas from the field is used for LNG production which became operational in August 2007 and CO₂ reinjection into the Tubåen formation started in April 2008. It is operated by Equinor and is the first Oil and Gas development in the Barents Sea. The project, with partners Equinor, DEA, Neptune, Total and Petoro, was the world's first offshore CO₂ pipeline with a subsea well.

The plant was the world's most efficient liquefaction plant when built. About 700,000 tonnes of CO₂ is removed from the feed stream and injected into the Tubåen formation annually. Accumulated over the 30-year design life of the development, this is expected to account for approximately 12 GSm³ CO₂. The CO₂ is separated in an amine process operating at high pressure and low temperature (approximately 66 bar and 45 °C) in the absorber, and low-pressure and high temperature in the regenerator (approximately 1.5 bar and 113 °C). The separated CO₂ is then dried and recompressed to ensure that free water does not form and that the CO₂ remains in the liquid region during transportation. Located 2400-2600

metres below sea level, the Tubåen formation is a heterogeneous fluvial system with good reservoir properties in the fluvial channels but poor connectivity between separate channels. This leads to higher operational pressures in the injection system at Snøhvit. The main impurities of the injected CO₂ are CH₄ and N₂, with maximum total impurities about 2.5 mol%.

The Snøhvit CO₂ transportation and injection system consists of a pipeline 153-kilometre long, 200 mm (8") ID, operating at pressures between about 80 and 140 bar (Eiken et al., 2011) into two injection wells F2H and G4. The CO₂ injection into F2H in the Tubåen formation started in 2008 and finished in 2011 and injection then started in the Stø formation. Injection into the G4 into the Stø formation started in 2017. The G4 well is tied into the F2 well head by a 5-kilometre long, 200 mm (8") ID pipeline. In all operational conditions, the CO₂ is in the liquid phase from the pump to the storage reservoir.

https://www.equinor.com/no/how-and-why/climate.html?gclid=EAIaIQobChMI2JHftcrj6QIVFYXVCh2MGQH7EAAYASAAEgJfKPD_BwE

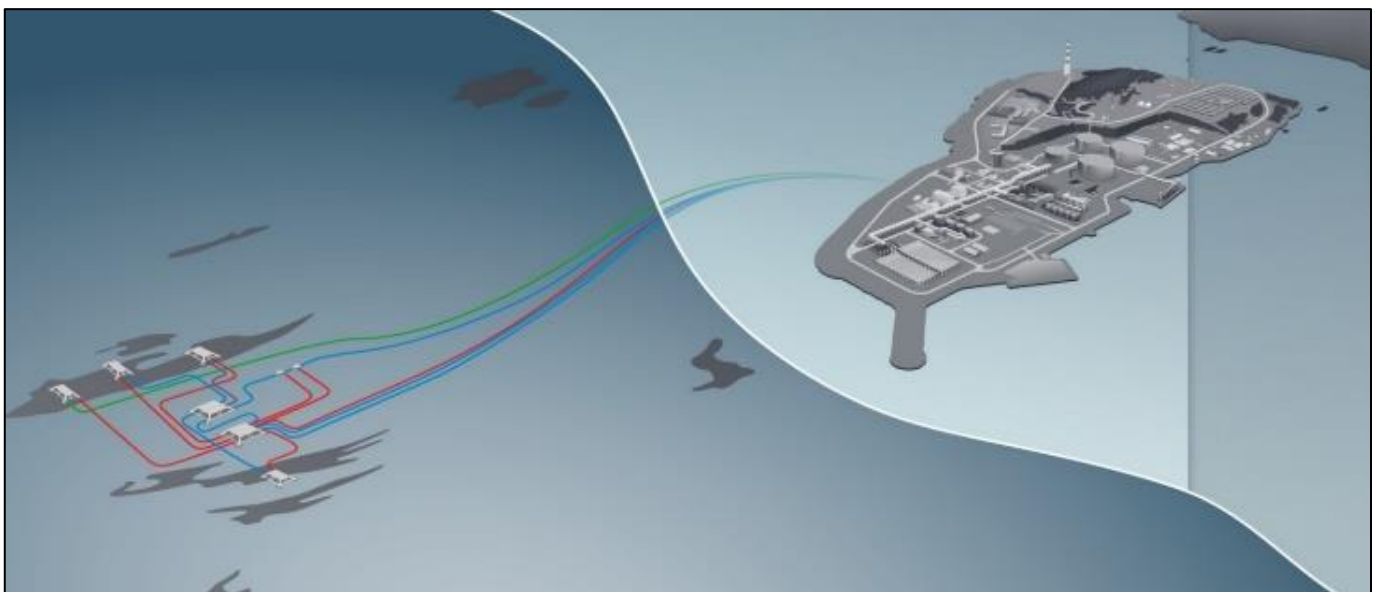


Figure 4. Schematic layout of the Snøhvit project (Norway). Figure courtesy of Equinor.

2.4 Northern Lights (Norway)

The Northern Lights project is part of the Norwegian full-scale CCS project which is a result of The Norwegian government’s ambition to develop a full-scale CCS value chain in Norway by 2024. The full-scale project includes the capture of CO₂ from industrial sources in the Oslo-fjord region (comprising of cement and waste-to-energy emitters) and shipping in the liquid phase to an onshore terminal on the Norwegian West coast. From there, the liquefied CO₂ will be transported by pipeline to an offshore storage location in the North Sea for permanent storage 3,000 meters below the seabed.

The Northern Lights project is a partnership between Equinor, Shell and Total and comprises the transportation and storage scope of the Norwegian Full-Scale CCS Project. Liquefied and pressurised CO₂ will be loaded from the capture site onto the ships which will transport it to the Northern Lights onshore terminal at Naturgassparken in Norway. At the terminal, CO₂ will be offloaded from the ships into onshore intermediate storage tanks. ‘Buffering’ the CO₂ in onshore intermediate storage tanks allows for the continuous transportation of CO₂ by pipeline to the subsea well(s) for injection into a subsurface geological storage complex. The Northern Lights project is planned to be developed in two phases.

Phase 1 is planned with a capacity to transport, inject and store up to 1.5 Mtpa. However, already in this phase the concept will include the basic functionality of the receiving terminal, offshore pipeline and the umbilical to the offshore template to handle a total of 5 Mtpa of CO₂. For this phase the project has finished the FEED (Front End Engineering Design) phase and received a license from the Norwegian State for CO₂ injection in their planned reservoir named ‘Aurora’.

Given a positive Final Investment Decision (FID) by the Norwegian Government and project partners in 2020, the Northern Lights project is scheduled to be operational in Q4 2023.

If there’s market demand for additional CO₂ storage, the Northern Lights partners will hopefully take a positive FID to develop Phase 2. Phase 2 would include capacity to receive, inject and store an additional 3.5 Mtpa, adding up to a total of 5 Mtpa. This phase is currently in the feasibility study phase and could be operational in 2025.

Both phases will offer the flexibility to receive volumes from European CO₂ sources, beyond the 0.8 Mtpa of CO₂ which would come from the Norwegian CCS full scale project, assuming both of the initial Norwegian capture projects being realised (Fortum Oslo Varme and Norcem, each with 0.4 Mtpa capacity).

The Northern Lights project is an open access project offering a transportation and storage solution to future third party customers. The flexibility of transporting CO₂ by ship opens the option of collecting CO₂ at any harbour at a coastal location in Europe.

<https://northernlightsccs.com/en/>

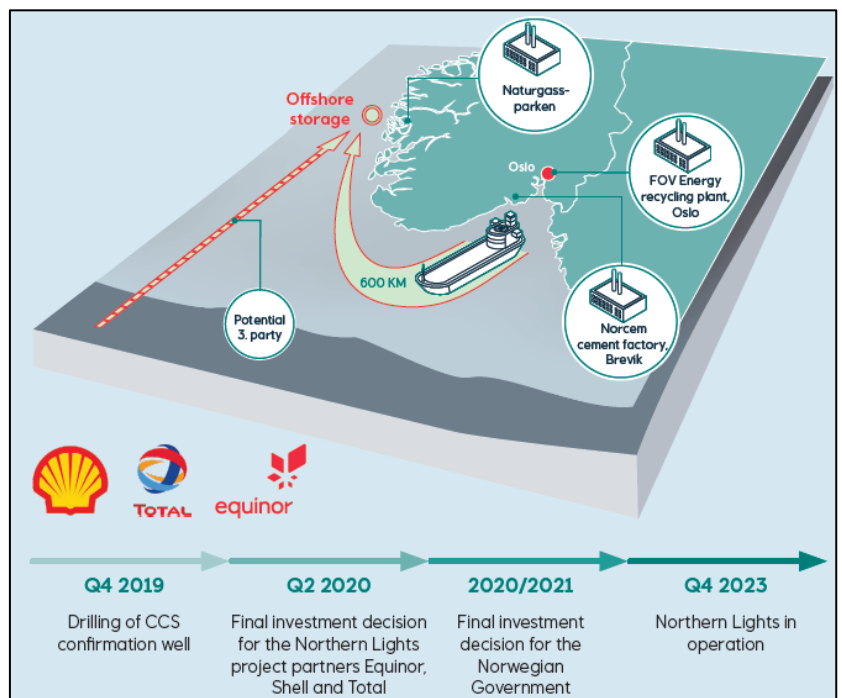


Figure 5. Schematic layout of the Northern Lights project (Norway). Figure courtesy of Equinor.

2.5 North Sea Ports/Porthos (The Netherlands and Belgium)

The Porthos consortium, consisting of EBN (Energie Beheer Nederland B.V.), Gasunie and the Port of Rotterdam, is preparing a project to transport CO₂ from industry in the Port of Rotterdam and store this in empty gas fields beneath the North Sea (Figure 6).

CO₂ supplying companies will connect to an onshore collection network operating at a pressure between 15 and 40 bar (NRD, 2019). The CO₂ will then be pressurised to about 30 bar at the start of the project, to about 110 bar when the fields are almost full. The CO₂ will be transported through an offshore pipeline to a platform in the North Sea, approximately 20 kilometres off the coast. From this platform, the CO₂ will be pumped into an empty gas field. The empty gas fields are at a depth of over 3 kilometres.

It is expected that, in its early years, the project will be able to store 2 to 2.5 Mtpa. The start of injection is planned to take place early 2024.

<https://www.rotterdamccus.nl/en/>

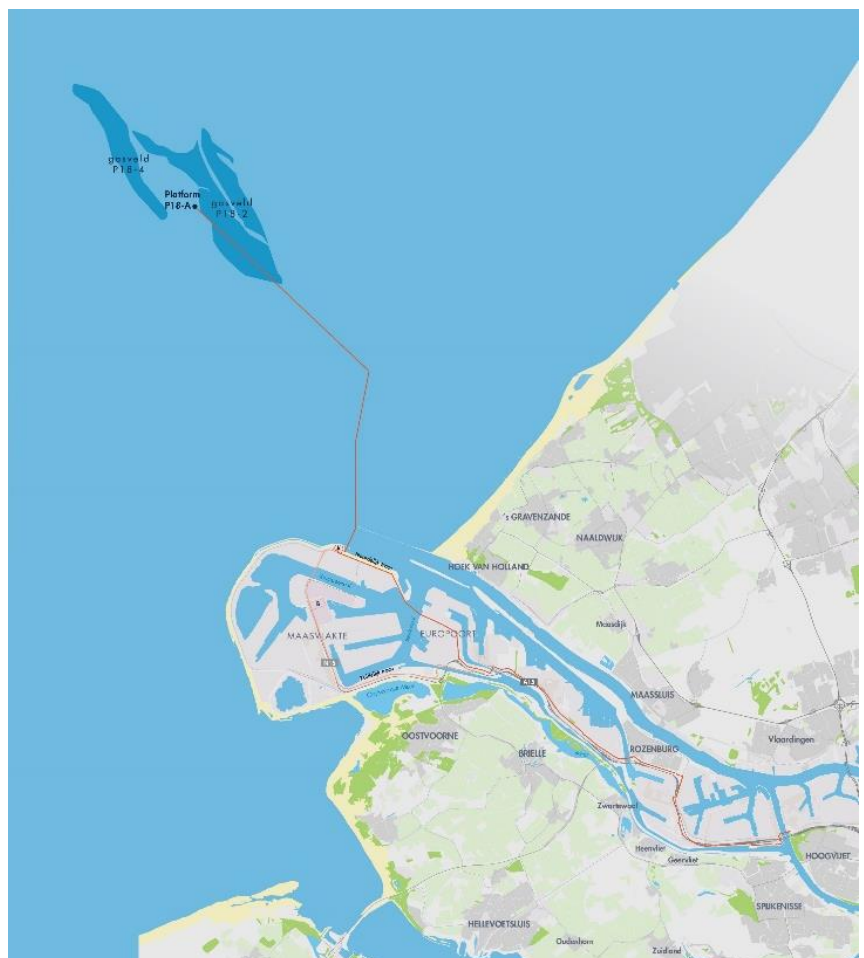


Figure 6. Schematic layout of the Porthos project (The Netherlands). Figure courtesy of Porthos.

2.6 Athos Consortium (The Netherlands)

Activities similar to those of the Porthos consortium are being undertaken by the Athos consortium, consisting of EBN, Gasunie, the Port of Amsterdam and Tata Steel (located near IJmuiden). The Athos consortium plans to use depleted offshore fields (oil, gas) or saline formations for the storage of CO₂ captured at industrial sources near the North Sea Canal (see Figure 7), with the Tata steel plant near the coast expected to be one of the first and largest suppliers of CO₂. Transport is foreseen to be done by subsea pipelines, re-using existing pipelines where possible. Start of injection is planned for 2027.

As illustrated in Figure 7, the Athos project is likely to connect users of the captured CO₂; the figure shows the example of horticulture and contains a potential, future link with the OCAP system (<https://www.ocap.nl/nl/index.html>).

<https://athosccus.nl>

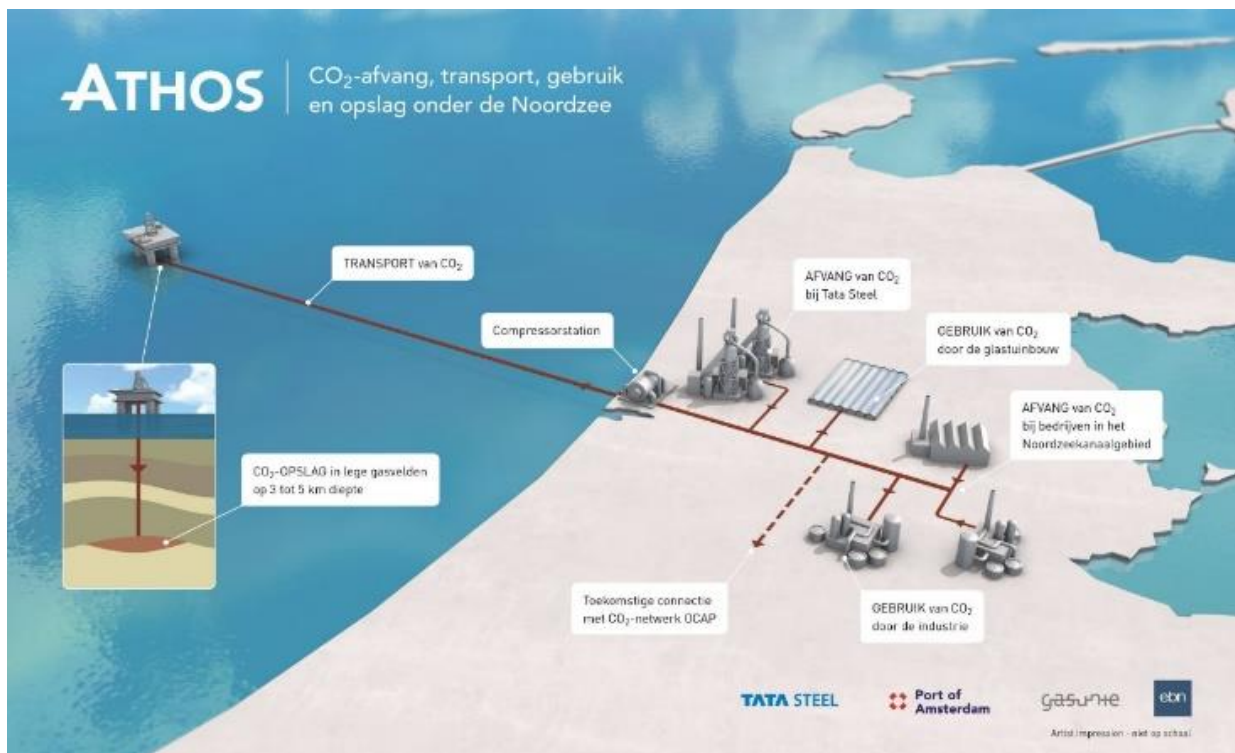


Figure 7. Schematic layout of the Athos project. Figure courtesy of Athos consortium.

2.7 ACORN CO₂ SAPLING (UK)

The Acorn CO₂ SAPLING project is the CO₂ transport infrastructure element of the Acorn CCS project. Acorn CCS is a CCS project designated as a European PCI, strategically designed to repurpose legacy oil and gas infrastructure and make best use of Scotland's excellent geology for CO₂ storage. The Acorn Project is led by Pale Blue Dot Energy, with support and funding from study partners, Shell, Total and Chrysaor.

Modest quantities of existing CO₂ emissions (~340,000 tonnes) from the St Fergus gas terminal in North East Scotland are used to kickstart a CO₂ transport and storage system capable of dealing with over 2 Mtpa. An important catalyst for clean growth opportunities in Scotland, and in regions where CO₂ transport and storage is limited, Acorn can help transform our carbon intensive industries and sustain jobs. Acorn CCS unlocks the CCS and hydrogen infrastructure essential for meeting the Scottish and UK government Net Zero targets.

Acorn aims to establish a strategic and transnational CO₂ transportation infrastructure capable of delivering over 12 Mtpa of CO₂ from emissions sources around the North Sea for permanent sequestration in deep geological

storage sites located beneath the Central North Sea. The work undertaken has confirmed the suitability of the Atlantic and Goldeneye offshore pipelines to be repurposed for transporting 5 Mtpa and 4 Mtpa, respectively. The project proposes to repurpose the existing 'Feeder 10' onshore gas pipeline to transfer 3 Mtpa captured from emitters in the Grangemouth area, increasing to 6 Mtpa with the installation of an intermediate CO₂ compression station.

A new build CO₂ compression plant constructed at the St Fergus industrial site could transport locally captured and build-out quantities of CO₂ to the Acorn CCS project offshore storage sites. Acorn build-out options include using existing Peterhead Port infrastructure and a local industrial site to transport up to 3 Mtpa to St Fergus via an inland pipeline. Larger vessels can be accommodated within Peterhead Port which could see 6 Mtpa arrive at St Fergus.

With the continued support of governments and industry, the first phase of Acorn CCS could be operating in 2024.

<https://pale-blu.com/co2-sapling/>



Figure 8. Schematic layout of the Acorn CO₂ SAPLING project. Figure courtesy of Pale Blue Dot

2.8 Humber Project (UK)

In the Humber, the UK's largest industrial cluster by emissions, eleven leading energy and industrial companies have formed a consortium to progress a plan for a decarbonised industrial cluster that will become the world's first net zero cluster by 2040. The plan is to capture CO₂ at scale from industry around the Humber estuary and transport it via pipelines and then to permanent storage in naturally occurring aquifers under the southern North Sea. Negative emissions (through bioenergy with CCS) and fuel switching to low carbon hydrogen (produced from natural gas using CCS, as well as potentially through electrolysis) are being pursued. Due to proximity to some of the largest ports in UK, there is also the potential for the CO₂ terminal to accept volumes from industries located elsewhere by ship or through a CO₂ pipeline infrastructure.

In its initial phase the project is planning to utilise the Endurance field in the South North Sea as the offshore CO₂ storage site with an estimated technical storage limit of up to 400-450 MT, expanding to the Bunter Closure formations in the next deployment phases. There is a clear mutual benefit of combining the CO₂ transport and storage for both the Humber and Teesside clusters in injection flexibility, brine management strategy, shared costs and risks. The project expects to start CO₂ injection in 2027.

<https://www.equinor.com/en/where-we-are/united-kingdom/develop-plan-for-the-worlds-first-zero-carbon-cluster-in-the-humber-region.html>

2.9 Cork CCS Project (Ireland)

The Cork CCS project involves the capture of CO₂ at refineries and power stations and transportation to an offshore depleted gas field. CO₂ capture can be developed at two gas fired power stations in the Cork region (Aghada and Whitegate) and at the existing Irving Oil Refinery at Whitegate. An existing gas pipeline can be re-used to transport CO₂ offshore for storage in the depleted Kinsale Head gas field. If developed, 1.5 to 2.5 Mtpa could be captured with the Cork CCS Project.

The ERVIA transportation and storage project is illustrated in Figure 9. The project aims to re-use an existing gas transportation pipeline and two platforms. The CO₂ will be transported in dense phase at a rate of up to about 2.5 Mtpa. The platforms are to be adapted to handle the CO₂. In principle, production wells will be worked over and converted to CO₂ injectors.

The project includes the development of the option to connect to backup storage capacity elsewhere in the EU through ship transport. This requires the construction of ship offloading facilities. Developing a ship transport option would also

enable CO₂ shipping from other sources in the country either to the Cork CCS project or to storage sites elsewhere.

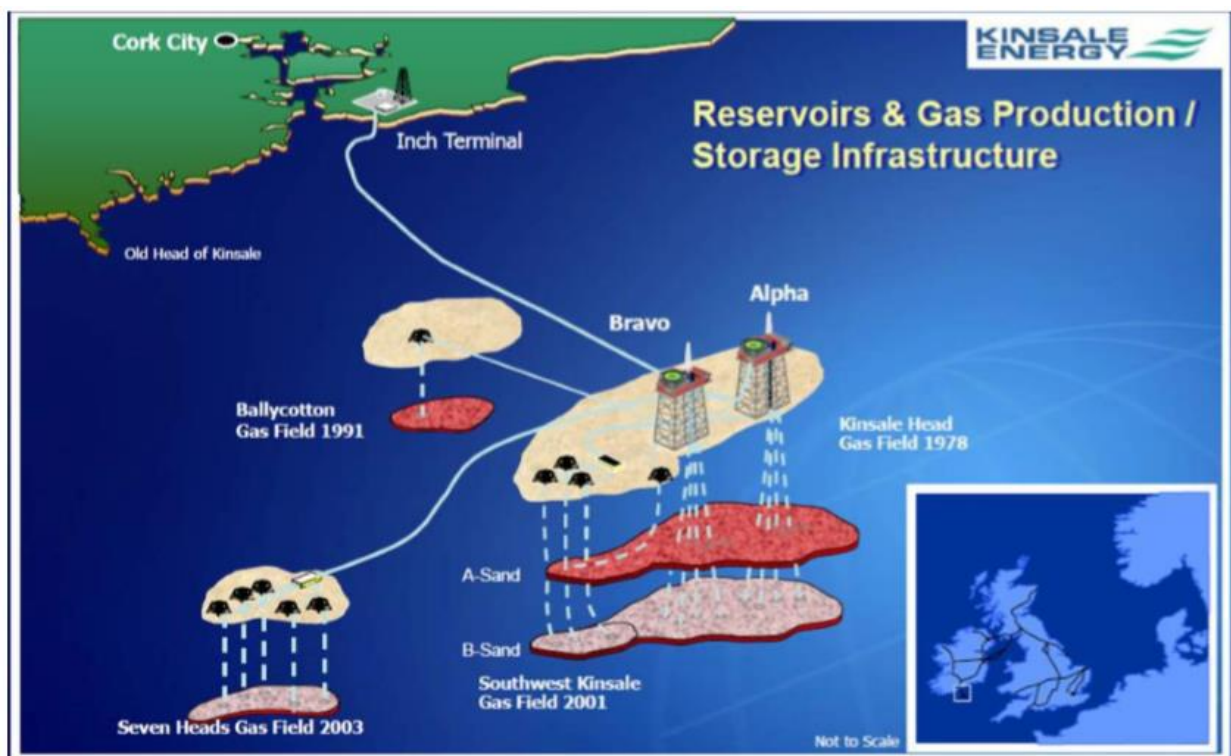


Figure 9. Schematic layout of the Cork CCS project (Ireland). Figure courtesy ERVIA.

2.10 Net Zero Teesside (UK)

The Net Zero Teesside CCUS project, based in Teesside, North East England, is the world's first of a kind industrial cluster which aims for net zero carbon emissions. In partnership with local industry, the project aims to decarbonise a cluster of carbon-intensive businesses by 2030 through capturing up to 6 million tonnes of CO₂ per year for safe storage in an underground reservoir in the North Sea. The region hosts Europe's first integrated modern chemical plant and is the second largest carbon emitting region in the UK. It aims to build a new gas fired power station and also capture the emitted CO₂ for storage. Infrastructure for local industry will be supplied to capture its CO₂ and for new companies to develop new manufacturing assets in the UK where they can be supplied with large volume energy at low or net zero carbon emissions. The consultation process that forms part of the development consent order required the holding of a stage 1 consultation event, held in Oct 2019, which gave the local community and stakeholders the opportunity to raise any concerns about the project moving forward.

The Net Zero Teesside project is now preparing for a stage 2 consultation to demonstrate how it has incorporated the comments raised by the local communities and engage with them further based on the increase in design definition.

<https://www.netzeroteesside.co.uk/project/>



Figure 10. The NetZero Teesside CCUS industrial cluster in the UK aiming to capture 6 million tonnes of CO₂ per year by 2030.

3. Technical and Operational Challenges

3.1 General Challenges of Multi-source CO₂ Streams

3.1.1 Transient Flow Modelling in Multi-source CO₂ Pipeline Networks

The cost-efficient and safe operation of CCUS industrial clusters poses many important challenges. A key difficulty is managing CO₂ streams of various quality and flow levels with varying operating regimes to meet the multitude of operational and safety constraints for the associated pipeline transportation and storage infrastructure including:

- Pipeline and wellhead internal corrosion
- Risks of pipeline ductile and brittle fracture
- Managing two-phase flows during normal operation
- Avoiding blockages during rapid depressurisation due to dry ice (solid CO₂), ice and hydrate formation
- Injection and storage constraints (e.g. constraints on N₂ to preserve storage capacity, limitations on O₂ to avoid biofouling and limitations on sulphur compounds on health and safety grounds)
- Facilitating the ongoing maintenance and inspection activities without causing a major disruption to the operation of the entire cluster.

Moreover, depending on the type of emission source joining the cluster, the CO₂ supply flow rate from each source may be intermittent and/or transient in nature, exacerbated by the operation of the capture plants to maximise profitability (Mac Dowell and Shah, 2015). Such fluctuations will alter the flow behaviour, i.e. pressure drop in the system and result in a possible variation in composition, fluid phase, pressure and mass flow rate of the delivered CO₂ stream.

As such the precise knowledge of the dynamic flow behaviour within CO₂ pipeline networks in CCUS industrial clusters operating under realistic conditions is of paramount importance.

Central to above, is the accurate modelling of the CO₂ mixture flow rate, fluid phase and composition at any point along the pipeline network and at the point of injection into the storage site. Such modelling capability can serve as a valuable 'real-time' control tool for CO₂ pipeline operators to:

- Define the CO₂ quality specification requirements for each emitter joining the transportation network within a cluster accounting for supply flow rate and any temporal fluctuations.
- Design resilient pipeline network systems to cope with additional capacity for future overall reductions in CO₂ emission targets, additional CO₂ emitters joining the network or changes in the energy supply landscape as intermittent renewable energy displace thermal power generation.

- Smooth out day-to-day fluctuations in the flow throughout the pipeline transport network to ensure stable CO₂ injection rates into the storage site through pipeline line packing or intermediate storage.

Transient flow models have been developed to simulate flow dynamics, but these are mainly limited to single CO₂ pipelines on ‘point-to-point’ type arrangements. Their extension to pipeline networks in CCUS clusters is significantly more complicated due to the different CO₂ stream compositions with varying flow rates from each connecting emitter, and the strong temperature and pressure dependence of the CO₂ fluid on phase behaviour.

Brown et al. (2015) developed a rigorous steady multi-source flow model for CCS pipeline transportation networks. The model was applied to a hypothetical UK cluster network connecting Cottam and West Burton coal fired power stations in North Yorkshire to Drax power station, via the steel works at Scunthorpe. Figure 11 shows a schematic of the CO₂ pipeline network. The Drax power station was assumed to be connected to the main pipeline system via a 0.5 km long interconnecting pipeline. From this point the CO₂ mixture is transported to its point of sequestration, a Morecambe Bay gas field in the East Irish Sea, via Hornsea and Carnforth. Four scenarios were assumed:

1. Both Cottam and Drax power stations used a post combustion capture technology (representing the lowest concentration of impurities for a commercial stream).
2. Both Cottam and Drax power stations used an Oxyfuel capture technology (highest level of impurities for a commercial stream).
3. Drax power station uses an Oxyfuel capture technology and Cottam power station post combustion.

4. Cottam power station uses Oxyfuel capture technology and Drax power station post combustion capture technology.

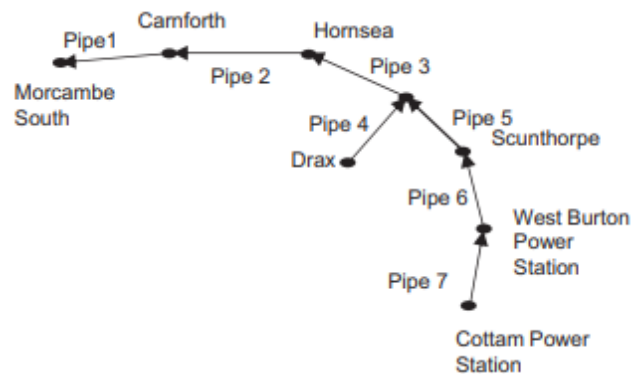


Figure 11. Schematic of a CO₂ pipeline network (Brown et al., 2015)

For assumed CO₂ supply flow rates and temperatures at Drax and Cottam power stations, using their flow model, the authors predicted the corresponding feed pressures to ensure the final delivery pressure of 90 bara at the point of sequestration, Morecambe Bay. In addition it was found that the compression required at each of the two supply points increased with higher levels of impurities in the CO₂ stream in order to reach the required pressure at the point of sequestration.

Despite its success, there were two limitations associated with the model that need to be addressed in order to enable its application as a highly valuable practical pipeline network operational control tool:

1. The model was based on steady state flow assumption. As such it is not possible to handle CO₂ supply flow transients and track the CO₂ composition at any point along the pipeline network in real-time.
2. The modelling was based on a Homogenous Equilibrium Model (HEM) where the constituent fluid phases are assumed to be at thermal and mechanical equilibrium. Such an assumption is of no consequence during ‘normal’ operation given that two-phase flow is to be avoided. However, the HEM assumption is invalid during rapid

transients such as venting/blowdown of isolated pipeline sections for routine maintenance purposes where heterogeneous multi-phase flow resulting solid CO₂ formation is likely to occur.

3.1.2 CO₂ Purity and Quality Techno-Economic Assessment

The CO₂ to be transported in CCUS industrial clusters is termed '*anthropogenic*' as it contains impurities due to the combustion or chemical processing used by industrial emitters which will affect the safety, integrity and hydraulic performance of pipelines used for CO₂ transportation. The purity of the CO₂ is affected, not only by the various types of capture technology and processes, but also by economics (i.e. the increased cost associated with the removal of impurities to low levels), legislative and regulatory requirements, specifications and safety considerations. With regard to safety considerations, the Health and Safety Executive (HSE in the UK) has indicated that CO₂ will be classed as hazardous substance under the UK legislation, Pipelines Safety Regulations 1996, and pipelines transporting CO₂ will be classed as Major Accident Hazard Pipelines (MAPDs) in the Regulations.

Based on an extensive techno-economic study backed by large-scale experiments, with safety being the over-arching factor, the EC funded CO2QUEST FP7 project¹² lead to the development of computational modelling tools needed to define the optimum CO₂ purity specification for a given CCS chain. The study was however confined to a limited range of impurities and the simple case of single point to point capture, transportation and storage.

The effect of impurities depends upon whether the CO₂ is in the gaseous or dense phase, and impacts on the phase behaviour of the fluid, significantly

extending the two-phase region. This is not a well understood area, and the availability of accurate models is limited. **CO₂ pipelines have not so far been designed for a wide range of impurities. CCUS industrial clusters will introduce a new generation of CO₂ mixtures for transportation.** Transportation pipelines must be designed to take account of the phase behaviour of the product being carried, and the effect of any impurities in the CO₂ stream.

Health and safety considerations will be the single most important factor influencing the design of any proposed CCUS projects to ensure that all potential major accidents caused by MAPDs are identified at the design stage to enable appropriate control and mitigation measures to be put in place. Once in place, these risk prevention measures should ensure that the risk to employees and the public is minimised.

Development of CO₂ quality requirements is complex as there are technical and economic implications, noting that initial '*point to point*' CCUS projects could ultimately form part of a wider CCUS industrial cluster network where the composition and the interaction of the CO₂ impurities being transported becomes even more important. The presence of impurities in the CO₂ may also impact legal, design, operational (including planned and unplanned releases) and the environment. The quality requirements need to limit the range of compositions that may be transported in a pipeline. This must take account of safety (toxicity), impact on pipe integrity (corrosion and corrosion induced cracking, running fractures), hydraulic efficiency and saturation pressure.

A number of CO₂ specifications and recommendations for maximum impurity concentrations have been published and an excerpt showing the tentatively most aggressive impurities (H₂O, H₂S, O₂, NO_x, SO_x, CO) is shown in Table 2.

¹² CO2QUEST: Impact of the Quality of CO₂ on Storage and Transport, EC FP7 Project, 2014 - 2017, Grant Number: 309102 <http://www.co2quest.eu/>

Table 2: CO₂ specifications and recommendations for maximum impurity concentrations

Comp. ppmv	Dynamis 2008	NETL* (for design)		CarbonNet 2016	Goldeneye/Peterhead 2014 (2016)	Northern Light (2019)	Ref. exp. 25 °C 100 bar
		2012	2013				
H ₂ O	500	730	500	100	50	30	122
H ₂ S	200	100	100	100	low	9	130
CO	2000	35	35	900-5000		100	0
O ₂	<40000	40000	10	20000-50000	5	10	275
SO _x	100	100	100	250-2500	low	10	96
NO _x	100	100	100	200-2000	low	10	69

*NETL (National Energy Technology Laboratory)

The most cited CO₂ quality recommendation was suggested in the DYNAMIS project in 2008 (Visser et al. 2008). The National Energy Technology Laboratory (NETL) issued in 2012 and 2013 Quality Guidelines giving recommendations for the impurity limits to be used for conceptual design of carbon steel pipelines (Matuszewski et al., 2012 and Herron et al., 2013). The recommendations were based on a review of 55 CO₂ specifications found in the literature. The Australian CarbonNet Project published in 2017 a preliminary CO₂ specification for its hub-based carbon capture and storage network (Harkin et al. 2017). The limits given for the various impurities in the specifications/recommendations are not only based on the risk of corrosion and formation of corrosive phases but are also based on HSE (toxicity limits) and reservoir requirements.

It is important to note that neither of the recommendations were intended to be used in actual projects without further refinement. It should also be noted that when the specifications/recommendations were published, they had not been experimentally verified. The last column (green) in the table shows a CO₂ stream composition denoted "Ref. exp.". This composition, which is stricter than the Dynamis recommendation, has been tested at IFE and the

results have been published (Dugstad et al., 2014). Testing at 25 °C and 100 bar showed that the impurity in the CO₂ stream reacted and formed sulphuric acid, nitric acid and elemental sulphur, i.e. an environment that is highly corrosive for carbon steel.

The two blue columns in the table show CO₂ specifications proposed for actual CCS projects, i.e. the Peterhead (Peterhead, 2016) and Northern Lights (Northern Lights, 2019) projects. The project specifications are much stricter than the general recommendations given in the pink columns. Most of the low limits are a result of the capture technology (amine based) that gives low impurity concentrations anyway, but to achieve for instance the low O₂ content will most probably require additional cleaning steps.

National Grid in the UK developed a set of CO₂ quality requirements to support a range of CCS/CCUS projects which were based on the 'Dynamis CO₂ Quality Recommendations' (Ecofys, 2007) except for the limits on water (H₂O) and H₂S.

One of the key requirements for pipeline operators is maintaining pipeline integrity. In this respect, the control of the potential failure rate due to internal corrosion, which has the potential to increase the risk levels posed by CO₂ pipelines, is of major importance. There is currently insufficient

operational data available in Europe to derive a failure rate based on operational experience of CO₂ pipelines, so unless the product is confirmed not to precipitate corrosive aqueous phases, the conservative assumption of a high internal corrosion failure rate would be expected. The quality requirements should engineer out potential problems relating to the failure frequency due to internal corrosion through the control of the impurity levels (i.e. H₂O, H₂S, O₂, SO_x and NO_x), while accommodating the various carbon capture technologies.

The following sections discuss some of the key factors that need to be considered in the context of the impact of CO₂ stream impurities in CCUS industrial cluster pipeline networks.

Safety

CO₂ is an asphyxiant and a powerful cerebral vasodilator (i.e. it stimulates the respiratory rate resulting in a greater intake of CO₂). As with any gas other than oxygen, if its concentration reaches about 25% or more by volume, asphyxiation can occur rapidly. In addition, CO₂ is toxic at concentrations greater than about 2% (Harper, Wilday, & Bilio, 2011).

As mentioned above, anthropogenic CO₂ captured from industrial emitters contains other compounds. In particular, CO₂ captured from power plants, depending upon the fuel source and capture technology, may contain the toxic compounds including carbon monoxide (CO), H₂S and oxides of sulphur and nitrogen (SO_x and NO_x). An accidental release from a pipeline may not pose any additional risks beyond those posed by the CO₂ given their small concentrations. However, the long-term cumulative impact of these impurities during geological storage especially in aquifers may pose serious environmental challenges if unchecked.

Pipeline codes require that the design and location of a pipeline should take account of the hazard potential of the product to be conveyed, the density of population in the areas crossed by the pipeline

and the likely causes of failures.

Data relating to the safe limits for short-and-long-term exposure will need to be used to confirm the maximum allowable levels of these other toxic compounds.

Pipeline integrity

Pipeline codes require that a pipeline is designed, constructed, tested and operated to ensure integrity and the avoidance of failure. In terms of fluid properties, codes require:

- Fracture control to be considered.
- The quality of the product to be transported to be specified to avoid/minimise the potential for internal corrosion.
- The corrosivity of the product to be assessed so that the pipeline design includes requirements for the control of internal corrosion, including a corrosion allowance on material thickness (if applicable), fluid quality monitoring, corrosion monitoring and pipe wall inspection.

The wall thickness of a typical onshore pipeline is determined by the limit on the design factor specified in the pipeline specification being used (e.g. 0.72), and the population density along the proposed route of the pipeline. However, the decompression characteristics of dense phase CO₂ are such that the nominal wall thickness may, in fact, be determined by the requirements for fracture control. The toughness required to arrest a running ductile fracture in a pipeline transporting CO₂ in the dense phase depends upon the geometry and grade of the pipeline material, and the '*saturation pressure*' of the CO₂ rich mixture to be transported. The implication is that the geometry, material grade and toughness of a pipeline define the limit on the saturation pressure.

The saturation pressure is defined by the composition of the mixture and the initial pressure and temperature of the fluid, and the addition of other components increases the saturation

pressure. If a 'severe' composition (in terms of saturation pressure) is transported, then an increased wall thickness is required. This area requires further work as there is currently no recognised way of determining the pipe wall thickness.

Hydraulic efficiency

CO₂ can be transported at high-pressures as a liquid or a 'dense phase' fluid, or at low pressures as a gas. In contrast, natural gas exists only as a gas within the typical operating temperature range of a pipeline.

Transportation of CO₂ in the dense phase is much more efficient than the gas phase due to its much higher density and lower compressibility, but it is important that the potential for phase change during normal operation is avoided. This means that the minimum operating pressure and maximum operating temperature must be set to ensure the operating envelope of the pipeline is outside the phase envelope for the CO₂ mixture being transported. Also, impurities change the thermodynamic properties and the phase envelope of the fluid.

Operational efficiency

The presence of impurities in the CO₂ stream affects operational efficiency. The transportation of CO₂ is dependent upon the initial pressure of the CO₂ stream entering the pipeline, friction in the pipeline causing pressure loss and the requirement for additional compression or pumping located along the pipeline system. Two-phase conditions need to be avoided as operating in this area is costly, the capacity is not optimised and there is a high likelihood of operational instability such as compressor malfunction. The likely impurities in the CO₂ stream, in particular non-condensable components such as H₂, N₂, argon (Ar), O₂, methane (CH₄), increases the size of the two-phase region.

The density of the CO₂ stream changes with pressure and temperature and also with the level of impurities present. Adding non-condensable components reduces the density of the CO₂ stream.

High density is desired as it reduces pipeline diameter and increases pipeline capacity. The cost of higher purity of the CO₂ must be balanced against the cost of network design and construction, and against operational costs associated with the energy for compressors and pumps to operate effectively.

Flow metering

Flow metering should only be conducted under single-phase conditions to ensure the metering technology works correctly and the accuracy level required is obtained. Current flow meters do not work well in two-phase conditions. The design of the CO₂ transport and storage system should be such that two-phase flow conditions do not occur near the location of flow meters.

Storage

Impurities in the CO₂ stream can have the following potential impacts on storage (and permanent sequestration):

- Reduction of effective storage capacity.
- Reduced injectivity and reservoir permeability (IEAGHG, 2011).
- Impact on the rates of subsurface geochemical reactions (with both the formation and cap rock) consequently affecting the trapping mechanisms in play.
- Increase of the potential for corrosion of well components leading to system reliability issues.

The most significant of these effects is the reduction of storage capacity caused by the presence of non-condensable components (for example H₂, N₂, Ar and O₂) (IEAGHG, 2011). This effect is due in part to replacement of the CO₂ by the impurity component which decreases the amount of CO₂ stored so reducing storage efficiency and also by the ensuing reduction in density because these components are less compressible than CO₂. The extent of the reduction in capacity is a function of pressure, temperature and mixture composition (Eickhoff et al. 2017).

The presence of impurities affects injectivity principally by the reduction in density which thus decreases the effective mass flux into the storage reservoir. However, the impurity content may also result in a decrease in viscosity (IEAGHG, 2011) which would tend to increase mass flow. All non-condensable gases lead to a net reduction in injectivity.

Impurities can also affect injectivity through geochemical reactions in the vicinity of injection wells, although for reservoirs these effects are small. 'Dissolution' of CO₂ and reactions with minerals present may affect a storage site as geochemical reactions important for pressure stabilisation and brine displacement. Geochemical reactions can potentially affect the integrity of cap rock sequences above storage sites.

The relative permeability of the CO₂ rich mixture in the formation rock system is also impacted by the mixture composition and this will affect storage operations via injectivity, trapping mechanisms and the ensuing dynamic capacity.

Non-condensable gases also increase the buoyancy of the CO₂ plume (effect of the reduced density). This decreases the sweep efficiency of the injected CO₂ and leads to less efficient residual and solubility trapping of the CO₂ in the formation.

Corrosion of well materials is impacted by H₂O content. The water content of the CO₂ stream should be low enough to avoid free water formation throughout the transport and storage system (Brunsvold et al., 2016).

3.1.3 Challenges in Online Monitoring Impurities in CO₂ Streams

Routine analyses will be required to verify that the CO₂ stream compositions comply with the approved CO₂ specifications for the pipeline transportation network. A monitoring plan must be set up and sampling procedures and

instrumentation will have to be developed, evaluated, calibrated, certified and be routinely inspected and maintained. Real-time measurement should be considered as it will give the possibility to closely monitor CO₂ compositions and quickly take measures in case a CO₂ source delivers off-spec CO₂.

As discussed above, several tentative CO₂ specifications and recommendation have been discussed in the literature and the ranges of acceptable impurity concentrations vary a lot. The concentration of non-condensable impurities (i.e. Ar, N₂, CH₄, H₂, O₂) affecting the CO₂ liquid-gas phase equilibria is typically >> 100 ppmv. Impurities at these concentrations should be reasonably straight forward to monitor on a continuous basis. The concentration ranges suggested for the reactive impurities (i.e. H₂O, NO₂, SO₂, H₂S, O₂) taking part in chemical reactions giving corrosive aqueous phases are much lower, < 100 ppmv. The maximum concentration of NO₂, SO₂, O₂ and H₂S in the Northern Lights (Northern Lights, 2019) CO₂ specification is about 10 ppmv each. A maximum O₂ concentration as low as 1 ppmv was discussed in the Peterhead project (Svenningsen, et al., 2017). It is challenging to measure such low concentrations accurately, particularly in high-pressure systems. Stability of the instrumentation and sampling and depressurisation of the CO₂ stream upstream the analysers become important issues. How to interpret the analyses will probably be even more important and challenging since impurities may react and form new species and separate aqueous phases. Under such conditions, a decrease in the impurity concentration will be experienced in the bulk CO₂ phase. Experiments where several streams were mingled have shown that depending on the stoichiometry the concentration in the bulk phase can be almost nil for impurities that were originally present in the feed streams streams (Morland, et al., 2019a and 2019b). Without taking chemical reactions into account in these cases, the resulting CO₂ stream would be regarded as very clean and well within the limits given in the CO₂ specifications. *More work is required to understand*

and quantify the relationship between the measured concentration of impurities and the actual concentration taking precipitated phases into account.

3.1.4 Flow Metering

The accurate measurement of the quantity of CO₂ being added or removed at each part in the CCUS cluster network and associated transportation infrastructure is essential.

This could be for several reasons including leak detection and capacity management. The principle purpose of quantity measurement considered in this section is for the determination of payments or charges for quantities of CO₂ being transferred from one 'owner' to the next. This is implicitly a fiscal metering application where CO₂ mass is the metered quantity. Given the large-scale nature of CCUS, the monetary value of such transfers will be high, and, therefore, more accurate flow metering methods than the 2.5% accuracy proposed by EU ETS scheme are required. Considering EU Allowance (EUA) values of €20/tonne of CO₂ (European Energy Exchange approximate futures price for December 2021) every 1% of measuring accuracy 'costs' €0.2M per Million tonnes of CO₂. The calculation is simple and obvious, but the order of magnitude is often not appreciated until the volumes of CO₂ are considered. With the EUA price projected to rise in the coming years, the 'cost' of CO₂ accuracy will rise proportionately to whomever is the bearer of that cost – typically this will be either the 'producer' or 'receiver' but could also be the state in respect of lost taxes. CO₂ is no different in this respect from other forms of fiscal metering such as with oil and natural gas. What is lacking, though, is a set of fiscal metering standards for the CCUS industry.

While there are no specific standards for fiscal CO₂ metering, the measurement of CO₂ is mentioned in several fiscal standards (EU, 2012) (OIML, 2007) (Butcher, et al., 2017) – notably EU Directive 2014/32, OIML R117-1 and NIST Handbook 44.

Annex VII of Directive 2014/32 specifies an accuracy class 1.5 for a liquefied CO₂ measurement system wherein the flow meters must have an accuracy of 1%. Similarly, chapter 2.4 of R117-1 specify a system accuracy of 1.5% and meter accuracy of 1.0% for the measurement of liquid CO₂. NIST 44 has a dedicated chapter (3.38) for 'CO₂ liquid measuring devices' – though this is mainly aimed at smaller scale applications such as for road tanker loading. An accuracy class of 2.5 with an acceptance tolerance for the measuring devices of 1.5 % is specified.

Studies into CCUS flow meter solutions by, for example, TUV NEL (Hunter, et al., 2009) (Glen, et al., 2011), have identified three main meter types that might be suitable: differential pressure e.g. orifice plates, volumetric e.g. ultrasonic time of flight and mass flow e.g. Coriolis.

The operating principle of each type of meter is quite different leading to advantages and disadvantage for CO₂ measurement.

Orifice plates are a well-established, relatively low-cost technology that can be easily scaled for large pipelines. They rely on the principle that there is a pressure differential proportional to the flow rate across an orifice placed in a pipe. Figure 12 shows a typical design with the differential pressure transmitter mounted on top.

In general, the mass flow rate Q_m measured across the orifice can be described as:

$$Q_m = \frac{C_d}{\sqrt{1 - \beta^4}} \epsilon \frac{\pi}{4} d^2 \sqrt{2\rho_1 \Delta p}$$

where C_d is the coefficient of discharge, β (beta ratio) is the ratio between the orifice diameter d to



Figure 12. Orifice plate

pipe diameter D , ϵ is the expansibility factor, d is the internal orifice diameter under operating conditions m , ρ_1 is the fluid density in the plane of the upstream tapping, and Δp is the differential pressure measured across the orifice.

There are detailed standards, e.g. ISO 5167, for determining the values of the various coefficients. The key influences on accuracy are the differential pressure measurement accuracy – especially at lower flow rates and knowledge of the fluid properties – particularly the density which must be either measured or inferred. Measuring the density leads to an added uncertainty. Inferring the density from the equations of state becomes more challenging when there are significant levels of impurities in the CO₂ stream.

For CCUS applications, ultrasonic time of flight meters are a scalable volumetric meter technology. A basic schematic is shown in Figure 13. They work on the basic principle that a sound wave travelling in the direction of fluid flow will reach the other side of a pipe quicker than one travelling against the flow. The time difference is proportional to the fluid velocity. If the pipe diameter is known, then the volumetric flow rate can be calculated from:

$$Q_v = \frac{\pi \cdot D^3}{4 \sin(2\alpha)} \frac{T_{BA} - T_{AB}}{T_{ba} \cdot T_{AB}}$$

where Q_v is the volumetric flow at flow velocity v , T_{AB} and T_{BA} are the transit times of a sound wave from A to B and vice versa. D is the inside pipe diameter and α is the relative angle between the sound wave and the flow direction.

It can be seen from Figure 13 that if the flow profile is not uniform, potential errors can occur because the velocity of the sound wave will vary across the flow profile. This problem can be solved by adding flow conditioners upstream of the meter and increasing the number of transducer pairs. This leads to a highly accurate volumetric flow meter for most applications, which, unlike orifice plates has minimal pressure drop. The difficulty for CCUS is that the density needs to be measured or calculated

in order to obtain a mass value as per orifice plates. A further potential issue is sound attenuation in CO₂ that can lead to signal attenuation in the flow meter which impacts on uncertainty. This is a current area of research.

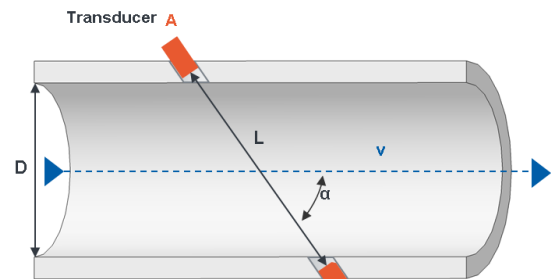


Figure 13. Ultrasonic meter schematic

In principle, Coriolis meters would appear to be the best type of meter for CCUS applications as they measure mass directly. However, an understanding of the basic principle also highlights some limitations.

A Coriolis flow meter is a mechanical system consisting of one or two measuring tubes usually straight or curved – though other more complex shapes exist. The basic layout of a twin straight tube meter is shown in Figure 14. The tubes are made to vibrate at their natural frequency. As fluid moves through the vibrating tube(s), it is forced to accelerate as it moves toward the point of peak-amplitude vibration. Conversely, decelerating fluid moves away from the point of peak amplitude as it exits the tube. The forces exerted by the tubes on the flowing fluid causes a delay, or time shift, in the oscillation of the tube end close to the inlet compared with the tube end close to the outlet which is accelerated by the force of the exiting fluid (labelled A and B in Figure 14). These forces are proportional to the inertia and, therefore, mass flow of the fluid and, thus the time shift is also directly proportional to the mass flow.

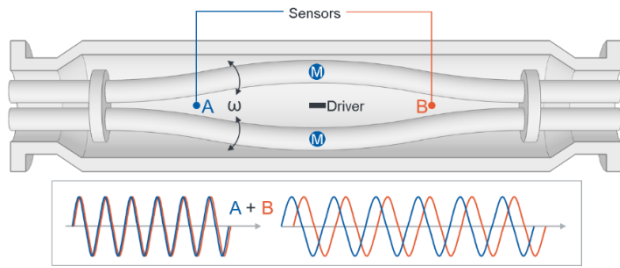


Figure 14. Coriolis meter schematic

According to Hooke's law, the natural frequency of the tubes will vary with the total tube mass (tubes plus process fluid). Given that the tubes themselves are of fixed mass and volume, any change in natural frequency will be proportional to the density of the fluid.

One key disadvantage of Coriolis meters is that they are a mechanical system that needs a high degree of mechanical integrity. This generally means a strong mechanical structure which makes scaling beyond 400 mm (16") nominal flange sizes a challenge because the meters can become very heavy and unwieldy. Coriolis meters generally also have a higher pressure drop than an equivalent ultrasonic meter except for those with a single measuring tube.

A limitation of all the metering technologies is that their accuracy significantly deteriorates under multiphase flow conditions – where gas bubbles form in the liquid. Ensuring single-phase flows could be a major constraint on the transportation network. It is clear from the above descriptions that the performance of flow meters for CCUS applications requires further research and testing.

Small-scale studies (Nazeri, et al., 2016) have shown that Coriolis mass flow meters perform adequately under reference conditions and with some impurities, but this needs to be further proven at a larger scale. Orifice plates have also been used for larger scale CO₂ measurement – especially for EOR but not qualified for fiscal metering. Testing of ultrasonic flow meters is limited by a lack of suitable test facilities. A multiphase test rig has been constructed in China

(Sun L. et al., 2016) but the capacity is too small for representative testing at CCUS flow rates or for ultrasonic flow meters – though it has been used for Coriolis meter testing.

The key challenge now is to develop a representative scale test facility to determine the appropriate flow metering technologies across the CCUS value chain with the aim being to determine what, if any, special requirements in the design, algorithms or calibration of such meters is required for direct use in CCUS applications. From this will come the standards that will then provide industry with the confidence required to trade and measure CO₂ flows across complex transport network.

3.2 Modelling Start-up Injection of CO₂ into Highly Depleted Gas Fields

The design and operation of CO₂ pipelines networks cannot be undertaken without due regard of their impact on the injection well and subsurface storage site. An integrated consideration is required when defining operational injection scenarios that take into account limitations arising from material specifications and down-hole and near-well phenomena. The latter include hydrate formation, the formation of a water-rich and a CO₂-rich liquid phase, and salt precipitation. Fully coupled models of pipeline, well and reservoir are required to simulate such scenarios.

Whilst most planned and operational projects worldwide use saline formations for CO₂ storage, new projects such as ERVIA (Ireland), HyNet (UK) and Porthos and Athos (The Netherlands) consider the use of highly depleted gas fields.

In the case of storage in saline aquifers, the sites are often in areas with sparse historical geological data and require new facilities to be constructed.

On the other hand, low-pressure highly depleted gas fields are better characterised given the availability of geological data derived from years of gas production and have seals that have successfully retained hydrocarbon gas for millions of years. Moreover, apart from significant storage capacity, they also offer a less costly route to implementation of CCUS projects given the potential of reuse of existing pipeline transportation and injection infrastructure (Sanchez Fernandez et al., 2016). For injection into these fields, transportation of CO₂ in the gas phase may be initially required followed by additional pumping or compression offshore to the dense phase. Indeed, the cancelled CCS ROAD project (ROAD, 2018) incorporated a transportation and injection system that was planned to follow this path.

However, the start-up injection of CO₂ arriving from the high-pressure pipeline or ship into depleted low-pressure gas fields requires appropriate injection strategies to manage the consequences associated with expansion induced temperature drop.

The dense phase CO₂ arriving via a subsea pipeline to the injection well will typically be at pressures greater than 70 bar and temperature between 4 to 8°C.

Figure 15 shows a schematic representation of a typical deep well CO₂ injection and storage facility. At the start of injection, the pressure in the subsurface reservoir can be substantially lower and appropriate system design and injection protocols are needed to control the pressure drop and associated temperature decrease (commonly known as Joule Thomson cooling effect).

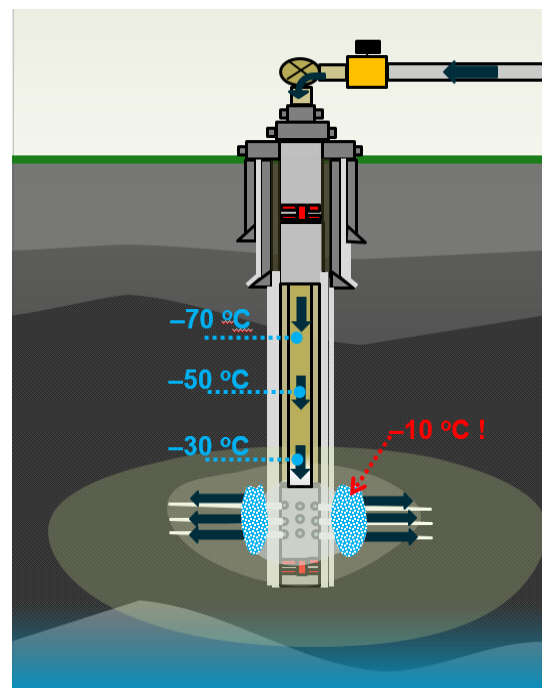


Figure 15. Schematic representation of a deep well CO₂ injection and storage facility (Sacconi and Mahgerefteh, 2019). Temperatures shown are representative of an unsafe injection procedure.

The temperature values shown in the figure represent an unsafe injection procedure. In practice, this process can give rise to several risks, namely:

- Blockage at the wellhead or at perforations at the bottom of the well to CO₂ hydrate or dry ice formation; or in the presence of appreciable concentrations of water, formation of ice.
- Thermal stress cracking of the steel well bore leading to the escape of CO₂.
- Sudden rise in the pressure at the well-head due to rapid boiling of liquid CO₂ leading to backflow into the pipeline system although in practice such risk may be minimised through the provision of non-return valves.

Preheating of the CO₂ prior to the injection into the well is not a viable option to overcome the above risks given the prohibitively high energy costs. As such developing appropriate start-up injection protocols involving the stepwise ramping up of the injection flow rate using in-line pressure control valves is the most practical option.

3.2.1 State-of-the-Art

A limited number of modelling studies with varying degrees of sophistication aimed at stimulating the start-up injection of CO₂ into depleted gas fields have been reported. Böser and Belfroid (2013) analysed the temperature and pressure in a CO₂ injection well during steady-state and transient flow modes, to show that safe operational procedures can be found when starting the initial injection with CO₂ in gaseous phase. Veltin and Belfroid (2013) considered CO₂ transport in a multi-store network to explore the feasibility of dense-phase CO₂ transport for storage in depleted fields, concluding that safe operational procedures could be found.

Sacconi and Mahgerefteh (2019) provide a comprehensive review of the relative merits and disadvantages. Based on their review, the authors conclude that many of the proposed models are based on steady-state flow assumption where the rapid pressure and temperature transients associated with the start-up injection process cannot be handled. The drift-flux flow models dealing with multi-phase flow behaviour usually contain several empirical parameters that must be

determined experimentally. They are also notoriously prone to numerical instabilities. The commercial simulator OLGA, also incorporating drift-flux flow, complicates its verification since little information is publicly available regarding its background theory.

To address the above, in the same paper, Sacconi and Mahgerefteh (2019) report the development and verification of a rigorous fully coupled fluid-structure injection model based on the Homogeneous Relaxation Model (HRM). The model accounts for the detailed design of the well, including its tapered geometry, deviation from the vertical, multilayer heat transfer characteristics of the well tubing, casing and the surrounding rock. The permeability of the storage site was obtained from the available empirically driven pressure-flow relationships based on the reservoir properties.

The authors used their model to simulate CO₂ injection into the depleted Golden eye Reservoir (ETI, 2016) in the UK sector of the North Sea using publicly available design and operational data. Realistic rapid, medium and slow linear ramping-up CO₂ injection rates up to the peak nominal value of 33.5 kg/s were simulated.

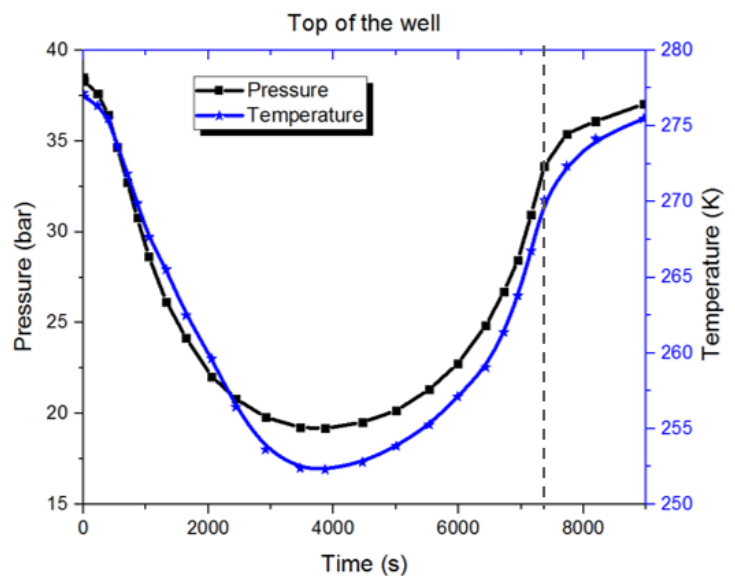


Figure 16. Transient pressure and temperature profiles at the top of the well for the slow injection ramping rate (Sacconi and Mahgerefteh, 2019)

Figure 16 shows a typical plot showing the transient variation of temperature and pressure at

the top of the well for the slow CO₂ injection ramp-up rate from 0 to 33.5 kg/s in 2 hrs. Based on the simulations of the corresponding transient temperatures at the wellhead and well bottom, the authors demonstrated the significant impact of the injected CO₂ pressure arriving from the pipeline or ship on the well integrity and storage performance namely:

- i) In all cases tested, the wellhead temperature fell well below zero degree centigrade, leading to the risks of well blockage due to ice formation or thermal shocking of the steel wall leading to its fracture and escape of CO₂. Hydrate formation was unlikely.
- ii) Remarkably, within the ranges tested, the slowest injection resulted in the highest risk of well blockage.
- iii) For none of the cases tested, the bottom well temperature fell far enough to indicate any risk of blockage of the well bore bottom perforations due to dry ice, hydrate or ice formation.

3.2.2 Remaining Challenges

Despite the success of the described model, the following important challenges need to be met in order to facilitate the utilisation of such models as practical control tools for safe start-up injection of high-pressure CO₂ into depleted gas fields:

- i) More rigorous modelling of the transient multi-phase flow fluid flow along the well by accounting for a broader range of flow regimes.
- ii) Verification of flow behaviour of CO₂ with impurities near chokes and valves.
- iii) Fully coupled validated models of reservoir, well and pipeline (or multiple reservoirs, wells and pipelines) that can handle CO₂ flows with impurities. These models are needed to fully understand the interaction between reservoir, well and pipeline (or multiples thereof) during the design and operation of the system (Böser and Belfroid, 2013).

- iv) Validation against data obtained using realistic scale experiments to gain credibility.
- v) Optimal choices of materials in CO₂-injection wells with respect to well integrity and operational conditions (Aursand et al., 2017).
- vi) The Peng–Robinson Equation of State (EoS) was employed in the Sacconi and Mahgerefteh's (2019) model to generate the required phase equilibrium and thermophysical properties for CO₂. Apart from problems in handling low concentration impurities, the equation's performance is uncertain at low temperatures. Subject to overcoming the significant computational load, the application of the Span and Wagner EoS (Span and Wagner, 1996) is expected to overcome its shortcomings.

3.3. Pipeline Network Safety

3.3.1 Fracture Propagation

For pipelines transporting pressurised fluids, including CO₂, it is important to ensure that a defect does not form a running ductile fracture and that any running fracture be quickly arrested (Maxey, 1986). The likelihood of a leak or rupture depends on the size and shape of the defect, the pipeline design safety factor and the pipe diameter and wall thickness. For CO₂ pipelines, ensuring running-ductile fracture arrest will often be a restrictive design criterion.

Dense phase CO₂ is a high vapour pressure fluid and when a rupture is initiated the CO₂ starts as a liquid and rapidly decompresses to the pressure where bubbles of gas form. In the event of an uncontrolled release, the energy released by the decompressing fluid provides a driving force which can cause defects to propagate. It has been found that a pipeline carrying CO₂ in the dense phase will have a higher propensity to running-ductile fracture than a pipeline transporting, e.g. natural gas (Aihara and Misawa, 2010; Mahgerefteh et al., 2012). In simple terms, this is due to the high saturation pressure reached from a 'typical' dense phase state, as well as the very large difference between the single-phase and two-phase decompression. The fracture propagation is governed by a 'race' between the decompression speed in the fluid and the fracture velocity in the pipe steel. If the fracture velocity is faster, the pressure at the crack tip will remain high, and the fracture will propagate. On the other hand, if the decompression speed is faster, then the pressure at the crack tip will fall and the crack will arrest.

In a CO₂ pipeline network, it is important to consider the effect of different and likely varying CO₂ stream compositions. If the CO₂ contains typical 'non-condensable gases' like H₂ or N₂, this will affect the phase envelope and the maximum pressure at which a two-phase state can occur (see Section 4.1. The phase envelope can be significantly affected by impurities in the 1% range. From the discussion

above, it follows that this will affect the design against running-ductile fracture (Mahgerefteh et al., 2012; Cosham et al., 2014; Nordhagen et al., 2017).

There is no existing, validated methodology for defining crack arrest toughness levels for CO₂ rich mixtures. The most common engineering design method used to assess running-ductile fracture is the semi-empirical Battelle Two-Curve Method (TCM), although it has been shown that this method cannot be directly applied to dense phase CO₂ pipelines (Jones *et al.*, 2013). Current US, European and UK pipeline codes require fracture control by defining appropriate line pipe material toughness to ensure fracture arrest, or by the installation of crack arresters. CO₂ pipelines in the US are commonly equipped with crack arresters at regular intervals (IPCC, 2005, Sec. 4.2.3). Botros et al. (2013) recommended at least one to two full-scale burst tests for each design case, while the ISO Standard on CO₂ transportation (ISO, 2016) states that '*Where the combination of pipeline materials and CO₂ stream to be transported lies outside the range of available full scale test data, a full scale test should be conducted...*'. The ISO standard also gives a version of the TCM modified based on experimental data available at the time which was very limited – but without recommendation. Whence there is a need to better understand running-ductile fracture, which is a coupled fluid-structure problem (Mahgerefteh and Atti, 2006).

One hypothesis is that additional insight may be gained by building models representing more of the fluid and structure physics (Nordhagen et al., 2012). The insights gained from such models, validated by full-scale fracture propagation tests, as well as separate validation for the fluid and material submodels, may then be employed to obtain engineering models properly describing running-ductile fracture in CO₂ pipelines.

Experimental validation against medium-scale crack-arrest experiments for CO₂ was performed by Aursand et al. (2016). The coupled-model calculations showed that the pressure load on a

bursting pipeline filled with CO₂ is significantly more severe than in the case of natural gas. This may be one reason why TCM has been found to fail for CO₂.

More work is needed to validate the above-mentioned coupled models against experiments conducted with CO₂. Full-scale pipeline tests with CO₂ or CO₂-rich mixtures have been published by Jones et al. (2013), Cosham et al. (2014), Cosham et al. (2016), Di Biagio et al. (2017) and Michal et al. (2018). In addition, some medium-scale instrumented burst ('*West Jefferson*') type tests have been performed (Cosham et al., 2012; Jones et al., 2013; Aursand et al., 2016). The scale here relates to the pipeline length; over 100 metres for full scale, and around 10 metres for medium scale.

Many CO₂ storage sites are expected to be located offshore. It is therefore relevant to consider the integrity of offshore pipelines. Long running fractures may be less of a challenge offshore, among other things, due to the high surrounding pressure. The model described by Aursand et al. (2016) was employed on an offshore pipeline design considered for the Northern Lights CCS project (see Gruben et al., 2018). It was found that, according to the model, the pipeline was safe. However, should a pipe rupture occur, it is of interest to estimate the leakage rate and the extent of the CO₂ plume generated. Herein, it may be necessary to consider the complex phase behaviour of CO₂ water mixtures.

3.3.2 Pipeline Corrosion

Pipelines and tanks in ships are usually made of carbon steel. If the carbon steel surface is wetted by a water containing phase the question is not if corrosion will take place, but at what rate. The corrosion rate of carbon steel exposed to aqueous phases and CO₂ can be high (several mm/y) and keeping the pipeline system 'dry' is therefore essential for the safe operation of a CO₂ pipeline network. When "dry" CO₂ streams with different CO₂ composition are mingled the

product stream can become "wet", as corrosive aqueous phases form due to reactions between the impurities. A CO₂ transport network is therefore more challenging to control than a single transport line from one source to one sink.

When acceptable water contents in CO₂ streams are discussed, it is usually argued that no water containing phase will precipitate and cause corrosion as long as the water concentration is well below the solubility in pure CO₂. The water solubility in pure CO₂ is more than 1000 ppmv in the and pressure range relevant for pipeline transportation, and both laboratory experiments and field experience confirm very low corrosion rates for pipelines where the water content is in the 20 to 650 ppmv range (Oosterkamp et al., 2008).

The water solubility will change when impurities are present. The predicted water concentration giving precipitation of aqueous phases in systems with non-condensable impurities like Ar, N₂, and CH₄ will not change very much compared to the pure CO₂ system. Due to lack of data there are presently no publicly available models that can predict the precipitation of aqueous phases when reactive impurities (combinations of NO_x, SO_x, H₂S, O₂, H₂O, CO) are present. The lack of data was recognised in the ISO standard for CO₂ transportation that was issued in 2016. In the standard it is stated that "*Since the maximum (allowable) concentration of a single impurity will depend on the concentration of the other impurities, it is not possible due to lack of data and current understanding to state a fixed maximum concentration of a single impurity when other impurities are, or may be, present*". The standard therefore recommends consulting the most up to date research during pipeline design.

Dugstad et al. (2014) and Morland et al. (2019a and 2019b) have shown that aqueous phases can form at low water concentrations (< 100 ppmv) when small amounts (< 100 ppmv) of impurities like SO₂, NO₂, H₂S and O₂ are present. These impurities can react and form elemental sulphur and strong acids giving aqueous phases with high concentrations of

dissolved sulphuric acid (H_2SO_4) and nitric acid (HNO_3).

Defining a safe but non-conservative operation window without corrosive phases in complex transportation networks is challenging. The number of possible impurity combinations and operational conditions (pressure, temperature, flow velocities) can be huge when CO_2 streams with different compositions are mingling.

In order to systematise the data and to predict the possible formation of aqueous phases for combinations of impurities that have not been tested experimentally, it is necessary to develop a thermodynamic approach for extrapolation. Such work is ongoing in the industry driven KDC project (Kjeller Dense phase CO_2 project, phase I, II & III) at IFE, where a thermodynamic model taking chemical reactions into account is developed in cooperation with OLI Systems.

3.4 The Viability for the Use of Existing Infrastructure: Change in Use

There are significant cost savings to be made in utilising existing infrastructure for transportation and injection of CO₂ into the storage site. The following discusses the opportunities and the remaining technical and legislative challenges that must first be overcome in the context of using existing natural gas pipelines. In the case of offshore storage of CO₂, bearing in mind the scope of this report, and for the sake of completeness, a preliminary discussion regarding the potential for using existing oil and gas production platforms is also presented.

3.4.1 Natural Gas Pipelines

An extensive hydrocarbon pipeline network is present in the North Sea which is over 45,000 kilometres in total length. Some of these pipelines could be suitable for the transportation of CO₂ to secure geological sites for sequestration or to existing oil fields for EOR activities. The condition of redundant pipelines is often uncertain and would require assessment and potentially remedial intervention before reuse.

In the UK and Norwegian sectors, 850 pipelines with a combined length of 7,500 kilometres are planned to be decommissioned during the next decade. It is estimated that this activity will have a cost close to £1 billion. Reusing an existing oil or gas pipeline for CO₂ transportation in a CCS project may cost 1-10% of the cost of building and installing a new pipeline (IEAGHG, 2014). However, EBN-Gasunie (2017) note that pipeline re-use on the Dutch continental shelf may be limited because gas production will continue for several decades and the location of the pipeline entry points at the shoreline may not be close to CO₂ collection and compression sites.

The change in use of existing natural gas pipeline assets and the associated Above Ground

Installations (AGIs) involves assessing the design and construction requirements on a 'case by case' basis in order to ascertain their suitability for the transportation of a different product and potentially at different operating conditions (IEAGHG, 2018). General statements about the feasibility of re-using oil or gas pipelines for CO₂ transport cannot be made.

Change in use can only be performed following a detailed assessment and demonstration that the existing natural gas pipeline assets and the associated AGIs are suitable and safe to be operated with a different product and under different operating conditions. Noting that with some Member States legal and regulatory obligations will have to be complied with, and any change in use may have to be approved by the safety regulator prior to it taking place.

The following sections outline the key areas that need to be considered at a high level and outline a procedure for pipeline change of use.

3.4.1.1 Key Factors to be Considered

Design factor limits

The design factor limits at the 'new' maximum operating conditions need to be checked to ensure compliance with the pipeline specification or code being used.

Assessment of probability of failure due to all mechanisms

All possible failure causes (external interference, external corrosion, seam and girth weld defects, defect free pipe subject to pressure and external loading) are to be identified and the possible risk of failure at the proposed new operating conditions assessed using probabilistic studies. This must include the impact of the change in product on asset integrity and the probability of existing damage or defects failing at the proposed 'new' operating conditions.

Identification of additional damage/deterioration mechanisms under changed

operating conditions

All additional failure mechanisms relating to the changed operational conditions must be identified, considered and evaluated; when changing from natural gas to CO₂, e.g., the potential for internal corrosion needs to be evaluated.

For changes in operational conditions the pipeline's maximum operating pressure, potential for fracture propagation and pressure cycling (fatigue) effects need to be evaluated.

Probability of failure and failure frequencies on changing operating conditions

The probability of failure of any existing damage or defect failure following a change in use must be evaluated using the most recent internal inspection (i.e. In-Line Inspection (ILI)) information prior to the change in operation.

The probability of failure following change in use should include an uncertainty analysis and must be compared to the pipeline's operation to date and be demonstrated to be acceptable.

The probability of failure analysis for each damage mechanism is used to develop cautious best estimates of the frequency of failure for specific pipelines.

Hazard distance and evaluation of consequences under changed operating conditions

The hazard zone within which harm to people may occur as a result of a release of product when the pipeline is operating at the maximum pressure must be determined. The assessment must consider:

- The type of hazard posed (i.e. thermal radiation, toxicity).
- Failure mode (leak or rupture).
- Fluid momentum, density and dispersion characteristics.
- Exposure limits for toxic hazards.

The consequences of failure in terms of the harm to

people in the hazard distance for each failure mode must be determined and are normally calculated in terms of the concentration level with distance from the point of release.

Individual and societal risk assessment

The failure frequencies and consequences of failure are used to calculate the individual and societal risks posed by the pipeline being considered for change in use.

This procedure involves determination of the:

1. Failure frequency due to all damage mechanisms.
2. Rate of release for each failure mode and the calculation of consequences (i.e. toxic concentration level) with distance and its time variation.
3. Effects on people (taking account of shelter and escape).

Justification of safe operation under changed conditions

Justification for the change in use is carried out by assessing the probability and frequency of pipeline failure during service using Societal Risk Assessment (SRA) and assessing the consequences of failure in terms of individual risk and societal risk. The aim is to ensure the risks posed by the pipeline under changed operational conditions satisfy the ALARP (As Low As Reasonably Practicable) principle.

The SRA process is used to demonstrate that the change in failure probability of the pipeline following change in use compared to previous operation is acceptable. This involves:

- Identification of all credible failure mechanisms, based on consideration of the impact of the product on pipeline integrity, the loads on the pipeline and the resistance of the pipeline to these loads.
- Assessment of the proportional change in failure probability for each failure mechanism when operating at the changed operating conditions compared to the

current operating conditions.

- Assessment of whether the absolute value of failure probability due to a particular failure mechanism at the changed conditions is a significant contributor to the overall pipeline failure probability. This applies for each failure mechanism for which the proportionate increase in failure probability is significant.

- Modifications and repairs since construction.
- Condition monitoring results and actions.
- Pressure cycling/fatigue history.
- Corrosion protection history.
- Proximity and population density infringements and area classifications.

3.4.1.2 Procedure for Change in Use

The procedure for changing the use of a pipeline and its associated installations is carried out in the following stages:

1. Viability - identification of any fundamental characteristic which may prevent change in use.
2. Design and operability data assessment - design review and identification of all modifications necessary.
3. Detailed technical assessments.

Each of the three stages are considered below.

Viability

The viability study involves an initial assessment of the original design assumptions and features, and of the physical characteristics of the pipeline and the existing route to confirm the viability of operation with a different product and/or under a differing set of operating conditions.

Design and operability data assessment

The following data needs to be compiled to assess the design and operability for the proposed change in use of a pipeline and associated installations:

- Original design criteria.
- Construction standards and procurement details.
- Previous test results.
- Metallurgical details of all pipeline materials and those of the attachments to it.
- Operational records including, but not limited to:

This data is used to carry out a detailed integrity assessment and risk analysis of the pipeline and associated installations. Any modifications required for the change in operation must be identified and specified.

Detailed technical assessments

The technical assessments required for justifying the change in use of a pipeline are:

- Design factor(s) along the pipeline route.
- Hydrostatic pressure testing either conducted or required.
- Fittings.
- Fracture toughness.
- Known defects.

- External loads and areas with reduced depth of cover.
- Temperature.
- Risk Assessment of infrastructure infringements (e.g. proximity and population density wise).
- Risk on implementing the change in use.

The technical assessments required for justifying the change in use of the associated installations cover pipework and fittings, pressure vessels, equipment and associated systems such as control and instrumentation, and includes, but are not limited to, the following:

- Integrity assessment of pipework, fittings, vessels and equipment.

- Equipment functionality and operability for use with a change in product and/or at the new operating conditions.
- Material durability.
- Condition of all assets including, but not limited to:
 - Damage assessment of exposed pipework, equipment and vessels.
 - Corrosion assessment of buried pipework and equipment.
 - Vibration analysis.

3.4.2 Platforms

No general statement can be made about the feasibility of re-using production platforms for CO₂ injection. In the North Sea, some platforms have seen a production lifetime of several decades and adding another 10 to 20 years of injection activity may not always be possible (e.g., IEAGHG, 2018). Nevertheless, projects like ERVIA (Ireland), HyNet (UK) and Porthos and Athos (The Netherlands) base their transportation and injection system on re-use of existing production facilities. The ROAD project in Rotterdam completed a pre-FEED (Front End Engineering and Design) level platform workover (ROAD, 2019), which is evidence of at least one feasible re-use case.

Significant cost savings can be reached by re-using platforms/topsides. While again highly case-specific, an analysis of storage costs for the Dutch offshore infrastructure suggests that extensive re-use could lead to 30% lower cost, compared to new built platforms and wells (EBN-Gasunie, 2017).

In the case of storage in saline aquifers, platforms or sub-sea installations generally are new build. The advantage is that well placement can be optimised and the wells can be designed specifically for the injection of CO₂.

3.5 Capacity to Cope with Changes in the Energy Supply Landscape: Pipeline Right Sizing

Mechleri et al. (2017) developed an optimisation methodology to 'right-size' CO₂ transportation infrastructure accounting for the transient flow of CO₂ arising from the co-deployment of intermittent renewable energy generators corresponding to scenarios for the 2030s, 2040s and 2050s in the UK. By application of their methodology for three CCS power plants in the UK, they predicted a decadal reduction in the average CO₂ emissions concluding that pipelines with sufficient capacity to cope with the expected 2030 emissions are already oversized by as much as 30% to what would be required in the 2050s.

Identifying the size of the pipelines required on a CO₂ transportation network is a challenging and complex task that has to balance a wide range of factors whilst ensuring assets are not under or over utilised, including but not limited to, the following:

- The business models in place including the rate of return on investment and the approach taken to pre-investment options.
- Accounting for likely emitters with credible cross-sector decarbonisation plans and possibly incorporating an element of 'future proofing' to facilitate additional emitters connecting onto the CO₂ transportation system as decarbonisation progresses.
- Composition of the CO₂ stream and the co-mingling of the various supplies whilst ensuring compliance with the pipeline systems design.
- Operating regimes for the various emitters (e.g., is operation envisaged to be continuous for 24 hours per day and 365 days per year, several shifts per day, a rolling cycle of 24 hours per day operation for a defined period then the process will be

shut down for a period before restarting the sequence etc.).

- Flow requirements and how the flowrate varies during normal operation.
- Flow profile over defined planning horizons into the future.
- Variations in flow requirements due to plant changes, etc.
- Capital cost of projects.
- Operational considerations and costs.
- Pipeline constructability.
- Project consentability.
- Pipeline system operability.
- Resource availability (e.g. availability of pipe in the sizes required etc.).

3.6 Marine Transportation

3.6.1 Introduction

Ship transportation of food grade CO₂ in small scale (mostly 1000-2000 tonnes) has taken place for decades. Food quality CO₂ is transported at 15 to 20 bar from coastal point sources to distribution terminals.

Publicly available work on large scale ship transport of Liquid CO₂ (LCO₂) started appearing in the early 2000s with several patents by Mitsubishi Heavy Industries (Mitsubishi, 2002). Kaarstad (2003) conducted an overall assessment for ship and pipeline transportation of CO₂ to an oil field in the North Sea. The first detailed technical and economic study on CO₂ ship transport, by Aspelund et al. (2006), recognised the potential role for shipping in developing the use of CO₂ for EOR, identifying the financial incentive of EOR which give a value to CO₂. Further benefits of ship transport pointed out by this study were the flexible collection of CO₂ from several low-cost sources, flexibility for delivery to different locations and the relatively low capital expenditure for ship based transport compared to pipeline transport.

3.6.2 Transport Conditions for LCO₂

Ship transport of CO₂ on a larger scale will be economically viable for relatively long transport distances or relatively small volumes (e.g. Barrio et al., 2005; Munkejord et al., 2016, Vermeulen 2011) compared to pipeline transportation. In addition, the flexibility of ships could have an advantage in early CCUS deployment. Ship transport was considered at low (6-8 bar), medium (15 bar) and high-pressure (45-60 bar) (Ministry of Petroleum and Energy, 2016) for the Norwegian CCS demonstration project. As the volumes to be transported (7500m³ ship) were small and the timeline demanded low technical risk, it was decided to transport at a medium (conventional) pressure (Northern Lights 2019). However, it was noted that an increase in transport volume would warrant a lower pressure carriage condition to gain

greater economies of scale. From a pure ship transport point of view, low-pressure (with a corresponding low temperature) is considered optimal due to the high liquid density and low gas density (Aspelund et al., 2006). In the recent literature there is a consensus on the low-pressure based transport approach being the techno-economic optimal transport condition (Geske et al., 2015; Knoope et al., 2015; Roussanaly et al., 2013).

3.6.3 LCO₂ Impurities

The Norwegian CCS demonstration project (Northern Lights 2019) have developed a specification for the impurity levels of LCO₂. The purpose of this specification is to avoid ice and hydrate formation in LCO₂ operations, to avoid corrosion in cargo vessels and piping, and other potential risks to the installations. If the specification is conservative it will induce a higher purification cost than required. In any case the specification will need revision in the case of transportation at low-pressure.

Very few studies have included the impact of CO₂ stream composition on ship transport. Engel and Kather (2018) considered the liquefaction of a pipeline CO₂ stream. They found that an increased impurity concentration leads to an increased energy demand of the liquefaction process and to a shift from electrical to thermal energy demand for the injection. Deng et al. (2019) studied the effect of ship transport pressure and impurities on the economics of CO₂ liquefaction. Impurities were found to increase the liquefaction cost significantly, especially for the low-pressure case. In order to get the holistic view, these results must be integrated with the transport cost.

3.6.4 Operation

During normal filling and unloading of the ships, the pressure in the storage vessels will be maintained by gas unloading/injection. This implies that the net transport is defined from the liquid-gas density difference at transport conditions. For the food grade conventional LCO₂ transport it is common practice to fill the vessels

using subcooled LCO₂ to prevent pressure creep during transport. This practice will be more complicated for low-pressure transport.

Controlled or accidental depressurisation might happen with the formation of solid CO₂. Special consideration is therefore required for the vent system used.

3.6.5 Legislation and Regulations

Requirements and rules for transporting LCO₂ and other liquified gases (ethylene, ammonia, Liquified Petroleum Gas (LPG) and Liquified Natural Gas (LNG)) are specified by the International Gas Carrier Code (IGC Code) 'International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk' (IMO, 2016)). These regulations and requirements would also govern the design of LCO₂ tankers in addition to applicable Classification Society rules and regulations.

A standing legal issue in regard to ship transportation of CO₂ in the European CCS-context is the scope of the EU ETS. The wording of Directive 2003/87/EC Annex I only covers the transportation of CO₂ by pipeline. This creates legal uncertainty in regard to the effects of ship transportation for the need of EU ETS allowances (Rydberg and Langlet, 2015).

3.6.6 Carrier Tank Design for LCO₂

Carriers designed for the transportation of liquefied gas can be divided into two main groupings dependent on the type of cargo they are designed to carry:

- LPG carriers are designed to carry butane, propane, butadiene, propylene and Vinyl Chloride Monomer (VCM) type products.
- LNG carriers are designed to carry LNG mostly comprising of methane.

Gas carriers can be subdivided further into three main types based on the hazard potential of their cargo. These include Type 1G carriers which are designed to carry highly hazardous cargoes, Types 2G/2PG carry less hazardous gases and finally Type

3G for the least hazardous carriage.

Depending on the cargo type (LPG/LNG/CO₂), the product may be transported at varying temperatures and pressures.

Independent tanks, as their name suggests, are self-supporting in design and generally do not contribute to the structural design of the vessel. Independent tanks can be categorised into A, B and C type pressure vessels as follows:

- Membrane and Type-B (Prismatic Self-Supporting) tanks are designed to manage temperatures at or below -160°C; however, the IGC Code (IMO, 2016) restricts pressures to around 0.7 bar limits.
- Type-C and BiLobe Tank Designs could be constructed to suit the pressure and temperature requirements of liquefied CO₂ transport; however, the selection of material and wall thickness will be a key criterion. The typical maximum pressures of BiLobe tanks range between 6–7 bar. Type-C tanks are traditionally shell type designs and can operate up to a design vapour pressure of around 20 bar.

3.6.7 Multi-Gas Ships for LCO₂ Transport

Existing LCO₂ carriers

There are a number of existing small-scale vessels which are designed for transporting LCO₂. The Nippon Gases vessel fleet which are operated by Larvik Shipping comprise of the Froya, Embla and Gerda vessels and are actively transporting around 1,800 tonnes food grade CO₂. The Embla features a double tank design with working pressures of 15–20 bar and temperatures of -30°C, (Tel-Tek, 2014). It is important to note that these vessels are reconfigured bulk carriers so the cargo to weight ratio of the tanks may not be fully optimised for the vessel size.

The Coral Methane multi-gas (LNG, LPG, Liquefied Ethylene Gas (LEG)) vessel, designed by Anthony Veder has a capacity of 7,500 m³ but is limited to

cargo densities of around 650 kg/m³ and working pressures of approximately 3.0 bar (Tel-Tek, 2014, Decarre et al., 2010).

The Coral Carbonic '*semi-ref*' was the first vessel constructed for transporting liquefied CO₂ and features a single cylindrical cargo tank with capacity of 1,250 m³ rated for pressures of up to 18 bar.

Gas-carrier conversion

A number of previous studies have investigated conceptual designs for LCO₂ carriers, considering both new build and conversion of existing gas carriers, for high volume loads (Tel-Tek, 2014, Decarre et al., 2010, IEAGHG, 2019). The design of any large capacity dedicated CO₂ cargo vessel will depend on the size and quantity of pressure vessels onboard. The key drivers for sizing the pressure vessels will depend on the pressure of the liquefied CO₂.

Currently there are no large LPG carriers with Type-C pressure vessels. Whilst the CO₂ temperatures proposed would be compatible with Type-C tanks, the pressures would be outside of the design parameters and IGC code requirements (IMO, 2016). One of the challenges would be the density of the CO₂, which may be possible to manage through partial loading.

Because the density of CO₂ is about twice that of LPG, the cargo volume capacity of the LPG carrier will be greatly reduced when carrying LCO₂. This presents some particular challenges with the product in the tanks '*sloshing*' during transit. CO₂ '*sloshing*' can cause damage to the membranes of the tanks under hydraulic loading and/or excessive generation of Boil Off Gas (BOG) as the product heats-up.

There are a number of '*Moss*' type LNG vessels that were certified to carry Naphtha at a density of around 750 kg/m³ and when stationary could manage tank pressures in the order of 4 bar. These vessels may be able to operate partially loaded with CO₂. However, however they have been known to

have stability limitations (i.e. too stiff) when partially loaded, so carrying a product with increased density would require further study. Changes to the gas carrying codes (IMO, 2016) would be required to permit such an arrangement.

3.6.8 Offshore Offloading

Vermeulen (2011) published a knowledge sharing report considering the entire chain of liquid CO₂ transport by ship. Several types of infrastructure for offshore offloading systems were considered and well simulations were performed to characterise the temperature dynamics stemming from the batchwise injection of CO₂.

The offloading systems available can be categorised for use as either '*direct*' injection systems in the case of offloading via a Single Point Mooring (SPM) or as an '*indirect*' systems used to offload cargo to another facility for injection.

Both the '*indirect*' and '*direct*' loading systems feature a flexible hose or pipe required to transfer the LCO₂.

Jetty mooring platform

A fixed jetty with marine loading arms can be used for offloading LCO₂ onto cargo vessels from a third-party supply port. Jetties are commonly used near-shore for shallow water and sheltered coastal areas. Jetties are therefore typically used in water depth ranging from 15 meters to 20–25 meters. Jetties are used as a permanent mooring for near-shore terminals. The vessel is moored in a fixed position and can therefore not weathervane into the prevalent weather.

Tandem offloading

Tandem offloading takes place with the cargo vessel positioned astern of the moored vessel on approximately the same heading relative to prevailing weather conditions. During the transfer the cargo vessel is at a stand-off distance between vessels typically between 80–100 metres. Tandem offloading was traditionally performed under a taut

hawser¹³ condition whereby the cargo vessel maintains an astern thruster (30% power) during operations or as a passive hawser operation with the cargo vessel on full Dynamic Positioning (DP) (minimum DP class 2). More recently, with the advancement of DP systems, tandem operations are being performed with a slack hawser or in some cases without the use of any hawser. Today, over 15 fields in the Norwegian Continental Shelf operate using tandem offloading systems.

According to key vendors (MacGregor Pusnes, Royal IHC, APL Offshore) there are no major design obstacles prohibiting application of Bow Loading and Stern Discharge systems for LCO₂ transfer.

Articulated loading arms

Significant efforts have been made to develop dynamic loading arms capable of supporting side-by-side transfer between Floating Liquefied Natural Gas (FLNG) and LPG/LNG carriers in order to offer LNG transfer to standard LPG/LNG carriers which have manifolds positioned mid-ship.

One example is the Articulated Tandem Offshore Loader (ATOL) designed by TechnipFMC.

Yoke mooring

Yoke mooring designs feature a vessel moored to a fixed structure while being allowed to weathervane into the prevailing weather. Initial designs were based around rigid arm structures connecting the vessel bow to a fixed turret structure, however this design is typically limiting the system to benign environments only. Subsequently soft yoke mooring systems were developed to provide additional flexibility and withstand harsher environments. These systems consist of a pendulum structure that allows increased movement of the vessel. Yoke mooring systems are typically designed for use in shallow water depths typically between 20 meters and 50 meters.

CALM buoy

Catenary Anchor Leg Mooring System (CALM) buoys are typically turntable or turret designs and the offloading tanker moors to the SPM using a hawser similar to a tandem offloading operation and offloads via a floating hose arrangement connected to the tanker midship manifolds. Offloading vessels can typically moor to the SPM in head-sea conditions ranging from 2 – 2.5 meters with offloading operations possible up to a maximum wave height of 4.5 meters. One of the challenges of using CALM buoys is that mariner support is typically needed to assist with the connection and often disconnection of floating hoses during offloading operations.

The Single Anchor Loading (SAL) system designed by APL (NOV) is a single-leg mooring system where the vessel is moored to a subsea swivel anchor base. The SAL was developed as a low-cost alternative to the STL system. The SAL system is typically located a distance from the offshore installation allowing the cargo vessel to connect and weathervane freely without risk of collision. Polyester mooring rope is used to maintain the connection with the subsea swivel. The rope is buoyant in order to maintain acceptable loads at the bow hang-off.

Submerged-Turret Loading (STL)

The Submerged Turret Loading (STL) system offers a fully disconnectable offloading system. The STL consists of a buoy which is moored to the seabed. When an offloading vessel comes on-site the buoy is retrieved and pulled in and secured in a dedicated mating cone positioned in the hull of the vessel. The submerged buoy incorporates a turret which is connected to the mooring lines and riser(s) and to the umbilical. All STLs are based on standardized mating cone geometry in the vessel. The primary drawback with the STL system is the requirement for dedicated custom-build or modified vessels and hence eliminates the possibility of using vessels of opportunity. The mooring system allows a passive station-keeping

¹³ A 'hawser' is a rope/chain arrangement is used to moor a tanker to a buoy or another vessel.

with DP required for connection and disconnection only.

STL systems are field-proven for use with '*re-gas*' systems with existing systems designed with 350 mm (14") diameter flexible risers and design pressures up to 150 bar.

3.7 Stranded Emitters: Onshore Transport, Truck and Rail

In order to meet the stringent decarbonisation targets across the EU, it will be necessary to extend deployment of CCUS to small emitters (less than 0.2 Mtpa). Examples include hydrogen production plants, refineries, gas fired process heaters, paper and food industries (Yorkshire Forward, 2008). The above catchment should also include 'stranded emitters', i.e. those for which the distance from planned clusters makes their inclusion impractical, many of which will also be industrial sites (Psarras et al., 2017). Given their wide geographical spread and their relatively low emission rate, the rollout of CCUS to these sites and, in particular, connection onto the CO₂ transportation infrastructure, presents unique challenges over and above those faced by the large clusters. Furthermore, while there has been significant international policy attention in driving the formation of CCUS clusters, comparatively little attention has been given to smaller emitters and, as such, the available transportation options have not received the same level of attention. Here, we will briefly explore the challenges posed in connecting these sources into the wider CO₂ transportation infrastructure. We then present the available options and propose areas of work that are required to gain the understanding required to address these issues.

3.7.1 Challenges

The challenges faced in the rollout of CCUS transportation infrastructure can be summarised as:

- Firstly, and most obviously, the benefit of economies of scale to reduce costs that is gained through the clustering of emitters and developing 'shared use' infrastructure which could be cost prohibitive for a single site. Indeed, for some locations, the cost incurred providing transportation infrastructure may be sufficiently high that in order to decarbonise, the relocation of

operations may be preferable (Element Energy, 2013)

- Secondly, questions remain regarding the business models for transportation infrastructure as it is not clear how the development of CCUS transportation and storage infrastructure is to be funded and how the smaller emitters outside of the larger clusters would be connected to the transportation pipelines to facilitate industrial decarbonisation, whilst accepting that for some of transportation options (e.g. truck or rail) that they don't necessarily represent the same kind of shareable infrastructure.
- Finally, and in addition to any issues with regards the capture plant, the energy requirement for conditioning and compression/liquefaction, which is already a substantial operating cost (Bui et al. 2018), may present a significant additional barrier to accessing transportation infrastructure. Existing work for non-pipeline transportation has indicated that these costs may be higher than for pipelines (Roussanaly et al., 2017).

3.7.2 Options

In order to address these challenges, four options, or some mixture thereof, exist:

A. Onshore pipelines connecting to an existing cluster's infrastructure

This requires consideration of the potential for this during the initial design of the high-pressure transportation pipelines for clusters, though this has already been foreseen in existing cluster studies (National Grid, 2014). In the case where a cluster is not available or sufficiently close, a 'point to point' arrangement may have to be adopted which would therefore represent a significant cost. As with all onshore pipelines, there will be challenges faced in consenting, though the reduction in both CAPital EXpenditure (CAPEX) and

Operational EXpenditure (OPEX) are also a priority. To this end, various design and operational alternatives might be explored, for example:

- Operation of a lower pressure pipeline system using smaller diameter pipe for the smaller emitters that might be tied into the cluster network with a central cluster providing conditioning. This would reduce CAPEX and OPEX for emitters and would allow some benefit from economies of scale from final compression. However, demands on pipelines transporting largely unprocessed CO₂ have not been thoroughly investigated yet.
- Centralised intermediate storage to provide an entrance point to the cluster pipeline system, which might potentially allow very small emitters to access infrastructure while providing constant flow into the pipeline network.

B. Road and rail transport: where volumes are low

Rail transport is obviously constrained by the availability of access to existing or, where there is potential for new, rail infrastructure, and an understanding of the overall maximum capacity that these can reach both globally and for individual sites. There have been comparatively few studies into the use of road or rail as an option for CCUS deployment and their operation within a wider transportation infrastructure system has not been considered in detail. Further on-site requirements, such as the need for on-site storage, present additional technical and economic challenges; however, there is transferable expertise from the intermediate storage systems that are already part of the existing projects described above.

C. Shipping for sites near ports that are properly equipped

The current state-of-the-art and issues of shipping as a primary transport vector have been discussed in Section 3.6 and won't be repeated here. However,

use of intermediate storage as part of plans for ongoing projects and proposed clusters obviously represents an opportunity for integration for smaller emitters, if cost effective transportation to the store can be provided.

D. Siting of CO₂ utilisation alongside emitters

Where emissions and demands can be adequately matched, and where sites are available, there is also the potential for the siting of CO₂ utilisation technologies close to the emitters. While this does not entirely ameliorate the issues with dispersed emitters and may well only be possible in a small number of cases, this may also encourage the deployment of CCUS (Psarras et al., 2017). There is also a possible link to the second point above where CO₂ captured could be transported by road or rail to another location for utilisation.

Overall, it is unlikely that any of the above represent a single solution to providing a means for stranded or smaller emitters to be brought into national and international CCUS transportation networks, and it's probable that a system containing the full range of emitters will eventually be seen. Understanding how such a system might operate and evolve and how clusters currently being designed or deployed might allow for these opportunities, is key to the expansion of CCUS technologies to support the deep decarbonisation of industry that is required.

4. Overarching Topics

4.1 Thermophysical Properties for Design, Approval, and Accounting

Differences between natural gas and CO₂ transportation largely result from differences in the thermophysical properties of both fluids. While the main component of natural gas, methane, is at far supercritical temperatures at typical onshore pipeline conditions, CO₂ is transported as a CO₂ rich mixture at temperatures close to its critical temperature and pressure ($T_c \approx 304.13$ K or 31 °C, $p_c \approx 7.38$ MPa or 73.8 bar). The transported CO₂ rich mixture can be gaseous, liquid, in vapour/liquid or liquid/liquid equilibrium, or at dense liquid-like states. Close to the critical point of a fluid both the impact of impurities on thermophysical properties and the uncertainty of commonly used property models become particularly large – this is why work on the accurate description of relevant mixtures has always been and still is integral part of CCS related research. And finally, equilibria with solids in the form of water ice, CO₂ hydrates, and solid CO₂ (dry ice) may become relevant to avoid blockage of pipelines and valves in the context of depressurisation or in conjunction with release scenarios.

Though a broad range of thermophysical properties is required for the design and operation of pipelines and pipeline networks, the properties commonly

considered most relevant are density, speed of sound and saturation temperature or vapour pressure. Accurate data for density are required not only for pipeline design itself, but also to close mass balances for leakage control during operation. In integrated networks with multiple suppliers and users, the highest demand on accuracy of calculated densities commonly result from custody transfer and avoidance of miss allocations – an aspect that is far less relevant for simple source to sink connections and needs no legal or contractual regulations in this case. In pipeline design, speeds of sound are required, e.g., in combination with phase equilibria to prove resistance against running ductile fracture or to calculate critical flow conditions during expansion. In operation speeds of sound are required for certain approaches to leakage allocation or for some flow measurement systems. Saturation temperature or pressure on the saturated liquid and vapour lines (in CO₂ containing impurities like water also for liquid-liquid equilibria) need to be known to ensure that no unwanted (for example corrosive) phases form during pipeline operation.

Thermodynamic properties of pure CO₂ are described with high accuracy by empirical equations of state (Span and Wagner, 1996). In the range primarily relevant for pipeline and ship transport this equation of state describes properties of CO₂ with an uncertainty of 0.03% in density and 0.5% to 1% in speed of sound. Vapour pressures are described with an uncertainty of less

than 0.02%. Software implementing this equation of state is readily available (for example see Span et al., 2019) and is implemented in common commercial simulation tools. However, CO₂ resulting from capture processes is not pure and even small amounts of impurities can have a significant impact on thermodynamic properties. Empirical multiparameter mixture models are commonly considered as the most accurate source of thermodynamic property data for CO₂ rich mixtures. Starting from the GERG-2008 model (Kunz and Wagner, 2012) developed for natural gases, models for CO₂ rich mixtures have continuously been improved and new components¹⁴ specific to capture processes have been added, see, e.g., Gernert and Span (2016), Souza et al. (2019), Herrig (2019), and Neumann et al. (2020). Like for all empirical and semi-empirical approaches the accuracy of these models depends on the availability of accurate experimental data. Internationally a few well established laboratories are systematically working on an improvement of the data coverage, see, e.g., Souza et al. (2019), Løvseth et al. (2018), and Ben Souissi et al. (2017).

Figure 17 illustrates the impact of minor components on density, as calculated from the most recent multiparameter models. While the minor components allowable according to specifications formulated by National Grid in the UK⁸ change the density by less than 1% except for states close to the critical point of CO₂ (a), accepting up to 2% of H₂ leads to densities deviating by more than 5% from the density of pure CO₂ over a broad range of temperatures and pressures (b). To accept reasonable amounts of other non-condensable components (specified by reference to the allowable saturation pressure; 5% N₂ is still allowable following this definition⁸) is mandatory to limit capture costs in particular for oxyfuel processes, but it results in large shifts in density. Figure 17(c) shows that densities in a mixture of 95% CO₂ with 5% nitrogen can deviate by 20% and more from those of pure CO₂.

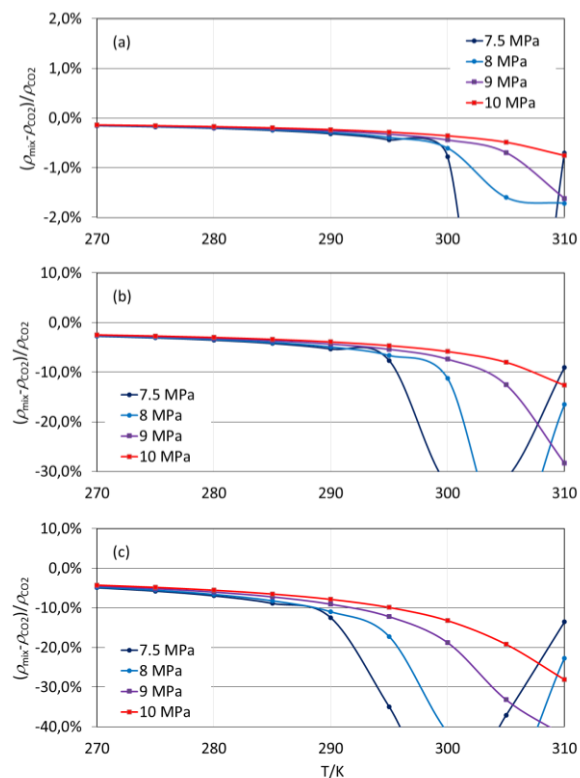


Figure 17. Deviations between densities calculated for pure CO₂ and (a) CO₂ with the minor components according to footnote 14 including CO, (b) CO₂ with the minor components including CO and H₂, and (c) a mixture containing 5% of N₂ (Herrig 2019).

Beside empirical multiparameter mixture models two other families of equations of state are frequently used in design and analysis of transport processes: Semi-empirical equations of state based on the Statistical Associating Fluid Theory (SAFT) and simple cubic equations of state. Both families have several members, see, e.g., Aavatsmark et al. (2016), Diamantonis and Economou (2011), and Chow et al. (2016), which are partly adjusted to certain categories of problems with correspondingly specific performance. However, to give an example for typical performances of these types of models, Figure 18 compares results for densities of a CO₂ rich mixture containing the minor components specified in footnote 14 (including CO but not H₂) as calculated from the most recent multiparameter model, from PCP SAFT equations of state (see Gross and Sadowski, 2001, Gross, 2005 and Gross and Vrabec, 2006), and from the so called SRK equation of state, see Soave (1972). SAFT-type

¹⁴ Preliminary specifications by National Grid allow for up to 50 ppmv of H₂O, 80 ppmv of H₂S, 2000 ppmv of CO, 100 ppmv of NO_x, 10 ppmv of O₂, and 2% mol of H₂. Other “non-condensable” gases like N₂, Ar, and CH₄ are limited by the request that the saturation pressure of the mixture should not exceed 8 MPa.

equations of state can describe liquid densities with an accuracy that is considered sufficient for most engineering applications. Larger uncertainties are typically observed in the extended critical region, making the use of this kind of property models less recommendable for custody transfer or leakage control. Cubic equations of state mostly fail to describe densities in the range of states and mixtures relevant for the transportation of CO₂ with appropriate accuracy. Other types of equations of state (see, e.g., Tsvintzelis et al., 2014 and Ibrahim et al., 2015) may come close to the performance of SAFT-type equations of state for CCS applications but are referred to less frequently in this context.

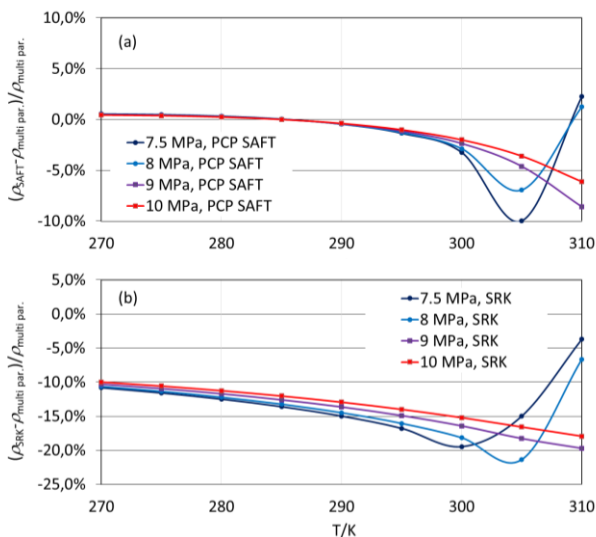


Figure 18. Deviations between densities of a mixture containing CO₂ and the minor components specified in footnote 14 including CO as calculated from a multi-parameter mixture model and (a) PCP SAFT equations of state and (b) SRK equations of state.

Effects in calculated speeds of sound are usually more pronounced than effects in calculated densities. However, conclusions drawn above for density calculations from different kinds of models and for the impact of impurities are in general valid for the calculation of speeds of sound as well.

For phase equilibria the situation is more complex than for properties in the single-phase region. All discussed types of equations of state are in principal able to describe phase equilibria in CO₂ rich mixtures, but none can claim to reliably describe systems without being fitted to accurate experimental data. In general, empirical multi-

parameter mixture models are considered most accurate for well measured systems, while SAFT-type equations of state are considered advantageous when it comes to a predictive description of systems with little or no accurate experimental data.

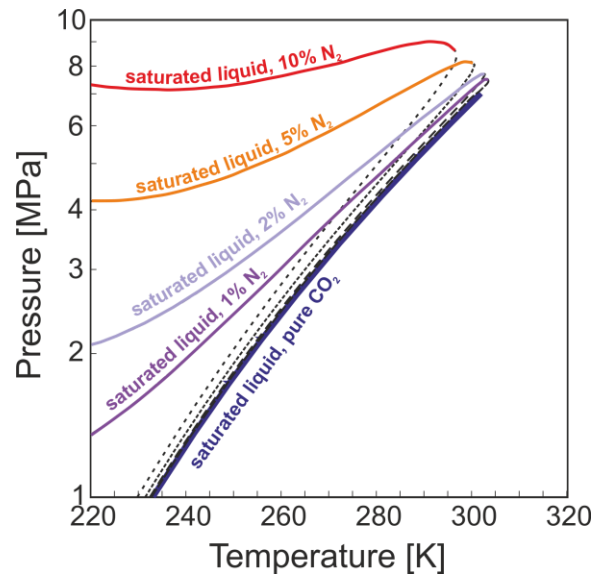


Figure 19. Influence of N₂ on the location of the saturated liquid line in CO₂ rich mixtures.

Mixtures that are characteristic for the transportation of CO₂ contain only small amounts of impurities. However, these impurities can still have a significant impact on phase equilibria. So called 'non-condensable' components like CH₄, N₂, Ar, CO or H₂ significantly increase the pressure on the saturated liquid line (the line at which the first gas-bubbles are formed in a liquid when the pressure is reduced at constant temperature). Figure 19 illustrates this effect for N₂ contents of 1%, 2%, 5%, and 10%. The effect of the non-condensable components typical for oxyfuel processes is rather well described by now; work on an accurate description of the (even stronger) effects of hydrogen is ongoing (Beckmüller et al., 2019).

More problematic is the description of traces of H₂O, of solvents like monoethanolamine (MEA) and diethanolamine (DEA), of acid formers like SO_x or NO_x, or of ammonia (NH₃) as residues of the capture process or of heavy organic components, which might be found in the CO₂ because it is known to be

a good solvent for lubricants. These components can cause the formation of a liquid phase when CO₂ is transported in the gaseous phase, or of a second liquid phase when CO₂ is transported in the liquid phase. In both cases the second phase will likely have undesired effects, e.g. with regard to corrosion. Chemical reactions involving different impurities can result in solid formation.

Work on a sufficiently accurate description of the effects of arbitrary combinations of these impurities is ongoing– still both the experimental data base and the ability of models to consistently describe certain effects are limited. In general, resulting challenges can safely be handled for simple sources to storage site connections in which the composition of the transported CO₂ rich mixture is usually constant and well known. In pipeline networks working with several sources of CO₂ rich mixtures compositions of the mixed stream change if feed-in volumes of the different sources fluctuate. Such changing compositions involving different minor components, which result from different capture processes, may result in unforeseen effects due to interactions between impurities. Limits on allowable impurities need to be overly strict and costly, unless reliable property models are available to assess the risks associated with mixing all possible minor components.

An operational risk resulting from the specific thermodynamic properties of CO₂ is solid formation in pipelines or during liquefaction processes. CO₂ cools down drastically during expansion; when being expanded to ambient or close to ambient pressure ($p < p_{Tr} \approx 5.16$ bar) it cools down even to temperatures below its triple-point temperature ($T_{Tr} \approx 216.6$ K = -56.5 °C). For pure CO₂ this effect can lead to dry ice (solid CO₂) formation. In the presence of traces of water, CO₂ hydrates or water ice may be formed. Solid formation is likely to occur in or directly behind valves, increasing the risk of pipeline clogging further. All three solid phases are relevant for dispersion modelling as well. Different models that describe the formation of water ice and dry ice are available (see, e.g., Martynov et al., 2013 and 2014), whereby one family of models is

consistent to accurate multi-parameter models describing the fluid phase (see Feistel and Wagner, 2006, Trusler, 2011, and Jäger and Span, 2012). To assess the risk of hydrate formation, models developed for natural gas processing are frequently used (see Sloan and Koh, 2007). However, these models rely on simple equations of state for the description of the fluid phases and are not consistent with more accurate fluid phase models. More recently hydrate models consistent to multi-parameter mixture models were published and implemented in an openly available software tool (see Jäger et al., 2016 and Hielscher et al., 2019). For different H₂O concentrations in CO₂, Figure 20 shows the limits at which solid formation occurs in a p,T diagram as calculated with these models. Work on the consistent description of the influence of salts solved in H₂O (brines) and of other inhibitors on the formation of hydrates is still pending and approaches describing the important kinetics of hydrate formation have not yet been adapted to the new generation of hydrate models. It is known that pipelines and even valves can be operated at conditions at which hydrates are formed in equilibrium due to dynamic limitations of hydrate formation and due to the fact that small hydrate particles do not stick to surfaces under certain conditions. However, these effects are not yet fully understood; resulting safety margins cannot be quantified properly and are not considered in simulation tools.

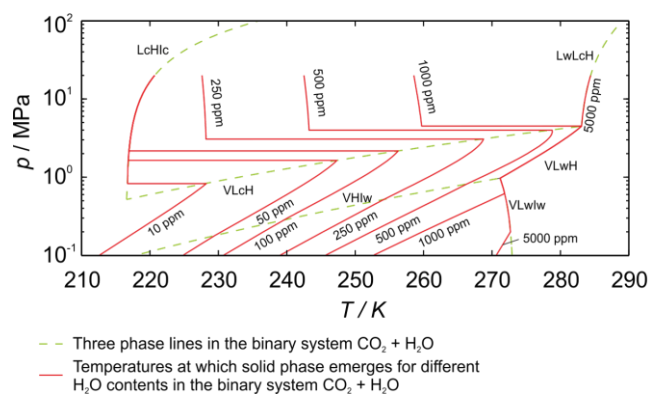


Figure 20. In a carbon dioxide / water mixture, solid phases are formed to the left of the red lines indicating different water contents. Results calculated according to Gernert and Span (2016) and Jäger et al. (2016).

4.2 Business Models

Transport and Storage (T&S) infrastructure is key to the deployment of CCUS in Europe. So, it is important to understand the risks, challenges and market failures that are currently preventing the CCUS deployment. A successful business model must address all of these challenges, including the following:

- **Lack of value proposition/business model/incentive for T&S infrastructure** is the key barrier. Although CO₂ utilisation such as CO₂ EOR has been a key driver for the deployment of T&S infrastructure in North America, T&S for geological storage of CO₂ requires government incentives.
- **Deployment of CO₂ pipelines and storage infrastructure requires a large upfront capital investment.**
- **Monopolistic market for CO₂ transport and storage** may require government intervention or regulation.
- **Long-term CO₂ storage liability** may be a showstopper for potential project developers and investors unless that risk is capped/shared by the government.
- **Coordination and timing alignment of T&S infrastructure with capture** may be needed for the first cluster projects.
- **CO₂ supply risk and uncertainty** (e.g. reduction in CO₂ capture may reduce transport and storage fees) should be addressed.

The CO₂ transport market is expected to be highly monopolistic so regulation or governmental ownership may be needed. Although other business models may also be considered, key business model options for T&S deployment in Europe include the following:

- **A Regulated Asset Base (RAB)** model has been proposed as the main deployment mechanism in the UK. Under this model the costs of projects are tightly regulated and

passed to the emitter as T&S fees. This mechanism is preferred in the UK due to the uncertainty over costs during the operational period which may be difficult to address under a fixed price model.

- **Public ownership.** Governments or state-owned enterprises could own the T&S infrastructure, given their essential role in deploying CCUS and minimising risks. Alternatively, Public Private Partnerships (PPPs) can be used. Under the PPP model, the ownership of T&S infrastructure is shared between the public and private sector. Each partner has designated responsibilities and plays different roles in the risk mitigation. It is possible for governments to start with full ownership and move onto PPP, with full private ownership models potentially developing later. To date, all CCS policies (e.g. CCS directive, ETS, CEF, TEN-E) are based on a conceptual model where the source is directly linked to the sink via one pipeline. Moreover, the pipeline is assumed not to leak (a sound assumption), and hence all the CO₂ is exported from source to sink. The pipeline can be “assumed away”, and hence the CO₂ accounting becomes simple. In transport networks, proper accounting avoiding allocation errors becomes a fiscally relevant issue.

Future directions for research and development of CO₂ T&S business models can be identified based on the following **gaps in the literature**:

- **Lack of CO₂ shipping business models in most countries** – most governments work on funding and business models for CO₂ pipeline infrastructure. The Northern Lights project has made significant progress, but the same model may not be suitable to all EU Member States.
- **Lack of emphasis on road/rail transport and dedicated onshore infrastructure** – which is a major issue for dispersed

industrial sites across Europe (e.g. cement and lime) that may require dedicated onshore pipelines or road/rail transport to connect to other clusters or pipeline networks. Most governments promote clusters so there is no progress on business models for small-scale CO₂ transport and who will own and operate these.

4.3 Legal and Regulatory Background

Since CCUS embraces a large number of partially interdependent and conflicting issues and interests, the legal and regulatory background is relevant for the feasibility of any CCUS project and has to be observed, even more so in the context of multi-polar transportation networks. Legal challenges that are specifically highlighted within the context of networks refer to cross-border issues, including the prohibition of export of waste pursuant to the London Protocol, and the coordination of CO₂ streams from different sources.

Examination of the legal and regulatory background focuses on current EU provisions as the international context which is relevant for Europe and – as examples – on the legal situation in the UK, the Netherlands, Germany and Norway.

4.3.1 London Protocol

For Parties of the 1996 London Protocol to the *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter*, the export (and import) of CO₂ for offshore CCS is prohibited pursuant to article 6 (Dixon et al., 2015). In the EU, this prohibition is directly applicable pursuant to article 11 (1) lit. f) of Regulation (EC) No. 1013/2006.

The 2009 amendment to the London Protocol to allow the export of CO₂ for offshore CCS was not ratified by a sufficient number of parties (Henriksen and Ombudstvedt, 2017), but on 11 October 2019 the parties agreed on the possibility for the provisional application of the 2009 amendment (Bankes, 2019). Therefore, parties to the London Protocol that wish to participate in a cross-border CO₂ network for (also) offshore CCS can now unilaterally declare the provisional application of the 2009 amendment and enter into respective agreements with other parties, allowing the export of CO₂ for offshore storage.

4.3.2 Cross-Border CO₂ Pipeline Transportation and Differences in Legal Requirements

Differences in the legal requirements with regard to the construction and characteristics of pipelines can impede cross-border pipeline projects because the developers have to consider additional specifications (Heffron & others, 2018). Especially, if the national requirements contradict each other, challenges for the project are created, e.g. in the case of different approaches to the conceptual design or different safety philosophies. Yet, as far as the different requirements do not have an impact on the pipelines and networks beyond the respective border, the adverse effect is limited.

The following discussion focuses on specific requirements for CO₂ pipelines. But diverging national requirements for pipelines in general can have the same effects.

In most countries, there are no or little specific requirements for CO₂ pipelines. On first inspection, there are no or little requirements that would impact the conceptual design/operation of CO₂ transportation pipelines or other aspects relating to CCS/CCUS with major relevance for potential cross-border conflicts. For example:

- **The United Kingdom:** There is no specific safety legislation for CO₂ pipelines. General safety legislation and other legislative requirements are applicable to CO₂ pipelines. Safety legislation in the UK is constructed as a series of specific regulations under the umbrella of the *Health and Safety at Work Etc. Act (HSWA) 1974*. Under the framework set by the HSWA, there are a number of sets of regulations, which apply to specific activities and assets. In relation to pipelines, the specific regulations which apply include the *Pipelines Safety Regulations (PSR) 1996* and the *Pressure Systems Safety Regulations (PSSR) 2000*. PSR applies to all pipelines in Great Britain

(England, Scotland and Wales), and to all pipelines in territorial waters and on the UK Continental Shelf (UKCS). In the *Pipelines Safety Regulations (PSR) 1996* and the *Pressure Systems Safety Regulations (PSSR) 2000*, duties for pipeline owners and operators are defined in regard to safety. In addition, PSR specifically defines and applies additional duties for major accident hazard pipelines (MAHPs), which are pipelines that convey 'dangerous fluids' and for which the consequences of failure would present a major accident resulting in significant danger to people. Since CO₂ streams from industrial sources may contain toxic components (e.g. CO, H₂S, NO_x and SO_x) and due to the behaviour of CO₂ in its dense phase, the safety regulatory will presumably consider CO₂ pipelines for CCS as MAHPs although the legislation is not explicit on this. Legal compliance in the UK is generally met through the application of recognised codes and standards. In terms of hazardous pipelines, the relevant UK requirements are specified in the approved British Standards Institution (BSI) code PD 8010: Part 1:2015, titled '*Code of Practice for Pipelines - Steel Pipelines on Land*' for all hazardous pipelines (except for natural gas) such as for CO₂.

- **The Netherlands:** There is no specific safety legislation for CO₂ pipelines in the Netherlands. General safety requirements for pipelines are stipulated by article 93 Mining Decree (*Mijnbouwbesluit*) and further specified by chapter 10 of the Mining Regulation (*Mijnbouwregeling*). The regulation refers to standardisation, especially standards developed by the company NEDerlandse Norm. These standards are aimed at general pipeline requirements or pipelines with certain characteristics (cast iron pipes, flexible pipes), not specifically at a CO₂ pipeline context. Article 10.3 Mining Regulation

demands frequent investigations of the pipelines.

- **Germany:** In Germany, CO₂ pipelines for CCS are covered by the Carbon Dioxide Storage Act (*Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid – Kohlendioxid-Speicherungsgesetz – KSpG*), which refers to stipulations in the Energy Industry Act (*Gesetz über die Elektrizitäts- und Gasversorgung – Energiewirtschaftsgesetz – EnWG*) in regard to natural gas pipelines. Pursuant to § 4 (3) sentence 2 KSpG, § 49 (1) EnWG, pipelines for CO₂ have to be constructed to be technically safe (to the generally accepted state-of-the-art). The competent authorities will accept the requirements that are issued by the national standardisation body (*Deutscher Verein des Gas- und Wasserfaches – DVGW*), § 4 (3) sentence 2 KSpG, § 49 (2) no. 2 EnWG; but there are no DVGW standards in regard to CO₂ pipelines. Therefore, in effect, there are no specific specifications in regard to the construction and characteristics of CO₂ pipelines. In regard to major accidents, the KSpG-regime supersedes the general rules. Yet, relevant ordinances to create substantial duties in regard to major accidents have never been enacted. Thus, there are currently no specific duties for CO₂ pipeline operators with regards to major accidents.
- **Norway:** CO₂ pipelines are in general covered by chapter 6 of the Regulations relating to exploitation of subsea reservoirs on the continental shelf for storage of CO₂ and relating to transportation of CO₂ on the continental shelf (FOR-2014-12-05-1517, *Forskrift om utnyttelse av undersjøiske reservoarer på kontinentalsokkelen til lagring av CO₂ og om transport av CO₂ på kontinentalsokkelen*). Chapter 6 provides the requirements for (inter alia) CO₂

pipeline permits if the permits are not covered by the plan for the actual storage site (section 4-5). Section 1-6 lays down the relevant definitions: 'Facility' is defined in letter i) as an installation, plant, and other equipment for the exploitation of undersea reservoirs for the storage of CO₂; it also includes pipelines and cables, unless otherwise decided. 'Transport' is defined broadly in letter v) as the shipping of CO₂ in pipelines as well as the building of pipelines; the placement, operation and use of a facility for transport. Chapter 10 of the regulations stipulates special safety requirements for CO₂ storage and transport. This includes the requirement of a high level of safety in line with the technological development (section 10-1) as well as rules for emergency preparedness (section 10-2), safety zones (section 10-4) and safety documentation (section 10-6). None of these stipulations provides specifications for the construction and characteristics of the pipelines. For CO₂ pipelines in the context of petroleum activities, chapter 4a of the Regulations to Act relating to petroleum activities (FOR-1997-06-27-653, *Forskrift til lov om petroleumsvirksomhet*) is applicable, but does not add any further specifications for CO₂ pipelines.

There are specific international standards for CO₂ pipelines (ISO 27913:2016 '*Carbon dioxide capture, transportation and geological storage – Pipeline transportation systems*'; also DNVGL-RP-F104 '*Design and operation of carbon dioxide pipelines – Recommended practice*'). But these are rather broad and have little impact on potential conflicts in regard to resolving disparities between specific requirements or clarifying which requirements should take precedence. In the case of the transborder transportation of CO₂ for CCS/CCUS within the EU, the competent authorities have to cooperate in order to meet the requirements of the CCS-Directive, article 24 of Directive 2009/31/EC. Any further cooperation is not legally required.

Furthermore, there are institutional settings in place, in which requirements for CO₂ transportation in an international network can be discussed, e.g. the North Sea Basin Task Force or ACER (Heffron et al., 2018).

4.3.3 Cross-Border CO₂ Pipeline Construction and Permitting Procedures

For the permitting of pipeline construction, different countries use procedures with different requirements and timetables. These differences can create confusion, additional costs and delays.

To streamline certain aspects of the permitting procedures might facilitate the timely construction of CO₂ pipelines. Yet, such mechanisms can also have adverse effects: Experiences in the context of the TEN-E Regulation (EU) No 347/2013 show that streamlined procedural requirements can add complexity to the existing procedures and slow down the process. Especially specific procedural requirements in a streamlined timetable – such as consultations pursuant to article 9 (5) of Regulation (EU) No 347/2013 – have the potential to frustrate or delay the overall process due to the different procedural contexts of these requirements in the different countries.

4.3.4 Coordination of CO₂ Streams

In general, the system operators are responsible for the requirements for the CO₂ streams (with regard to the design of the pipelines). In the EU context, operators are not entirely free to set CO₂ specifications, especially to ensure compatibility with a potential future network, because they have to grant third party access which can only be refused if it is due to technical incompatibility which cannot be reasonably overcome, article 21 (1) and (2) lit. c of Directive 2009/31/EC.

On the international level, there is no legal mechanism to coordinate requirements on CO₂ streams in an international CO₂ network. At the EU level, the Commission can adopt guidelines in

regard to CO₂ streams pursuant to article 12 (2) of Directive 2009/31/EC. But these are aimed at the requirements of article 12 (1) of Directive 2009/31/EC and not at issues relating to coordination. So far, the guidelines issued by the Commission – especially Guidance Document 2: *Characterisation of the Storage Complex, CO₂ Stream Composition, Monitoring and Corrective Measures* in 2011 – do not address the specific challenges of CO₂ networks. Yet, on an international and EU level, there are institutionalised contexts in which the coordination of requirements on CO₂ streams can be discussed, e.g. the North Sea Basin Task Force or ACER (Heffron & others, 2018).

On the national level, there are no or little coordination mechanisms. A specific coordination mechanism at the national level is not needed where pipeline networks are monopolised and the pipeline operator can ensure consistency of the requirements. But also, in these countries, a situation might materialise in which the first ‘point to point’ CO₂ pipelines are constructed by other parties outside of the monopolised network context.

4.3.5 Carbon Accounting Framework

CO₂ removal and CCS policies should be made to fit and support the CCUS industrial clusters that are evolving. These clusters incorporate many emission sources and transport modes. Some may involve intermediate storage, and CO₂ can be taken out for utilization at any point in the system.

For European CO₂ capture projects, there are different CO₂ sources apart from industrial emissions, such as process emissions, biogas, biofuel and probably more to come. Each is covered by different regulatory framework. As such, a carbon accounting framework (monitoring under EU ETS or other frameworks that account the CO₂) that enables transport in networks is needed. This issue is already relevant for the CCS value chain in Norway.

A conceptual illustration of carbon accounting through the CO₂ value chain is shown in Figure 21.

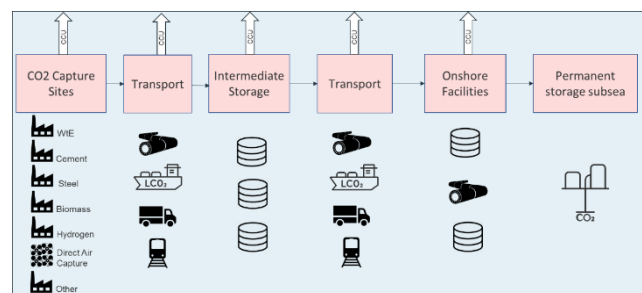


Figure 21. Conceptual illustration of carbon accounting through the CO₂ value chain.

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